ULAB JOURNAL OF SCIENCE AND ENGINEERING VOL. 4, NO. 1, NOVEMBER 2013 (ISSN: 2079-4398)

Prosthetic Arm – its Digital Realization

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Abstract—The technology that deals with the design and construction of prosthetic arm has shown great progress in recent years. The prosthetic arm considered in this article is a substitute of the natural arm and is capable of performing its function. Here two standard armsthat are modeled throughRecursive Least Squares (RLS) methods considered for processing. The present work is focused on PID tuning and discrete domain analysis which makes it interesting as prosthetic work in digital domain is less.Designing the arms is also concerned with proper realization of control system in terms of related parameters. The optimality of the system is achieved and the design proves its stability. In the design proportional integral and derivative (PID) type of compensation is incorporated appropriately. Discrete digital control design of conceptual hand prosthesis is realized through the work. Here, the system is processed in sample data domain using z-transformation, and it readily accommodates any change of data in system or input parameter. Accordingly Jury test analyzes the system to be stable.

Keywords—Prosthetic arm-RLS design, PID compensation, control parameter analysis Jury stability test.

Manuscript received on 21 June 2013 and accepted for publication on 22 July 2013.

1 INTRODUCTION

PROSTHETIClimb is an artificial device extension that replaces a missing body part. Normally a limb works as per the commands received from the brain via various neuromotors [1,2,3].The brain monitors the desired position and the sensed position, generating an error signal to the nervous system [4].The biological concept is to introduce the robotic arm and to develop its artificial organism with dexterity [2].The technology is based on prosthetic limb control modeling and analysis through error control system [4]. Here, mathematical models are initiated with two transfer function for two different arms by RLS method. Proper PID tuning is set up for both models. The parametric value from the response analysis is found to be effective for comparison. A stable system holds the set point without oscillating. Thus, satisfactory criteria of stability are established by Jury table representation which isone of the best suited tools in discrete domain [5,6].

2 DESIGNAND SIMULATION ASPECT TOWARDS DISCRETE DOMAIN ARM TRANSFER FUNCTION

2.1 Recursive Least Squares

The armsare modeled mathematically using the Recursive Least Squares method [8] using a program written in Borland C++ Builder. Next discussion gives the overview of the modeling using RLS method. The main advantages of using this system identification method are thefactors such as friction are taken into account. A model of the real system is obtained rather than a theoretical one where factors such as friction are ignored. Each of the individual limbs is considered as an independent system and all are controlled simultaneously. It is assumed that they do not affect each other although there is some (small) effect. Various parameters are experimented with in order to obtain the best model. The changing parameters are the number of poles and zeros.

The poles in the denominator of this model represent its stability. The stability can be represented by their position in the unit circle. The poles of this system are near the imaginary axis of the unit circle. This confirms the oscillatory motion that occurs [16, 17, 18].

If the poles are by the edge of the circle then the system is virtually unstable and oscillations are much more of a factor and take longer to dissipate. The “soft” nature of the springs lessens the effect.

The objective of the controller is to move the poles on to the real axis so that the oscillations are dampened and are not of much effect.

The mathematical model for the first arm that were obtained by the RLS methods was

$T(z) = C(z)/R(z)$

$$T(z) = \frac{0.00z + 0.0273}{(-0.7487)z^5 + (-0.2067)z^4 + (-0.5245)z^3 + 0.1424z^2 + 0.06z + 0.3053} \quad \text{……….(i)}$$

The mathematical model for the second arm that were obtained by the RLS methods was

$T(z) = C(z)/R(z)$

$$T(z) = \frac{0.0000z^2 + 0.0222z + 0.0143}{z^9 + (-1.8441)z^8 + 0.6365z^7 + 0.5541z^6 + (-0.3747)z^5 + 0.0054z^4 + 0.5070z^3 + (-0.6453)z^2 + 0.0841z + 0.1138} \quad \text{……..(ii)}$$

These models represent the response of each arm to a step input of 45 degrees. The first arm response is very similar to the mathematical model as shown in Fig.1

