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H_∞ loop Shaping Robust Postprandial Glucose Control for Type 1 Diabetes

Safa F. Fadhel [a*], **Safanah M. Raafat** [b]

[a] Control and System Eng. , University of Technology-Iraq, Baghdad , Iraq , safaf.fadhel@yahoo.com

[b] Control and System Eng. , University of Technology-Iraq, Baghdad , Iraq , 60154@uotechnology.edu.iq

*Corresponding author.

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K E Y W O R D S

Artificial pancreas (AP), Bergman Model, H∞ Loop Shaping (HLS), Robust Control

A B S T R A C T

The Bergman model is one of the most commonly used models applied to the representation of the artificial pancreas (AP). It is important to study the effects of the insulin infusion on blood glucose concentration. This work includes a case study for the design of a robust controller for an AP. Robustness is a structured control that improves a system's ability to keep its stability and performance under various conditions. The proposed H_∞ loop shaping HLS method will fulfill the design requirements of robust control and performance. The results of the simulation prove the superiority of the intended approach in terms of simple structure, robust performance, and stability with the least control effort

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1. INTRODUCTION

Diabetes mellitus (DM) is a category of heterogeneous chronic disorders because relative or absolute insulin lack characterized by hyperglycemia. There are twin major classifications of diabetes which known as type1 and type2 diabetes based on etiology and clinical appearance. Type 2 diabetes (T2D) accounts for more than 90% of diabetes [1]. Type1diabetes (T1D) is known as childish diabetes because it typically occurs in teenagers and children. This happens because of the destruction of progressive autoimmune in β cells. Due to the wide difference between autoimmunity onset and diabetes onset, more than 80-90 % of β cells were destroyed by diagnosis. Recent studies, however, have shown that in some known T1D patients they never hit zero [2]. T1D principal is symptoms are elevated thirst, exhaustion, and frequent urination. Exogenous insulin therapy is the main treatment. The AP is a close loop delivery system consisting of three parts: an infusion pump, glucose sensor, and a controller that controls concentrations of glucose via automated hormonal distribution adjustments depended on the measurement of glucose. Two AP configurations were suggested: a single-hormone AP that delivers insulin alone, and a dual-hormone AP that delivers both glucagon and insulin. Upon designing a wearable infusion pump, Arnold Kadish [3] developed the first AP in the early 1960s and linked it to a glucose analyzer. The AP stay a discuss tool and

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wasn't implemented in clinical practice due to a lack of compact, non-invasive pumps and sensors [4,5]. The modern development (the mid-2000s) of the continuous glucose sensors has resurrected the field and made it possible to create a portable AP for the first time [6].

The Minimal model is also referred to as the model of Bergman. In the past physiological, this model was popular work on the metabolism of glucose in the early 1980s, that used to describe the concentrations of insulin/glucose plasma behind the intravenous glucose allocation study [7,8]. In terms of mathematics, the insulin and glucose mathematical model of the human with complex interaction could be explained and represented, and then the control problem of glucose is a mathematical problem that could be solved by different mathematical strategies. The mathematical model makes it possible to simulate or check the control algorithm without needing a real patient. Many mathematical models can be explained the insulin/glucose regulatory system like Ackerman's Linear Model[9], Bolie's Model[10], Cobelli's Model[11], Hovorka's Model [12], Sorensen's Model [13] and others, in this work, we used Bergman Mathematical Model it is commonly used because it is a simple mathematical model [14].

Many controllers used to regulate the insulin-glucose system, Fisher [7], suggested a mathematical optimization strategy to obtain insulin infusion programs to regulate blood levels in diabetes. The algorithm encountered the same difficulties that previous algorithms faced in that it relies on fixed values for model parameters. That justifies the need to design a robust glucose-insulin regulatory system controller. Coman et al. [15], proposed an adaptive controller fractional in order to control the insulin and glucose systems that regulates its parameters along with a fractional-order model of the insulin and glucose system. In the case study, the amount of glucose meditation became extremely high, especially when taking meal and blood glucose, which had negative and dangerous impacts on patient life. These impacts increase depending on the rate of absorption, while removal of the meal intake effect may help to avoid critical situations which suggest an observer based on Lyapunov stability, capable of estimating disturbance input (meal). E. D. Lehmann & T. Deutsch, Suggested a clinical model for glucose and insulin interaction in insulin-dependent diabetes mellitus (DM) has been developed for the patient and medical staff training [16]. L. Kovács et al. applied two robust control methods on the minimal model of Bergman for blood glucose control of T1D patients. Firstly, the mini/max control is introduced, and it is shown to have drawbacks in reality. However, it is possible to approximate the theoretical solution obtained by using the reduced Gröbner method based on a rational field and thus get a better solution than Linear Quadratic (LQ) dose. Secondly, the authors then presented H_∞ control concepts that describe a graphic design procedure for fitting the complementary sensitivity function. The first control method has drawbacks in practice since the use of insulin from remote compartments is a slow variable. So, the second model equation which reduces the system equation and makes the system linear can be removed. This means some form of negative glucose injection into the body as the control input which is not physically possible. In fact, this means the minima control has limitations. Use H_∞ control as a controller on the glucose system would also reduce the effect of disturbance I/P by adding a proper disk inequality restriction for disturbance rejection [17].

