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Hedge Algebras Tuning of PID Controller

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ABSTRACT
In this paper, the author proposes a method modified on-line the parameters of the PID controller based on combining the hedge algebras control and model reference system. This proposal has inherited the adaption of hedge algebras control deal with the uncertain systems or nonlinear systems and the sustainability of model reference system for load disturbances and measurement noise. In addition, the parameters of fuzziness measure are taken into account as design variables. Experiment results of aerodynamic lift system are provided to illustrate the effectiveness of the theoretically analyzed results.
***Keywords* -**PID controller, Hegde algebras, aerodynamic lift system. Arduino mega**.**

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I. INTRODUCTION

To enhance a performance of the tracking under uncertainties and disturbances, several methodologies are combined with together in the control design approach such as robust design, adaptive update method, feed-forward, sliding mode control and so on. In following, there are many adaptive update control schemes for nonlinear with known or the unknown parameters is investigated [1, 2, 3]. However, there are several inherent difficulties associated with these approaches. First of all, the plant dynamic structure may not be known exactly, which is common in practice, this is caused the linearization method faced with serious obstacles in applying the adaptive update algorithms in practice. Second, it was shown that some of these designed methods may lack robustness against uncertainties. Besides, proportional-integral-derivative (PID) controllers combined with tuning the parameters are still the most adopted in practical case throughout decades.

S. Z. He et al. devised a methodology that consists of parameterizing a Ziegler Nichols like formula by a single parameter and then self-tuning this parameter by means of an on-line fuzzy inference mechanism [4]. Zhao et al. developed a fuzzy gain scheduling scheme where PID parameters are determined on the basis of fuzzy rules, depending on the value of the error signal and its time derivative or difference [5]. Antonio Visioli employed a fuzzy inference system, which is adopted to determine the value of the weight that multiplies the set point for the proportional action, based on the current output error and its time derivative [6]. Ker-Wei proposed a modified fuzzy gain scheduling PID controller via particle swarm optimization (PSO) method. Unlike traditional try and error method or other tuning methods, some important tunable variables of proposed controller are determined by PSO method, i.e., the boundary and slope of membership functions. The gain margin and oscillation frequency determined by traditional Ziegler-Nichols method are modified by proposed PSO method in the same time to improve the output performance of controlled system [7].

Hedge algebras were developed by Nguyen and Wechler (1990) to model the order-based semantics of the terms in term-domains of linguistic variables. Then, the fuzzy rules can be viewed as to define points in a Cartesian product of suitable hedge algebras, and approximate reasoning method on the controller knowledge can be transformed into an interpolation method on a real surface defined by these points by using fuzziness parameters values [8,9]. Since this transformation is defined by Semantically Quantifying Mappings (SQMs) of hedge algebras, which may preserve the relations between the variables based on the order-based semantic of terms in the controller knowledge, the resulting surface can be considered as an appropriate mathematical model of the controller knowledge. So, hedge algebras may provide a sound formalized basis to develop effective new reasoning methods for a kind of controllers, called hedge algebra (HA) controllers. It achieves better performance than PID controller. Combining the simplicity of PID and the robustness of HA can achieve high control performance in a simple manner.

On the basis of above review, the hedge algebras scheduling of PID controller is proposed. In which the parameters of the PID controller is adjusted online based on combining the hedge algebras control and model reference system. This proposal has inherited the adaption of hedge algebras control deal with the uncertain systems or nonlinear systems and the sustainability of model reference system for load disturbances and measurement noise. Moreover, the stability of the closed-loop system is investigated and the parameters of the fuzziness measure of primary terms and hedges of output are now considered as design variables.