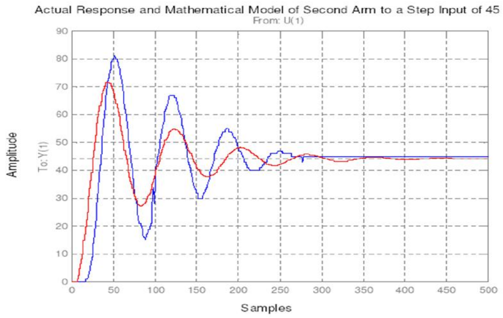

Figure 1.The mathematical model (red) and actual response (blue) of the first arm to a step input of 45.

The model of the second arm is less good due to the speed of response of the arm to a step input of 45. The graph is as follows:

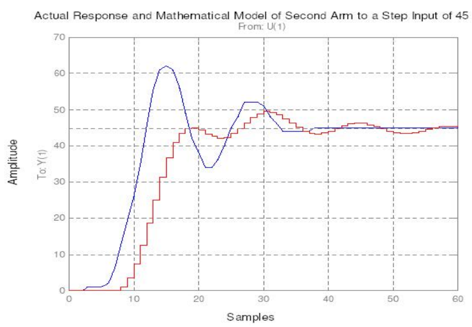

Figure 2.The mathematical model (red) and the actual response (blue) of the second arm to a step input of 45

These models are by no means an exact replica of the actual response of each arm. However they are a good approximation, which will be used to configure the control.

The first arm system is design with six poles and six zeros. The second arm system is design with three poles and nine zeros. These values are realized from experimentation.

2.2 Open-Loop Control Consideration

When a system is without any feedback path, an open loop control is achieved. This type of control causes this arm to move in a ballistic manner and oscillate before a final resting position is achieved. In maximum systems this type of control is of no use.

This type of control is used when the limbs move slowly. The speed of the arm has a direct relationship to the ballistic nature of the arm. If the arms move sufficiently slowly, virtually no recognizable oscillations can be seen, as very little energy is stored in the springs.

2.3 Closed-Loop Control Consideration

Closed loop control has a feedback path, which affects the input and helps in obtaining the desired output. This is the conventional controlling method when for systems such as robotic arms. There are different approaches such as Proportional-Integral-Derivative control and Lead Lag Control [7,9]. Fig.3. shows the block diagram of the system with the controller present. All of the controllers explained subsequently are negative feedback controllers and are implemented into the Controller block [10].

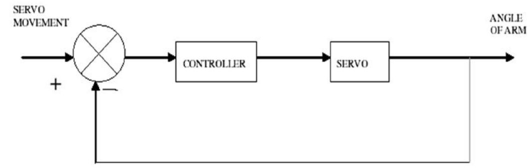

Figure 3.Block Diagram of the Whole System

2.4 Control Action for Proper Gain Tuning

Firstly a variable proportional controller is implemented which deals with different gains within the system.

The input is simply a voltage to the servo and the output is the joint angle. The potentiometer converts the angle to a voltage, which is compared to the desired values [11]. It should be noted that there is also another inner feedback loop within the servo but this is not controlled.

The control loop implemented looks at the size of the error and changes the speed at which the servo is moving accordingly. Greater the difference between the original and desired joint angle, faster the servo will move and vice versa. The user of the C++ program can set the error scalar to investigate different results and hence choose the most appropriate one. The block diagram describing this controller is shown in Fig.4.

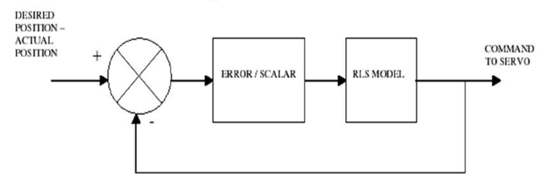

Figure 4.The Block Diagram for PID control

This control method can reduce the oscillations that occur from an un-damped system[12] but not completely, which is due to the nature of the simplicity of the control.