HLS is dependent on the weighting of corresponding nominal plant outputs and inputs, where it has many advantages with regard to the classical methods. First of all, there is no iteration process in HLS. Second, it blends the advantages of the classical loop shaping with the robust characteristics of the optimization of HLS. And it is also a simple approach that has many fields of applications [18].

In this work, we have implemented H_∞ Loop Shaping control in order to provide robust stability and performance even in presence of uncertainties. The Bergman mathematical model is used to simulate the regulation of the concentration of blood glucose.

2. BERGMAN MATHEMATICAL MODEL

To design a suitable system, an adequate model is required. One of the most widely employed measures of the effect of insulin infusion and glucose inputs on blood glucose production is regarded as Bergman's model or called three state minimal model. The following differential equations describe this model [14,19]

$$\frac{dG}{dt} = -p_1 G - X(G + G_b) + \frac{G_{meal}}{V_1}$$

$$\frac{dX}{dt} = -P_2X + P_3I$$
$$\frac{dI}{dt} = -n(I + I_b) + \frac{U}{V_1} \quad (1)$$

The physical meanings of the variables in Eq. (1) are given in Table 1. For the design of the control system, a linear state -pace model can be built [19]:

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\end{bmatrix} = \begin{bmatrix}-P_1 & -G_b & 0\\ 0 & -P_2 & P_3\\ 0 & 0 & -n\end{bmatrix}\begin{bmatrix}X_1\\ X_2\\ X_3\end{bmatrix} + \begin{bmatrix}0 & \frac{1}{V_1}\\ 0 & 0\\ \frac{1}{V_1} & 0\end{bmatrix}\begin{bmatrix}u\\ d\end{bmatrix} \quad (2)$$

$$Y = [1 \quad 0 \quad 0]\begin{bmatrix}X_1\\ X_2\\ X_3\end{bmatrix} + [0 \quad 0]\begin{bmatrix}u\\ d\end{bmatrix}$$

where $d = G_{meal}$, $y = G$, $X_1 = G, X_2 = X, X_3 = I$, $u = U - U_b$.

TABLE 1: The Physical meanings of the variables in Equation (1).

Variable	Physical meaning
G	deviation in blood glucose
I	the deviation in insulin concentrations
X	proportional for the insulin concentration in a remote compartment
G_{meal}	meal disturbance input of glucose
U	manipulated insulin infusion rate
P_1, P_2, P_3, n, V_1	the volume of blood
G_b	the "basal" base line or steady state value of blood glucose
I_b	The insulin concentration

In Eq. (1), the rate of absorption of glucose from the blood is indicated by G_{meal} which is a standard meal intake (disturbance input). The disturbance meal have described by many authors as [20]:

$$G_{meal} = (kt/b^2)\, e^{\frac{-t^2}{2b^2}} \quad (3)$$

where: G_{meal} is in (g/mmol/min),t is in min , b is constant value=80, k denotes carbohydrates quantity in meal = 180 (g/mol).

It is important to note that the states, input and output variables are described in deviation form. The set of parameters that are used for the modeled diabetic in (2) are given in Table (2) below. Since the concentrations are in mmol/L, and the glucose disturbance has units of grams, the conversion factor of 5.5556 mmol/g must be applied to the G_{meal} in addition, it is more common to work with glucose concentration units of mg/deciliter rather than mmol/L. Since the molecular weight of glucose is 180 g/mol, we should multiply the glucose state (mmol/L) by 18 to obtain the measured glucose output in (mg/deciliter).