II. PROBLEM FORMULATION

Hedge algebras (HA) are proposed by Nguyen & Wechleer [3] in 1990. Those are aimed to shown that the inherent ordered-based structures of term-domains of linguistic variables are useful to discover order-based semantic properties of terms and term-domain. Every term-domain of a linguistic variable X can be considered as a Hedge-algebra (HA) $AX = (X, G, C, H, \leq)$, where X is a term-set of X, $\leq$ is an order relation on X, which is regarded as to be induced by the inherent order-based semantics of the terms of X; $G = \{c^-, c^+\}$, where c^- or c^+ is called the negative or positive primary term, is the set of generators that satisfy $c^- \leq c^+$; $C = \{\mathbf{0}, W, \mathbf{1}\}$ is the set of constants satisfying $\mathbf{0} \leq c^- \leq W \leq c^+ \leq \mathbf{1}$, whose meanings state that $\mathbf{0}$ and $\mathbf{1}$ are, respectively, the least and the greatest term in X, W is the neutral term $H = H^- \cup H^+$, where $H^- = \{h_j; -1 \leq j \leq -q\}$ is set of negative hedges $h \in H$ satisfying $hc^- \leq c^-$ written as $sign(h) = -1$ and $H^+ = \{h_j; 1 \leq j \leq p\}$ is set of positive hedges $h \in H$ satisfying $hc^+ \geq c^+$ written as $sign(h) = +1$.

The sematic structure of AX discovered in the algebraic approach to the term semantics implies that the set $H_I(x) = \{x = h_n h_{n-1} \dots h_1 c : c \in G, h_j \in H\} \cup \{x\}$ for every $x \in X$, can be considered as the model of the fuzziness of x. The structure of the set of all such sets, $H(x), x \in X$, induces a fuzziness measure fm of the terms of X, which is equal to the "diameter" of $H(x)$ and can be calculated by given fuzziness measure of hedges, $\mu(h), h \in H$, called commonly the fuzziness parameters of X. We have that for every $x \in X, x = h_n h_{n-1} \dots h_1 c$,

$$fm(h_n h_{n-1} \dots h_1 c) = \mu(h_n) \dots \mu(h_1) fm(c), c \in G$$
$$\sum_{i=-q}^{p} fm(h_i c) = fm(c); \quad \sum_{i=-q}^{p} fm(h_i x) = fm(x);$$
$$\sum_{i=-1}^{-q} \mu(h_i) = \alpha; \quad \sum_{i=1}^{p} \mu(h_i) = \beta; \quad \alpha + \beta = 1$$
(1)

a given fuzziness measure fm of X induces numeric term semantics, defined by the so-called Semantically Quantifying Mapping (SQM) v_{fm} which is also calculated by the given fuzziness parameter values as follow:

$$v_{fm}(W) = \theta = fm(c^-), \; v_{fm}(c^-) = \theta - \alpha fm(c^-);$$
$$v_{fm}(c^+) = \theta + \beta fm(c^+) = 1 - \beta fm(c^+);$$
$$w(h_j x) = \frac{1}{2}[1 + Sgn(h_j x) Sgn(h_p h_j x)(\alpha - \beta)] \in [\alpha, \beta]$$
$$v_{fm}(h_j x) = v_{fm}(x) + Sgn(h_j x)\left\{\left[\sum_{i=sign(j)}^{j} fm(h_i x)\right] - w(h_j x) fm(h_j x)\right\};$$
(2)

An HA controller can be contructed following the schematic diagram given in Fig.1

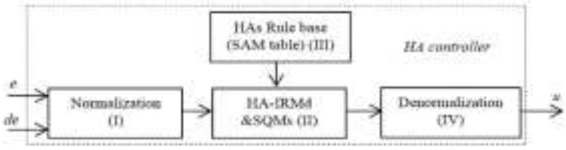

Fig 1. The hedge algebras based on controller

The HA controller constructed to solve control problem are three parts [3, 9]

1. Converting the ordinary linguistic labels into HA-terms and transferring the HA-terms into the real values (called Normalizations and Demoralization).
2. Determining mathematical model of a rule base and approximate reasoning method (SAM table), and the SQMs of the variables in question, for given their fuzziness parameters values, and to select an approximate reasoning method which would simply be ordinary interpolations (HA-IRMd).
3. Constructing a control algorithm to solve the given control problem and adjusting the numeric term semantics.