2.5 Proportional-Integral-Derivative (P.I.D.) Imposition for Optimal Response

Subsequently a Proportional-Integral-Derivative (P.I.D.) controller is investigating as a more complicated control strategy. This type of controller is widely used in control systems due to its flexibility. It can be employed to meet many different design needs. For example it can be used to decrease rise time, reduce overshoot and decrease oscillations [13]. This is due to the flexibility of the three sections of the control. That is the proportional, integral and derivative parts. The proportional part can be used to adjust the speed with which the system responds. The integral term provides zero error and the derivative term introduces damping. The derivative term is the important section in this case. The block diagram of the control system with a PID controller is as follows:

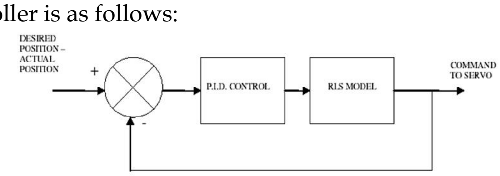

Figure 5.The Block Diagram for PID control

The Ziegler Nichols Tuning Method [14] is used to obtain initial values for the proportional, integral and derivative sections. These values are used as a guide and then tweaked in order to obtain a response that is desire. The response of the first arm with P.I.D control is shown in Fig. 6.

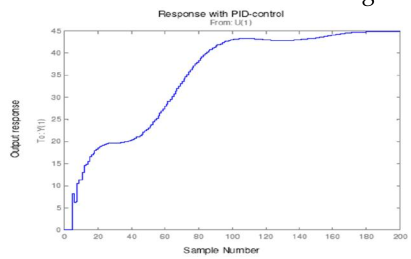

Figure 6.Response of the First Arm with PID Control

Fig. 7.Shows response of the second arm with PID control.

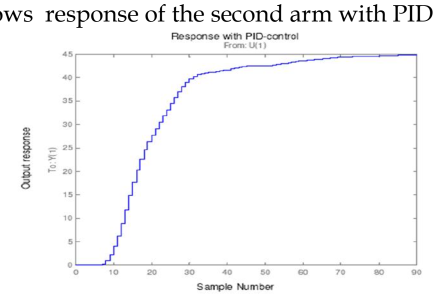

Figure 7.Response of the Second Arm with PID Control

2.6 Lead Lag Compensation Control for the Arm Model

There are various approaches to this method of compensation. The compensation can be cascade, feedback, output or load, or input [9]. The compensation used is cascade. That is the compensation control was placed before the plant. Fig.8. shows such system.

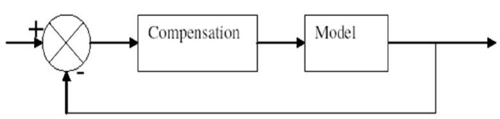

Figure 8.Block Diagram showing cascade compensation

The lead lag compensation is designed using the root locus method. Additional zeros are added to a lead component to cancel out the poles of the model. Then extra poles are added near the centre of the unit circle until a desirable transient response is achieved.

Poles are added near to (0, 0) as the decay time is less nearer to the centre. A lag term is then added to reduce the steady state error. The block diagram for lead lag controller is shown in Fig. 9.

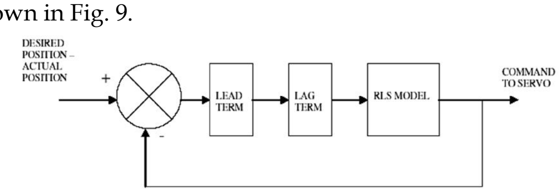

Figure 9.The Block Diagram for Lead Lag control

The simulated response with lead lag control for the first arm and second arm is as follows:

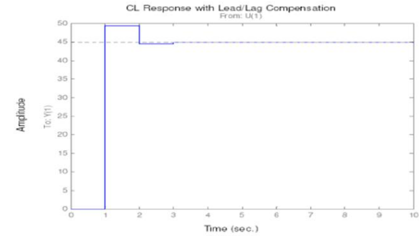

Figure 10.Response of the First Arm with Lead Lag Control

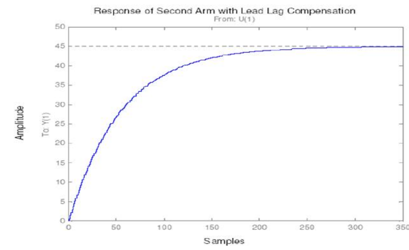

Figure 11.Response of the Second Arm with Lead Lag Control

All three of the control strategies has different characteristics such as complexity, transient response and overshoot. For real world applications however the desired features might be slightly different which would lead to different requirements.