Figure 1 shows the frequency response of the AP system open-loop (According to the first input (Insulin)). It shows that the system is unstable because the phase and gain margin are negative.

TABLE 2: Diabetic model parameters [19].

Parameter	Values

G_b(mmol/L)	4.5
I_b(mU/L)	4.5
V_1(L)	12
$P_1(min^{-1})$	0.000001
$P_2(min^{-1})$	0.02
P_3(mU/liter)	0.000013
$n(min^{-1})$	5/54

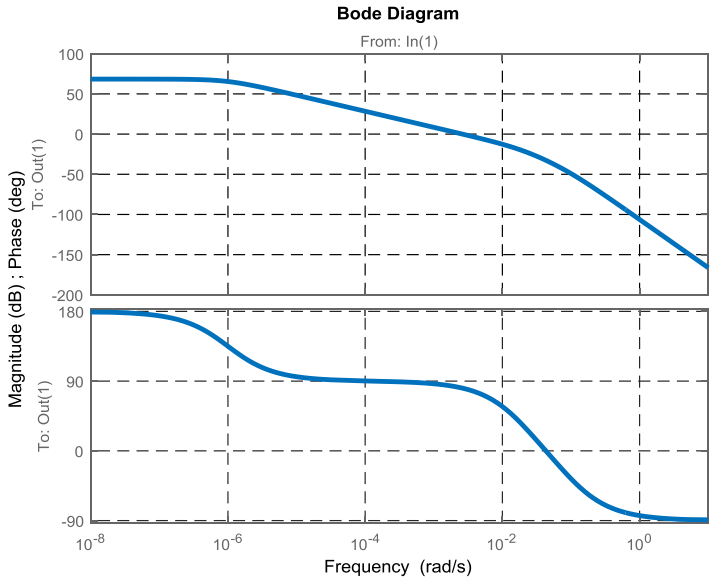

Figure 1: Bode Plot of the AP System.

3. H∞ LOOP SHAPING CONTROL DESIGN

McFarlane and Glover proposed the HLS approach in 1992 [21]. It can be summarized as follows:

$$G_S = W_1 G_0 W_2 \tag{4}$$

$$G_S = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{4}$$

$$G_S = (N_s + \Delta_{NS})\,(M_s + \Delta_{MS})^{-1} \tag{5}$$

where G_S is the shaped plant and G_0 is the nominal system, A, B, C, and D form the plant. G_S is in the form of state space. W_1, W_2 are Pre and Post-compensators respectively.

In this configuration, W_1, W_2 are selected to obtain the desired form in an open-loop reaction for the singular values. Using the loop shaping design technique, robust stable performance is obtained against the uncertainty of the co-prime factor. By using HLS, it is possible for a closed-loop system to compromise robustness, performance, and stability. Consequently, a specific shaped plant is designed as a normalized coprime factor in this method, in order to disperse the plant G_S into the normalized denominator and nominator coprime factors (M_s and N_s), and Δ_{MS}, Δ_{NS} are transfer functions of uncertainty.

In order to attain the normalized coprime factors, the following equation is used [21]:

$$[N_s \quad M_s] = \begin{bmatrix} A + HC & B + HD & H \\ R^{-1/2}C & R^{-1/2}D & R^{-1/2} \end{bmatrix} \tag{6}$$

where:

$$H = -(BD^T + ZC^T)R^{-1} \tag{7}$$

$$R=1+DD^{T} \quad (8)$$

while Matrix $Z \geq 0$ considered as an individual +ve definite settlement to the algebraic Riccate equation as below:

$$(A - BS^{-1}D^{T}C)Z + Z(A - BS^{-1}D^{T}C)^{T} - ZC^{T}R^{-1}CZ + BS^{-1}B^{T} = 0 \quad (9)$$

where $S=1+D^{T}D$

Therefore, when the desired loop shaping is achieved then ∞-norm of the specified transfer function from disturbance *w* to states *z* is turned to be minimized over the stabilizing controller *C* as shown in Figure 2.