The equation of PID rules in time domain presented as follows:

$$u(t) = K_p[e(t) + \frac{1}{T_i}\int e(\tau) d\tau + T_d \frac{de(t)}{dt}] \quad (3)$$

where $e(t) = y_{sp}(t) - y(t)$ is the system error (difference between the reference input and the system output), $u(t)$ control variable, K_p proportional gain, T_d derivative time constant; T_i integral time constant. We can also write (1) as

$$u(t) = K_p e(t) + K_i \int e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (4)$$

where it is obviously $K_d = K_p T_d$ and $K_i = K_p / T_i$. Let $g = K_p / T_i$, so $K_i = K_p^2 / g K_d$. Therefore, (2) is presented as

$$u(t) = K_p e(t) + \frac{K_p^2}{\gamma K_d} \int e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (5)$$

The tuning problem consists of the determining the values of these three parameters with the aim of satisfying different control specifications such as set-point following, load disturbance attenuation, robustness to model uncertainties and rejection of measurement noise. The several tuning rules proposed in the literature along many years are generally devoted to meet one in particular of these requirments. For example, the widely known Zieger-Nichols formula generally assures a good load disturbance attenuation, but it generally provides a poor phase margin, and thus it might proceduce a large overshoot and settling time in the step response. To avoid these situations partially, a modification can be applied to equation (3). Specifically, to reduce the overshoot, the setpoint for the proportional action can be weighted by means of a constant parameter $b < 1$ so that we have the following more general expession

$$u(t) = K_p (b y_{sp}(t) - y(t)) + \frac{K_p^2}{\gamma K_d} \int e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (6)$$

in which b may be either 0 or 1.

The main drawback of this method is that it leads to an increasing of the rise time, since, obviously, the effectiveness of the proportional action is somewhat reduced. Hedge algebras can be used in the above context to vary the PID parameters values during the transient response, in order to improve the step response performances, maintaining a basic tuning aimed at properly rejecting load disturbances (e.g. the Ziegler-Nichols parameters). In this way, it is possible to implement a nonlinear controller so that the rise time and the overshoot are reduced at the same time.

III. HEGDE ALGEBRAS TUNING OF PID CONTROLLER

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From (5), the integral time constant depends on two parameters, proportional gain and derivative time constant of the PID controller, and the coefficient g. Therefore, the parameters of PID controller are g, K_d and K_p. There are general rules of thumb for tuning PID parameters. Below are examples of such as: If the input is positive large, then proportional gain K_p must be large , integral term K_i small and the derivative K_d is small. Thus, speeding of the system ouput will be responed rapidly following the trajactory and reduced the overshoot. In addtion, if the input is small, then PID parameters K_p should be smaller, K_i large and K_d lager, the output will thus reduce overshoot and decreasing the rise time. With the PID formula (5). We suppose the range of these parameters are:

$$K_p = [K_{p\min} \; K_{p\max}]$$
$$K_d = [K_{d\min} \; K_{d\max}]$$

to avoid clutters we normalize K_{dn} and K_{pn} within the interval $[0 \quad 1]$ by:

$$K_{pn} = \frac{K_p - K_{p\min}}{K_{p\max} - K_{p\min}}$$
$$K_{dn} = \frac{K_d - K_{d\min}}{K_{d\max} - K_{d\min}}$$

if we assume $K_{d\min} = K_{p\min} = 0$, then we obtain

$$K_p = K_{pn} K_{p\max} \text{ and } K_d = K_{dn} K_{d\max} \quad (7)$$

where $K_{d\max}, K_{p\max}$ are collected from Ziegler-Nichols method.

The desired performance of the complete feedback system is described by the transfer function:

$$\frac{Y_m(s)}{R(s)} = \frac{w_n^2}{s^2 + 2zw_n s + w_n^2} \quad (8)$$

where w_n is the undammed natural frequency, and z is the damping ratio

As presented above, the parameters of PID control are γ, K_d and K_p, Following the formula (5), the adjustable parameters of PID controller are γ, K_{dn} and K_{pn}. They are designed by hedge algebras control in [3, 9], which has two input, error of output response and output reference model, respectively, $\varepsilon(t) = y(t) - y_m(t)$ and its time derivative, respectively, $de(t)/dt$ and an output is γ, K_d and K_p.

