
Intelligent Control Mechanism for Underwater Wet Welding

Joshua Emuejevoke Omajene¹, Paul Kah¹, Huapeng Wu¹, Jukka Martikainen¹,
Christopher Okechukwu Izelu²

¹LUT Mechanical Engineering, Lappeenranta University of Technology, Lappeenranta, Finland

²Department of Mechanical Engineering, College of Technology, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

Email address:

Joshua.omajene@yahoo.com (J. E. Omajene)

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Abstract: It is important to achieve high quality weld in underwater welding as it is vital to the integrity of the structures used in the offshore environment. Due to the difficulty in ensuring sound welds as it relates to the weld bead geometry, it is important to have a robust control mechanism that can meet this need. This work is aimed at designing a control mechanism for underwater wet welding which can control the welding process to ensure the desired weld bead geometry is achieved. Obtaining optimal bead width, penetration and reinforcement are essential parameters for the desired bead geometry. The method used in this study is the use of a control system that utilizes a combination of fuzzy and PID controller in controlling flux cored arc welding process. The outcome will ensure that optimal weld bead geometry is achieved as welding is being carried out at different water depth in the offshore environment. The result for the hybrid fuzzy-PID gives a satisfactory outcome of overshoot, rise time and steady error. This will lead to a robust welding system for oil and gas companies and other companies that carry out repair welding or construction welding in the offshore.

Keyword: Control System, Bead Geometry, Fuzzy Logic, Process Parameter, Underwater Welding

1. Background

Owing to the environmental conditions in which structures operate in the offshore, it is important that a high structural integrity is guaranteed. It is evident that structural failures can arise as a result of poor weld quality and other mechanical properties of the loaded structures operating in the offshore. The quality of welds achieved underwater experience a major setback because of the unique feature of the weld metal fast cooling rate and other factors such as the stability of the welding arc, loss of alloying elements and difficulty of a good visibility to weld underwater. This research paper addresses the issue of controlling the welding parameters at different water depth in achieving a desired weld bead geometry that is reasonably satisfactory of the weld quality that can operate in the offshore. A control mechanism which incorporates the design advantages of fuzzy logic control and PID control is implemented in this study. Experimental data to be analyzed in this paper is adopted from the work of Chon L. Tsai et. al. It is a well-known fact that high cooling rate and hydrogen embrittlement are characteristics of underwater wet welding

(UWW). Rapid cooling mechanism and their effects have been studied by Chon L. Tsai and Koichi Masubuchi [1]. The final microstructure of the heat affected zone (HAZ) for a given material is determined by the composition, peak temperature and cooling rate. It is possible to control the weld metal composition, the peak temperature and the cooling rate to yield favorable microstructure. However, it is not possible to control the composition of the HAZ of the parent material. Fast cooling effect of the water environment in UWW results in a martensitic heat affected zone having high hardness and poor notch toughness. In UWW, the dissociation of water is a source of hydrogen and this subjects the microstructure of the HAZ to hydrogen cracking. This makes it important to control the weld metal's cooling rate [2]. The ability to reduce cooling rate during underwater welding will ensure a decrease in the content of martensite and upper bainite, increase in proeutectoid ferrite and acicular ferrite [3].

2. Underwater Welding

The application of underwater welding for the repair of

ships and offshore structures like oil drilling rigs, pipelines, and platforms is of high importance in today's welding activities. The demand for quality wet weld at a greater depth and variety of materials is continually on the increase [4]. Nowadays, shielded metal arc welding (SMAW) and flux cored arc welding (FCAW), are the most widely used underwater welding process. FCAW has a high prospect in the future because of its high production efficiency and ease to be automated [5 - 8]. The water surrounding the weld metal reduces the mechanical properties of weld done underwater due to the effect of rapid cooling of the weld. Heat loss by conduction from the surface of the base metal directly into the moving water surrounding and heat loss by radiation are the major channels in which heat is lost during underwater welding. In order to achieve higher heat input in underwater welding, it is important to apply higher current to a comparable arc voltage for welds done in the air. Underwater welding high rate of cooling of the base metal results in the creation of unfavorable microstructure such as martensite and bainite for conventional welding of steels. Martensitic and bainitic constituents are high strength and brittle which are prone to cracking in the presence of high hydrogen content [3]. Underwater wet welding bead geometry have weld bead shape that are wider and lower penetration which is the opposite situation in air welding. The welding arc in underwater welding is constricted at a higher water depth. However, shallow water depth welding is more demanding than higher depth. The welding arc instability results in porosity which affects the soundness of the weld. Weld metal carbon content increases with increase in water depth. Also, deoxidizers such as manganese and silicon are lost in higher amounts at increased water depth [9] [10].