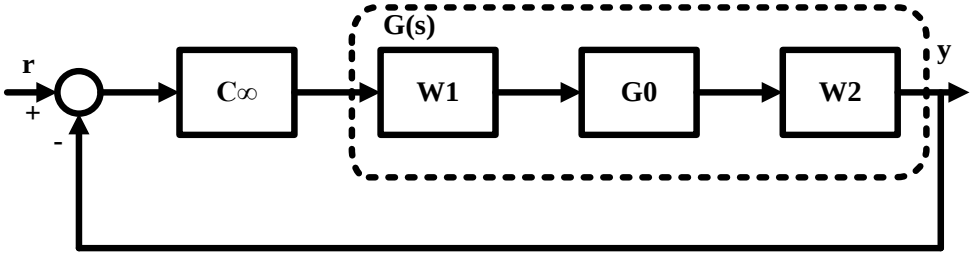

Figure 2: H_{∞} Loop Shaping control design.

By considering the precept HLS controller, the plant the following steps should be pursued [22]:

1) For the nominal plant G_0, the desired loop shape G_S is found by shaping the singular values using the pre and post compensators ($W_1$and/or W_2). Choosing W_1 and W_2 is extremely important. W_1, W_2 can be chosen by trial and error. W_1 is chosen to fulfill tracking performance, attenuation of disturbance, while W_2 is applied to reduce the noise of the sensor. Accordingly, weighting function W_1 has been selected as$(\frac{(s+0.1)}{s+0.12})$ whereas W_2 can be neglected. However, it is very necessary to bear in mind that the life of a patient is very valuable even when using a high-performance sensor. So, W_2 is chosen to be $(\frac{5*(s+0.01)}{s+1})$to ensure controller reliability.
2) To obtain the optimal cost $y_{Optimal}$. Then, the transfer matrix T_{zw} norm ∞ (provided by Eq. (13)) should be minimized:

$$y_{Optimal} = \varepsilon_{optimal}^{-1} = \infty \left\| \begin{bmatrix} 1 \\ C \end{bmatrix} (1 + G_s C)^{-1} M_s^{-1} \right\|_{\infty} \quad (10)$$

where the demanded loop shape robustness is indicated to be $\varepsilon_{Optimal}$. In addition, it elucidate the compatibilities of the computed weighing functions W_1 and W_2.

$y_{Optimal} \leq 1$ showed that W_1 or W_2, as formulated in step 1, is inconsistent with the desired robust stability. Therefore, it should be returning to step 1 and recalculating W_1 or W_2 using the unique method (HLS controller) [22].

$$y_{Optimal}=\varepsilon_{optimal}^{-1}=(1 + \lambda_{max}(XZ))^{1/2} \quad (11)$$

where K and Z represent the Reccati's equations solutions [23-25] and the maximum Eigenvalue is considered to be λ_{max}.

$$(A–BS^{-1}\,DT\,C)T\,K + K(A–B\,S^{-1}\,DTC) – K\,B\,S^{-1}\,BTK – CT\,R^{-1}C = 0 \quad (12)$$

3) Select $\varepsilon < \varepsilon_{Optimal}$, then synthesize controller C to achieve [22].

$$\|T_{zw}\|_{\infty} = \left\| \begin{bmatrix} 1 \\ C\infty \end{bmatrix} (1 + G_s C\infty)^{-1} M_s^{-1} \right\|_{\infty} \varepsilon^{-1} = \left\| \begin{bmatrix} 1 \\ C\infty \end{bmatrix} (1 + G_s C\infty)^{-1} [1 \quad G_S] \right\|_{\infty} \leq \varepsilon^{-1} \quad (13)$$

Then the controller C_∞ is performed by solving the optimal control problem in (13) where ε is the stability of margin (i.e. boundary of uncertainty).

4) The resulted controller (C) is:

$$C = W_1 C\infty W_2 \tag{14}$$

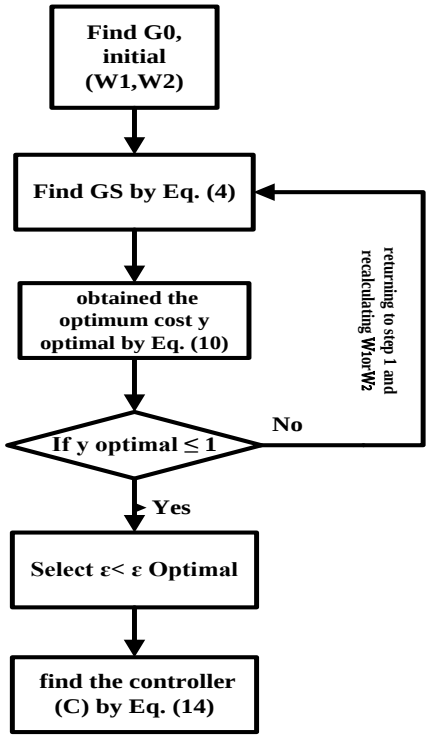

Figure 3: Steps of precept H_∞ loop-shaping for the plant.