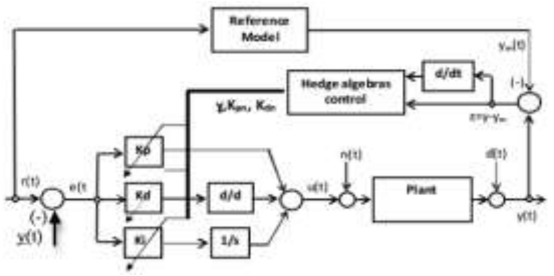

Fig 2. The structure of hedge algebras tuning PID controller

The rules may be extracted from operator's expertise. Here we drive the rules experimentally based on the dynamic error of the process. Fig 3 shows an example of an error between output reference and output response. At the beginning, i.e. around a, we need a big control signal in order to achieve a fast rise time. To produce a big control signal, the PID controller should have a large proportional gain, a large integral gain, and a small derivative gain. Thus the proportional gain K_i can be represented by a set Big, and the derivative gain K_d by a set Small. The integral action is determined with reference to the derivative action as in (5). For the PID controller, taking a small g or a small integral time constant T_i will result in a strong integral action. Whether the integral action should be strong or weak is determined in the scheme by comparison with the well-known Ziegler-Nichols PID tuning rule. In the Ziegler-Nichols rule, the integral time constant T_i, is always taken four times as large as the derivative time constant. That is, g equal to 4 (say big). In the proposed scheme, a takes a value less than 4 (say small) to generate a "stronger" integral action. Therefore, the rule around a reads

$$IF\ \ e\ is\ VB\ \ and\ \ de\ is\ Z\ \ THEN\ \ K_{pn} is\ B, K_{dn} is\ S, and\ \ g\ is\ S$$

When the error becomes negative during region 2 around point b, the system need to slow to reduce the overshoot. This accomplished by decreasing the proportional gain, small integral gain and large derivative gain. Thus, the rule base is given:

$$IF\ \ e\ is\ Z\ \ and\ \ de\ is\ B\ \ THEN\ \ K_{pn} is\ S, K_{dn} is\ B, and\ \ g\ is\ B$$

S	Small
Z	Zero
VS	Very Small
VB	Very Big
S	Small

Table 1. The linguistic variable

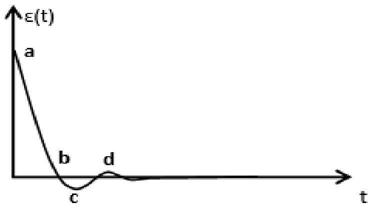

Fig 3. The error between output reference and output response

The other cases can be tuned as the same way. The rule base table of g, K_d and K_p shown in Table 2.

Table 2. Basic rule table

γ (rows: e, columns: de)

e \ de	VB	B	Z	S	VS
VS	S	S	S	S	S
S	Z	Z	S	Z	Z
Z	B	Z	Z	Z	P
B	Z	Z	S	Z	Z
VB	S	S	S	S	S

K_{dn} (rows: e, columns: de)

e \ de	VB	B	Z	S	VS
VS	B	S	S	S	B
S	B	B	S	B	B
Z	B	B	B	B	B
B	B	B	S	B	B
VB	B	S	S	S	B

K_{pn} (rows: e, columns: de)

e \ de	VB	B	Z	S	VS
VS	B	B	B	B	B
S	S	B	B	B	S
Z	S	S	B	S	S
B	S	B	S	B	S
VB	B	B	B	B	B

Stability: Since the parameters of the present PID controller are functions of time, it is very difficult to analyze the stability of the closed-loop control system. Even if the asymptotic stability is assured, wild start-up transients may be intolerable in many applications. Therefore, a hierarchical entity like a supervisor is desired to monitor the performance of the control system. Instability is detected preferably in an early stage if the system is unstable. Once stability is identified during process monitoring, certain corrective action is taken. For example, the controller parameters are switched to a set of known stabilizing parameters that guarantees that the control system will remain stable; or the system is shut down by setting K_p to zero if necessary.