3 Result and Testing

Various tests are carried out using several control strategies. These are divided into two sections: a comparison section to evaluate the different control strategies and an application section, which experiments with the arm doing real-life applications.

The first test is carried out on the first limb. This is reset to an angle of 45 degrees from the vertical section and will give a step input of 45 degrees to move it to 90 degrees to the vertical, which is repeated for all four-control strategies. That is no control (red line); variable gain (green line), PID (blue line) and lead lag compensation (purple line). The figure below show the result of the first limb to this step input under different control strategies.

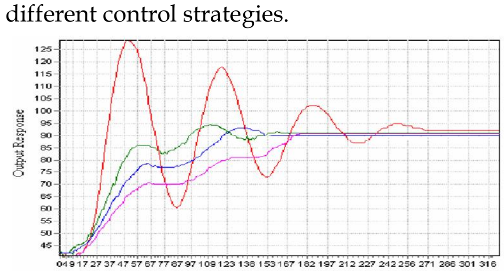

Figure 12.Graph showing the response of the first limb to a 45-degree step input under different control strategies

The table below is the analysis of the graph data above. It shows the different settling times, the steady state error and overshoots percentage values that occur with the different control strategies.

TABLE 1

NUMERICAL ANALYSIS OF THE RESULT OF THE DIFFERENT CONTROL STRATEGIES

Control Method	Steady State Error	Percentage Overshoot	Response Time (s)
Open Loop	+3	81%	4.15
Variable Gain	+2	6.4%	2.46
PID	0	6.6%	2.31
Lead Lag	+1	0%	2.69

As it can be seen for this particular step input to this particular arm the best overall control strategy is PID. This does overshoot however it has a zero steady state error as expected and a fast response time.

The second test on the first arm is a step input with a magnitude of 55 degrees. The start and end positions are also different to the first test. The starting angle from the vertical is 55 degrees and the end angle is110 degrees. Again all four-control strategies are shown.

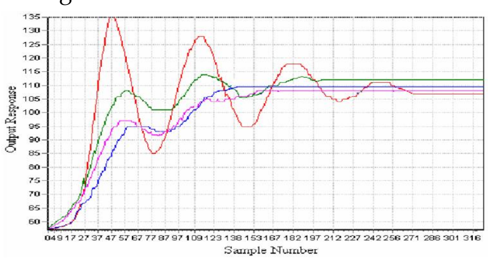

Figure 13.Graph showing the response of the first limb to a 55-degree step input under different control strategies.

The table below numerically analyses the graph data.

TABLE 2

NUMERICAL ANALYSIS OF THE RESPONSE OF THE 55-DEGREE STEP TO THE FIRST LIMB

Control Method	Steady State Error	Percentage Overshoot	Response Time (s)
Open Loop	-3	53.8%	4.16
Variable Gain	+2.5	3.4%	3.15
PID	-0.5	0%	2.12
Lead Lag	-2	0%	2.35

As the table shows the PID is the best control strategy. There is no overshoot but a slight steady state error. The response time is also the quickest of the four control strategies.

Tests are now carried out upon the second limb. The first limb is kept at an angle of 90 degrees to the vertical upright during these. The first test on the second limb involved giving it a 45-degree step input. The starting position is 45 degrees to the first limb and the desired end position was 90 degrees to horizontal first limb; that is vertical. The four control strategies are tested upon and the results are graphically represented below.