4. SIMULATION RESULTS

In order to authenticate the HLS procedure, the AP system as presented in Eq.2 is taken into consideration while the robust controller HLS design work was developed. In order to speculate the efficiency and robustness of the proposed argument, system responses without controllers and systems using HLS controllers are achieved. The algorithm and controller are coded in Matlab. PID controller is also used for comparison.

Equation (15) represents the transfer function of the obtained nominal plant (G_0) According to the first input (Insulin).

$$\text{Transfer Function } (G_{0,1}) = \frac{-4.875*10^{-6}}{S^3+0.1126S^2+0.001852S+1.852*10^{-9}} \tag{15}$$

And, Eq. (16) represents the transfer function of the obtained nominal plant (G_0) According to the second input (Disturbance meal).

$$\text{Transfer Function } (G_{0,2}) = \frac{0.08333}{s+10^{-6}} \tag{16}$$

The weights W_1 and W_2 are chosen by trial and error in the HLS method. The stability margin is obtained to be 0.7107. Actually, the value of stability margin ensures that the weights chosen are consistent with robust stability specifications. By using these weighting functions, the shaped plant system in Eq. (4) is shown in Figure 4 below.

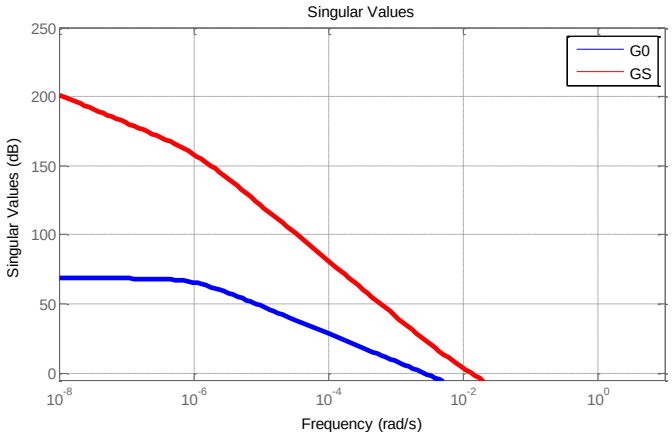

Figure 4: The Frequency Responses of the Nominal System and the Shaped plant where G_0 is the nominal system and G_s is the shaped plant.

The controller C is built for the AP system using the HLS technique can be assessed as shown:

$$(C) = C1+C2= \frac{5.938\ S^2+0.6801\ S+0.005092}{S^2+0.12\ S-5.709*10^{-8}} + \frac{-0.001297\ S^2-0.0002176\ S+2.065*10^{-6}}{S^2+0.12\ s-5.709*10^{-8}} \quad (17)$$

where C1 represents the controller according to the first input (Insulin) and C2 is the controller according to the second input (Disturbance meal).

The effectiveness of applying the robust controller to the *AP* system is investigated by two principal requirements: analysis of stability and analysis of performance.

I. Stability Analysis

This is an important analysis to ensure that the AP system operates in a stable manner under all circumstances. Figure 5 displays the closed-loop of the sensitivity function for the AP controlled system with the inverse weight function of the pre/compensator W_1.

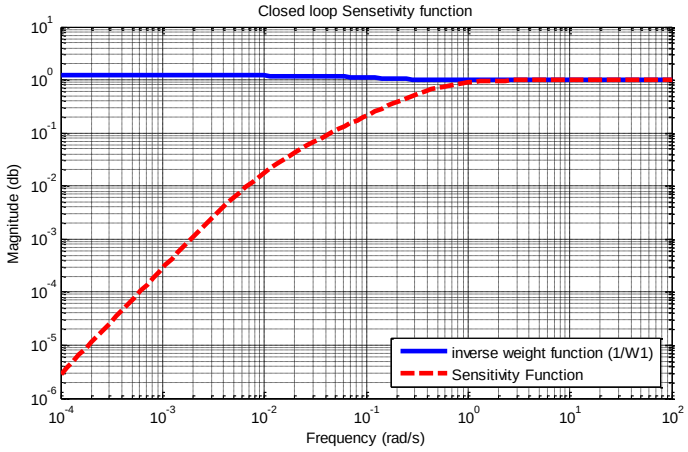

Figure 5: The Closed Loop of Sensitivity Function for the AP system.