Optimal tuning: the parameters of the fuzziness measure of primary terms and hedges of output are now considered as design variables and their intervals are determined as follows

$$\alpha = [0.4 \div 0.6]; \quad \beta = [0.4 \div 0.6]$$

and these free parameters have been determined using a genetic algorithm, which guarantees in a stochastic sense that a global optimum is achieved. The selected objective function to minimise is the integrated absolute error, defined as

$$IAE = \int_0^{\infty} \left| y_m(t) - y(t) \right| dt$$

which somehow takes into account at the same time the rise time, the overshoot and the settling time.

IV. ESPERIENT RECULTS AND DISCUSION

Description of aerodynamic lift system: As in Fig.4,5, the system has one BLDC motor (Sunny Sky 2212 980Kv), speed adjuster (ESC sky walker 40A UREC) and a beam, made of carbon fiber. The beam can be lifted down or up in vertical by BLDC motor combined with a fan, which is controlled by an angle controller.

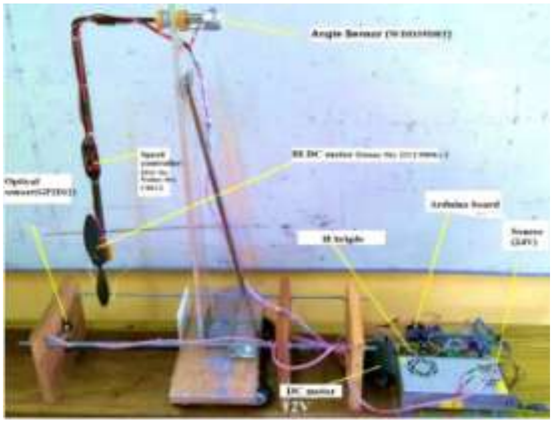

Fig 4. The structure of aerodynamics lift system

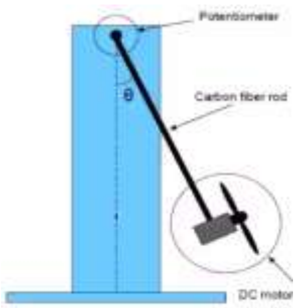

Fig 5. The structure of aerodynamics lift system

To measure an angle of the beam, an angle sensor (WDD35D8T-This is kind of resistance which has output in an interval [0-5] Voltage) is set perpendicular to the beam and hold on big plate. The Arduino Mega 2560 REV3 receive the information from angle sensor and transfer the control signal from Matlab to speed adjuster. In addition, the disturbance is investigated such as a horizontal directional motion of base while the beam is lifted up and down. The horizontal motion of base is controlled by the DC motor and H-bridge.

Target:The beam is stably controlled in the set point of angle.

There are two steps to implement the HA tuning PID controller. First of all, the parameters of PID controller is defined by Ziegler –Nichols $K_p = 0.08; K_d = 0.425; K_i = 0.0001$. Second, the HA based on controller as in Fig. 1 is constructed for $K_{pn}; K_{dn}; g$. In this part, we will set up HA for K_{pn} and $K_{dn}; g$ are constructed similarly. 1). Define the components of the HAC for inputs and output variables. There are $Le; Lde; Lk_{pn}$, respectively. 2). The linguistic labels of the linguistic variable such as

Table 3. The linguistic variables

Le, Lde	*VS*	*S*	*W*	*B*	*VB*
Lk_{pn}	-	*S*	*W*	*B*	-

and 3). Rule base for the HAC is shown in Table 4.