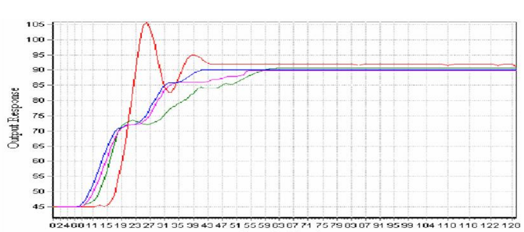

Figure 14.Graph showing the response of the second limb to a 45-degree step input with different control strategies.

A numerical analysis of the graph above is represented in the below table.

TABLE 3

ANALYSIS OF THE RESPONSE OF THE SECOND ARM TO A STEP INPUT OF 45 DEGREES.

Control Method	Steady State Error	Percentage Overshoot	Response Time (s)
Open Loop	+2.5	26.3%	0.66
Variable Gain	+1	0%	0.97
PID	0	0%	0.62
Lead Lag	-0.5	0%	0.83

As the table shows the PID is the best control strategy. There is no steady state error and overshoot and the response time is the quickest of all four-control strategies.

The next test on the second limb is a step of 55-degrees. The starting position of the arm for all four-control strategies is 55-degrees to the first limb and the desired end position is 110 degrees to the horizontal first limb. The response of each control strategy is below. The red line symbolizes the open loop no control strategy. The green line represents the variable gain control. The blue line represents PID control and the purple line represents the lead lag compensation.

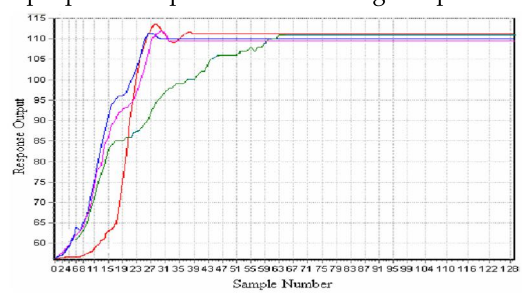

Figure 15.Graph of response to a 55-degree step input of the second limb.

The table below is the numerical analysis of the response of the arm to the 55-degree step input.

TABLE 4

ANALYSIS OF THE RESULT TO A STEP INPUT OF 55-DEGREES TO THE SECOND LIMB

Control Method	Steady State Error	Percentage Overshoot	Response Time (s)
Open Loop	+2	3.5%	0.6
Variable Gain	+1.5	0%	0.97
PID	0	1.8%	0.45
Lead Lag	-0.5	4.6%	0.55

The table above shows that PID control is the best control strategy. There is no overshoot and the response is quickest. However there is a slight overshoot of 1.8% but this is small enough to be ignored and still state that the test is a success.

The investigations on the second arm show that PID control is the most successful control strategy. The control is not as important with this limb due to the stiffer springs [15]. This is the reason why in the first test, three of the control strategies have a 0% overshoot. The second test overshoot is much less because the arm is moving upwards and is being acted upon by gravity.

Considering the first arm transfer function

$T(z) = C(z) / R(z)$

$$T(z) = \frac{0.00z + 0.0273}{(-0.7487)z^5 + (-0.2067)z^4 + (-0.5245)z^3 + 0.1424z^2 + 0.06z + 0.3053}$$

Characteristic polynomial:
F(z)=$(-0.7487)z^5 + (-0.2067)z^4 + (-0.5245)z^3 + 0.1424z^2 + 0.06z +$ 0.3053
F(1) = -0.9722[F(1)<0 not satisfied]
$(-1)^5$F(-1) = -1.4542 [$(-1)^4$ F(-1) < 0 not satisfied]