Figure 6 shows the characteristics of H_∞ Loop Shaping. And, Table 3 are Shown the characteristics of the suggested controller, it is clear that the system is stable.

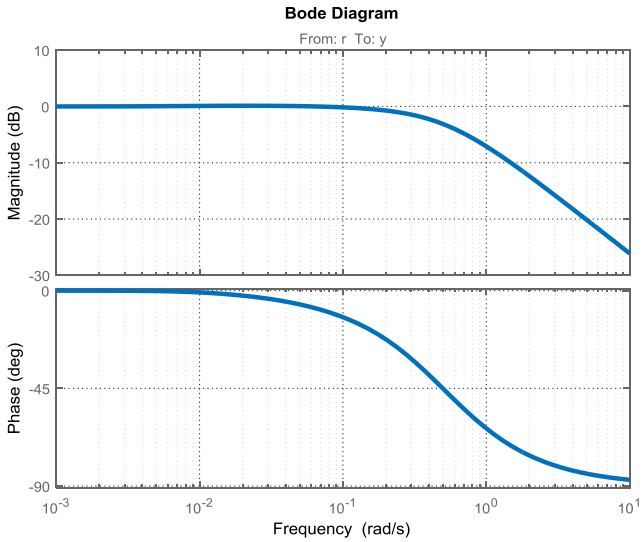

Figure 6: Bode Plot of the AP System with H_∞ loop shaping.

TABLE 3: characteristics of H_∞ Loop Shaping

Characteristic	Value
Phase Margin (deg.)	172°
Gain Margin (dB)	Infinity
PM frequency	0.0651

II. Performance Analysis

To test the performance of the suggested HLS the response of the AP before and after applying the robust controller will be analyzed. Figure 7 shows the response of the uncontrolled system. It's clear that it needs to improve stability and steady-state error.

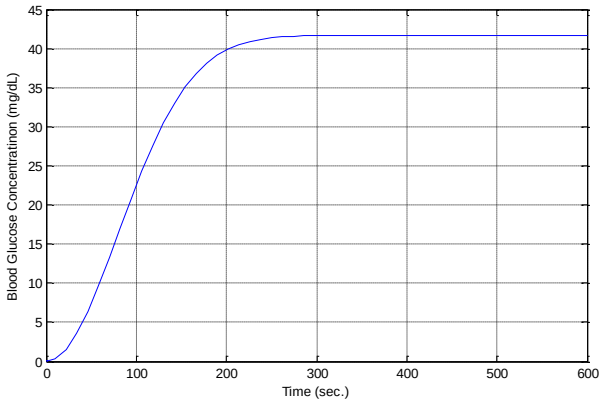

Figure 7: Glucose response for the uncontrolled system.

Figure 8 shows the deviation glucose level under meal disturbance with HLS controller. HLS controller gives performance of maximum glucose level does not exceed 1.4 (mmol/L).

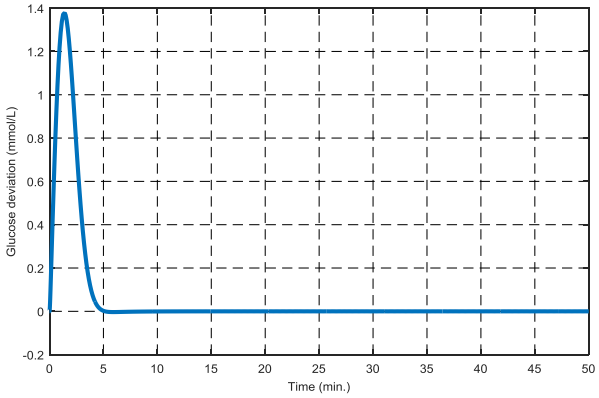

Figure 8: Deviation glucose response with HLS controller.

Figure 9 the characteristics of the AP system with HLS after the inclusion of 60 uncertainty has appeared. It is clear that the results of the AP system with the HLS controller after considering the uncertainty still deals robustly.