Table 4. The fuzziness parameters values

	Le	*Lde*	Lk_{pn}
$\theta = fm(S)$	0.5	0.5	0.5
$\alpha = \mu(B)$	α_s=0.4	α_{ds} =0.23	α_u =0.6

Next, we calculate the semantically quantifying values from linguistic terms in rule with the fuzziness parameters values of the linguistic variables, as presented in Table 5, which can be achieved by genetic algorithm.

$$Le = \{0, VS, S, W, B, VB, 1\}$$

$$v_{fmLe} = \{0; 0.125; 0.25; 0.5; 0.75; 0.875; 1\}$$

$$Lde = \{0, VS, S, W, B, VB, 1\}$$

$$v_{fmLe} = \{0; 0.2964; 0.385; 0.5; 0.615; 0.6414; 1\}$$

$$Lk_{pn} = \{0, S, W, B, 1\}; v_{fmLk_{pn}} = \{0; 0.2; 0.5; 0.8; 1\}$$

Table 5. SQM-values of HA terms (K_{pn})

Lde \ Le	0	0.125	0.25	0.5	0.75	0.875	1
0	0	0	0.5	0.5	0.5	0.8	0.8
0.2964	0	0.8	0.8	0.8	0.8	0.8	0.8
0.385	0	0.2	0.8	0.8	0.8	0.2	0.2
0.5	0.2	0.2	0.2	0.8	0.2	0.2	0.2
0.615	0.2	0.8	0.8	0.2	0.8	0.8	0.2
0.6414	0.8	0.8	0.8	0.8	0.8	0.8	1
1	0.8	0.8	0.8	0.8	0.8	1	1

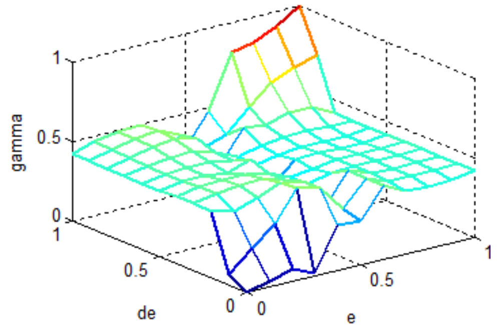

Fig 6. Surface of *Kpn*

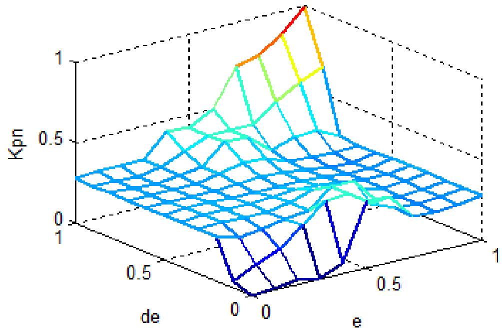

Fig 7. Surface of *gamma*

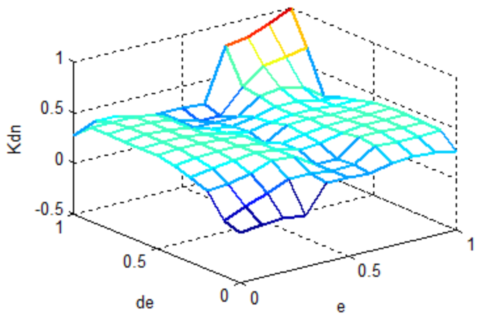

Fig 8. Surface of *Kdn*

The results in simulation using the HA tuning the parameters of PID controller for aerodynamics lift system.