TABLE 5
JURY TEST FOR FIRST ARM TRANSFER FUNCTION

Row	z^0	z^1	z^2	z^3	z^4	z^5
1	a_0 = 0.3053	a_1 = 0.06	a_2 = 0.1424	a_3= -0.5245	a_4= -0.2067	a_5= -0.7487
2	a_5=-0.7487	a_4=-0.2067	a_3= -0.5245	a_2 = 0.1424	a_1 = 0.06	a_0 =0.3053
3	b_o= -0.46734	b_1= -0.13643	b_2 = -0.34922	b_3 = 0.05351	b_4 =0.01819	
4	b_4 = 0.01819	b_3 = 0.05351	b_2 = -0.34922	b_1= -0.13643	b_o= -0.46734	
5	c_0 = 0.21807	c_1 = 0.06279	c_2 = 0.15685	c_3= 0.02253		
6	c_3= 0.02253	c_2 = 0.15685	c_1 = 0.06279	c_0 = 0.21807		
7	d_0 =0.04704	d_1 =0.01016	d_2 =0. 03279			

$$b_k = \begin{vmatrix} a_0 & a_{n-k} \\ a_n & a_k \end{vmatrix} \qquad c_k = \begin{vmatrix} b_0 & b_{n-1-k} \\ b_{n-1} & b_k \end{vmatrix} \qquad d_k = \begin{vmatrix} c_0 & c_{n-2-k} \\ c_{n-2} & c_k \end{vmatrix}$$

TABLE 6
JURY TEST FOR SECOND ARM TRANSFER FUNCTION

Control Method	Steady State Error	Percentage Overshoot	Response Time (s)
Open Loop	+2	3.5%	0.6
Variable Gain	+1.5	0%	0.97
PID	0	1.8%	0.45
Lead Lag	-0.5	4.6%	0.55

Row	z^0	z^1	z^2	z^3	z^4	z^5	z^6	z^7	z^8	z^9
1	$a_0 = 0.1138$	$a_1 = 0.0841$	$a_2 = -0.6453$	$a_3 = 0.5070$	$a_4 = 0.0054$	$a_5 = -0.3747$	$a_6 = 0.5541$	$a_7 = 0.6365$	$a_8 = -1.8441$	$a_9 = 1$
2	$a_9 = 1$	$a_8 = -1.8441$	$a_7 = 0.6365$	$a_6 = 0.5541$	$a_5 = -0.3747$	$a_4 = 0.0054$	$a_3 = 0.5070$	$a_2 = -0.6453$	$a_1 = 0.0841$	$a_0 = 0.1138$
3	$b_0 = -0.9870$	$b_1 = 1.8537$	$b_2 = -0.7099$	$b_3 = -0.4964$	$b_4 = 0.3753$	$b_5 = -0.0480$	$b_6 = -0.4439$	$b_7 = 0.7177$	$b_8 = -0.2939$	
4	$b_8 = -0.299$	$b_7 = 0.7177$	$b_6 = -0.4439$	$b_5 = -0.0480$	$b_4 = 0.3753$	$b_3 = -0.4964$	$b_2 = -0.7099$	$b_1 = 1.8537$	$b_0 = -0.9870$	
5	$c_0 = 0.8878$	$c_1 = -1.6187$	$c_2 = 0.5702$	$c_3 = 0.4758$	$c_4 = -02601$	$c_5 = -0.0985$	$c_6 = 0.2295$	$c_7 = -0.1635$		
6	$c_7 = -0.1635$	$c_6 = 0.2295$	$c_5 = -0.0985$	$c_4 = -02601$	$c_3 = 0.4758$	$c_2 = 0.5702$	$c_1 = -1.6187$	$c_0 = 0.8878$		
7	$d_0 = 0.7614$	$d_1 = -1.3995$	$d_2 = 0.4901$	$d_3 = 0.3799$	$d_4 = -0.1531$	$d_5 = 0.0058$	$d_6 = -0.0611$			
8	$d_6 = -0.0611$	$d_5 = 0.0058$	$d_4 = -0.1531$	$d_3 = 0.3799$	$d_2 = 0.4901$	$d_1 = -1.3995$	$d_0 = 0.7614$			
9	$e_0 = 0.5759$	$e_1 = -1.0652$	$e_2 = 0.3638$	$e_3 = 0.3125$	$e_4 = -0.0866$	$e_5 = -0.0811$				
10	$e_5 = -0.0811$	$e_4 = -0.0866$	$e_3 = 0.3125$	$e_2 = 0.3638$	$e_1 = -1.0652$	$e_0 = 0.5759$				
11	$f_0 = 0.3251$	$f_1 = -0.6205$	$f_2 = 0.2349$	$f_3 = 0.2095$	$f_4 = -0.1363$					
12	$f_4 = -0.1363$	$f_3 = 0.2095$	$f_2 = 0.2349$	$f_1 = -0.6205$	$f_0 = 0.3251$					
13	$g_0 = 0.0871$	$g_1 = -0.1732$	$g_2 = 0.1084$	$g_3 = -0.0165$						
14	$g_3 = -0.0165$	$g_2 = 0.1084$	$g_1 = -0.1732$	$g_0 = 0.0871$						
15	$h_0 = 0.073$	$h_1 = -0.0133$	$h_2 = 0.0066$							