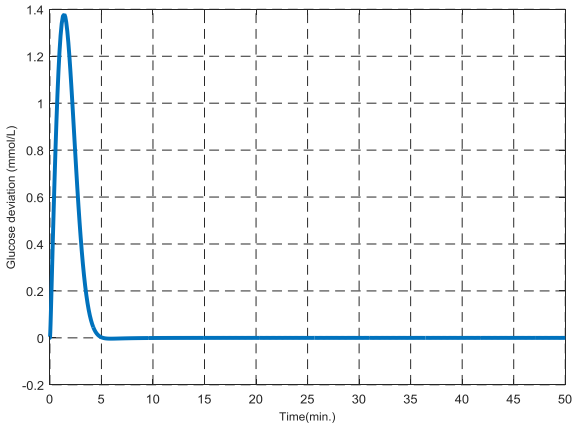

Figure 9: Response of the AP robustly deviation controlled System with uncertainty.

5. PROPOTIONAL INTEGRAL DERIVATIVE (PID) CONTROLLER

In order to validate the performance of the proposec HLS controller, a comparison with a well-known controller as the PID has been accomplished. The parameters of PID controller has been selected for the best possible performance as:

$$K_{pid1}(s) = \frac{0.1\,S^2 + 0.06\,S + 1}{S} \tag{18}$$

$$K_{pid2}(s) = \frac{0.5\,S^2 + 0.01\,S + 0.4}{S} \tag{19}$$

Figure (10) shows the deviation glucose level under meal disturbance with PID controller. PID controller gives performance of maximum glucose level does not exceed 1.6 (mmol/L).

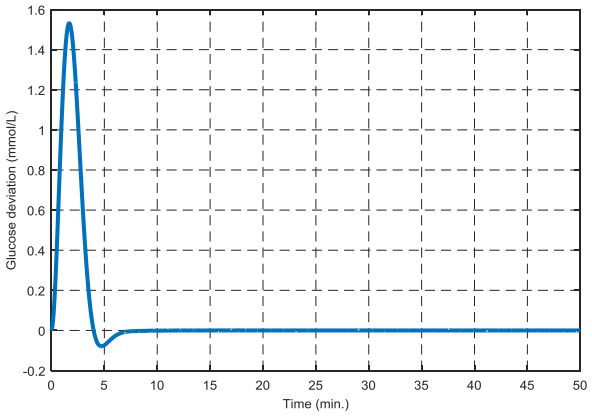

Figure 10: Deviation glucose response of the AP system with a PID controller.

From Figure 11 it is clear that the system is stable with the two controllers but by using the HLS controller the AP system can achieve better stability than the PID controller because the phase margin in the HLS controller is more than the PID controller. So the closed-loop system is clearly improved by the HLS controller. And, Table 4 shows the comparison result of characteristics between HLS, PID controller.

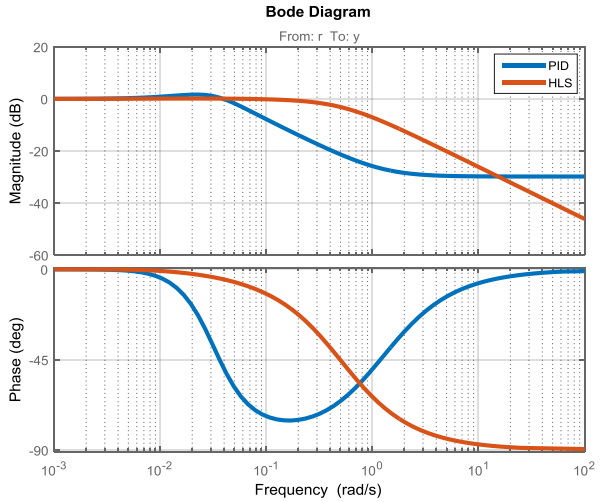

Figure 11: Bode plot of the AP system with HLS and PID controllers

TABLE 4: Comparison result of characteristics between HLS, PID controller

Characteristic	HLS	PID
Phase Margin (deg.)	172°	131°
Gain Margin (dB)	Infinity	Infinity
PM frequency(rad\sec)	0.0651	0.0393

6. CONCLUSIONS

In this work, a specific Bergman model insulin-glucose control system to artificial pancreas is researched and thoroughly assessed. HLS controller has been proposed and the PID controller is used for comparison. It has been clearly shown that the HLS controller results are better than that with the PID controller in regulating blood glucose concentration. The results display many good advantages as compared with the PID controller. And, the effectiveness of suggested parameters for the AP system is investigated by applied uncertainty on robust control to present the robustness of the controlled system.

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