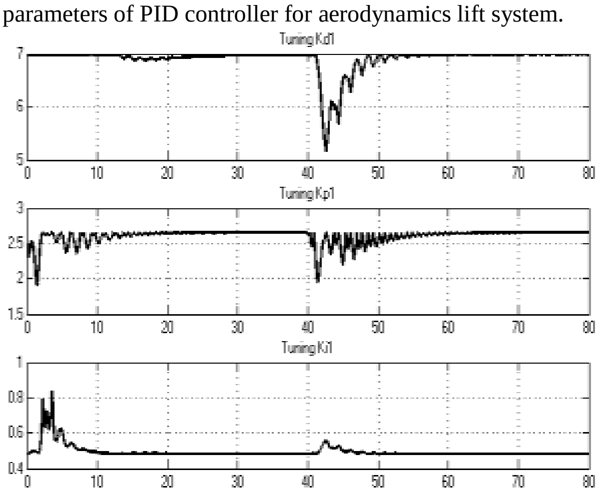

Fig 9. The updated parameters of PID controller

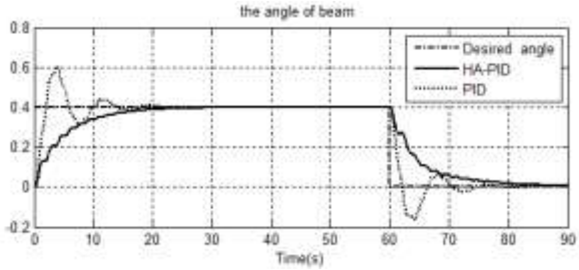

Fig 10. The response of the aerodynamics lift system

The structure of HA tuning PID controller in real-time ís expressed as following

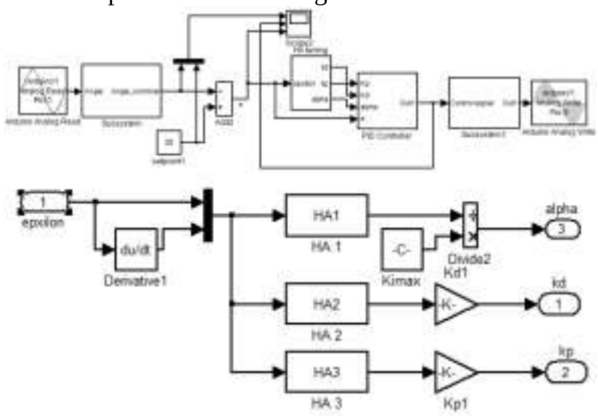

Fig 11. The structure of HA tuning PID controller in real-time.

where the angle signal is received by Arduino Analog Read and normalize in an interval $[0^0\text{-}100^0]$. The control signal is normalized from 0 to 5 and transmit to the actuator by Arduino Analog Write.

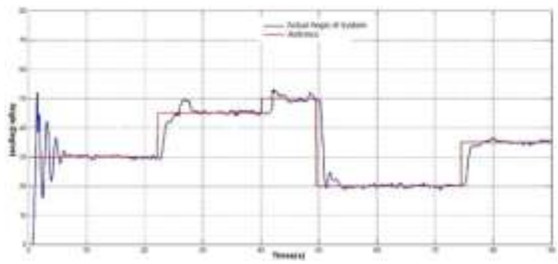

Fig 12. The actual angle of beam with the refernce 1.

Figure 12 shows for actual angle of beam with the set point changing from 30^0 to 45^0 in the interval [22-40]second. This means that the beam is lifted up and the beam is lifted down 20^0 in the interval [50-75]second. Similarly, in the Figure 13 the angle of beam is oscillation damping in the first interval set point $[0^0\text{-}35^0]$. However, based on the adjusted parameters of PID controller, the performance of system is better than in others interval times. It means that, the angle of beam is improved by using the HA scheduling gain PID controller.

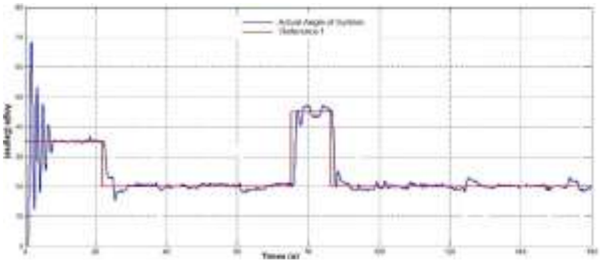

Fig 13. The actual angle of beam with the reference 2.

V. CONCLUSION

We propose a method, which adjusts the parameters of PID controller based on hedge algebras. The rules are extracted from operator's expertise. Here we drive the rules experimentally based on the step response of the process and/or error dynamic. The hierarchical entity like a supervisor is desired to monitor the performance of the control system. Once stability is identified during process monitoring, the certain corrective action is taken. In addition, the parameters of the fuzziness measure of primary terms and hedges of output are determined by the genetic algorithm. The aerodynamic lift system is constructed such as experiment device to test the proposed algorithm approaches.

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