$$b_k = \begin{vmatrix} a_0 & a_{n-k} \\ a_n & a_k \end{vmatrix}$$

$$d_k = \begin{vmatrix} c_0 & c_{n-2-k} \\ c_{n-2} & c_k \end{vmatrix} \qquad e_k = \begin{vmatrix} d_0 & d_{n-3-k} \\ d_{n-3} & d_k \end{vmatrix}$$

$$f_k = \begin{vmatrix} e_0 & e_{n-4-k} \\ e_{n-4} & e_k \end{vmatrix} \qquad g_k = \begin{vmatrix} f_0 & f_{n-5-k} \\ f_{n-5} & f_k \end{vmatrix}$$

$$h_k = \begin{vmatrix} g_0 & g_{n-6-k} \\ g_{n-6} & g_k \end{vmatrix}$$

Table 5 represents the Jury format of first Arm Transfer function. From Table 5 the sufficient conditions for stability are obtained.

$|a_0| < |a_5|$, Satisfied
$|b_0| > |b_4|$, Satisfied
$|co| > |c_3|$, Satisfied
$|d_0| > |d_2|$, Satisfied

So the first transfer function is appropriate for the system.

Now considering the second arm transfer function
T(z) = C(z)/R(z)

$$T(z) = \frac{0.0000z^2 + 0.0222z + 0.0143}{z^9 + (-1.8441)z^8 + 0.6365z^7 + 0.5541z^6 + (-0.3747)z^5 + 0.0054z^4 + 0.5070z^3 + (-0.6453)z^2 + 0.0841z + 0.1138}$$

Characteristic polynomial:

$$F(z) = z^9 + (-1.8441)z^8 + 0.6365z^7 + 0.5541z^6 + (-0.3747)z^5 + 0.0054z^4 + 0.5070z^3 + (-0.6453)z^2 + 0.0841z + 0.1138$$

F(1) = 0.0368[F(1)>0 satisfied]
$(-1)^4$F(-1) =3.669 [$(-1)^4$ F(-1) > 0 satisfied]
Sufficient conditions for stability are
[a_0] < [a_9] , Satisfied;[b_0] > [b_8] , Satisfied
[c_0] > [c_7] , Satisfied;[d_0] > [d_6], Satisfied
[e_0] > [e_5], Satisfied;[f_0] > [f_4], Satisfied
[g_0] > [g_3], Satisfied;[h_0] > [h_2], Satisfied
The required conditions are satisfied. Hence, the second arm transfer function is stable.

4 Conclusion

It is confirmed that both the prosthetic arms arrest able with the best control strategy but the second one is more acceptable in every aspect in terms of analysis. Appropriate PID tuning makes the system responses and parameters more adaptable. Analysis through RLS is already established. In future research, advance computational process like particle swarm optimization(PSO),bacterial foraging (BF),fuzzy logic, genetic algorithm (GA) will be incorporated in the study. Basically the biological systems are nonlinear and non-deterministic in nature. So, the z domain representation of the transfer function will also develop the nondeterministic and nonlinear performance analysis of the arm system. Controllability and observability testing can also be introduced for further analysis of the system.

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