3. Flux Cored Arc Welding Process

FCAW is a semiautomatic welding process and the operation continues until completing the weld pass, whereas SMAW process requires changing of the electrodes from time to time. The weld crack sensitivity for FCAW is reduced compared to SMAW because of the interruption of the welding pass in SMAW, especially for steels with CE less than 0.4 %. However, one major disadvantages of FCAW is the difficulty in tracking the joint precisely under the condition of poor visibility underwater. Another challenge is that the diver/welder has difficulty in hearing the arc sound or viewing the plasma during underwater welding and this poses the challenge of him having information regarding the frequent changes in the welding current and voltage. For this reason, it is very important to design a robust control system to control the welding process in the underwater environment [11].

4. Mathematical Model of FCAW

In FCAW, a constant voltage power source and constant wire feeding rate are usually used [11]. The output characteristics of the power supply at the working point is

described in the equations below. The mathematical model for the design of the controller in this paper is adopted from the work of Chon L. Tsai *et. al* [11].

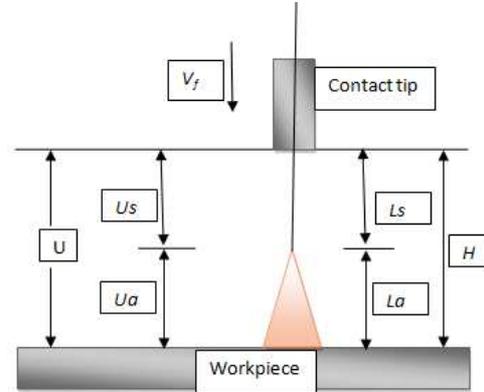


Fig. 1. Illustration of arc parameters adapted Chon L. Tsai *et. al* [11].

$$U = U_{ol} - R_s I \quad 1$$

Where U_{ol} is the equivalent open loop voltage, and R_s is the equivalent source resistance including the cables.

The output voltage is distributed in two parts which are the arc voltage and U_{ol} and the wire stickout voltage U_s .

$$U = U_a + U_s \quad 2$$

FCAW arc voltage-current characteristics can be described as in equation 3:

$$U_a = K_a L_a + R_a I + U_c \quad 3$$

Where K_a is electrical field intensity which is the voltage drop per unit length of arc column. R_a is the arc resistance. U_c is a constant that is related to the anode and cathode voltage.

The voltage drop on the wire stickout is described as equation 4:

$$U_s = \rho \frac{L_s}{A} = K_s L_s I \quad 4$$

Where ρ is the electric resistivity of the wire over the temperature ranges. A is electrode or wire cross-section area. K_s is average resistance per unit length of wire stickout.

The melting rate can be described as:

$$V_m = K_m I + K_c L_s I^2 \quad 5$$

Where V_m is the melting rate, $K_m I$ is the melting rate from the arc heat, K_m is the constant related to the anode voltage drop $K_c L_s I^2$ is the stickout wire resistance heat contribution to the melting rate, K_c is also another constant.

$V_m = V_f$ (when in steady state, the melting rate, if represented in wire length per unit time, equals the wire feed rate).

The contact-tip-to-workpiece distance comprises of the arc length and stickout length.

$$H = L_s + L_a \quad 6$$

In the welding process, the power source voltage, CTWD, wire feed rate, arc length and current are controllable parameters. In welding practice, it is observed that an increase in the length of CTWD will at the same time increase the arc length and will later shorten when a steady state is reached, that is at the state of fixed CTWD, wire feed rate, power source setting, and the arc is stable. The dynamic model of a welding arc power describes the transient characteristics in the change of one or more parameters. The dynamic model is based on the equation in the static model deviation [11].

The dynamic equation of power source

$$U = U_{o1} - R_s I - M_s \frac{di}{dt} \tag{7}$$

Where M_s is power source inductance.

Its frequency domain expression (Fourier Transform) is:

$$\Delta U(s) = -R_s(T_p S + 1)\Delta I(s) \tag{8}$$

The final dynamic model after setting a reasonable range of GMAW is given by the transfer function as represented in equation 9.

$$\frac{I(S)}{H(S)} = -3.46 \frac{0.0168s^2 + 0.457s + 1}{1.28e-005 s^3 + 0.01576 s^2 + 0.1776s + 1} \tag{9}$$

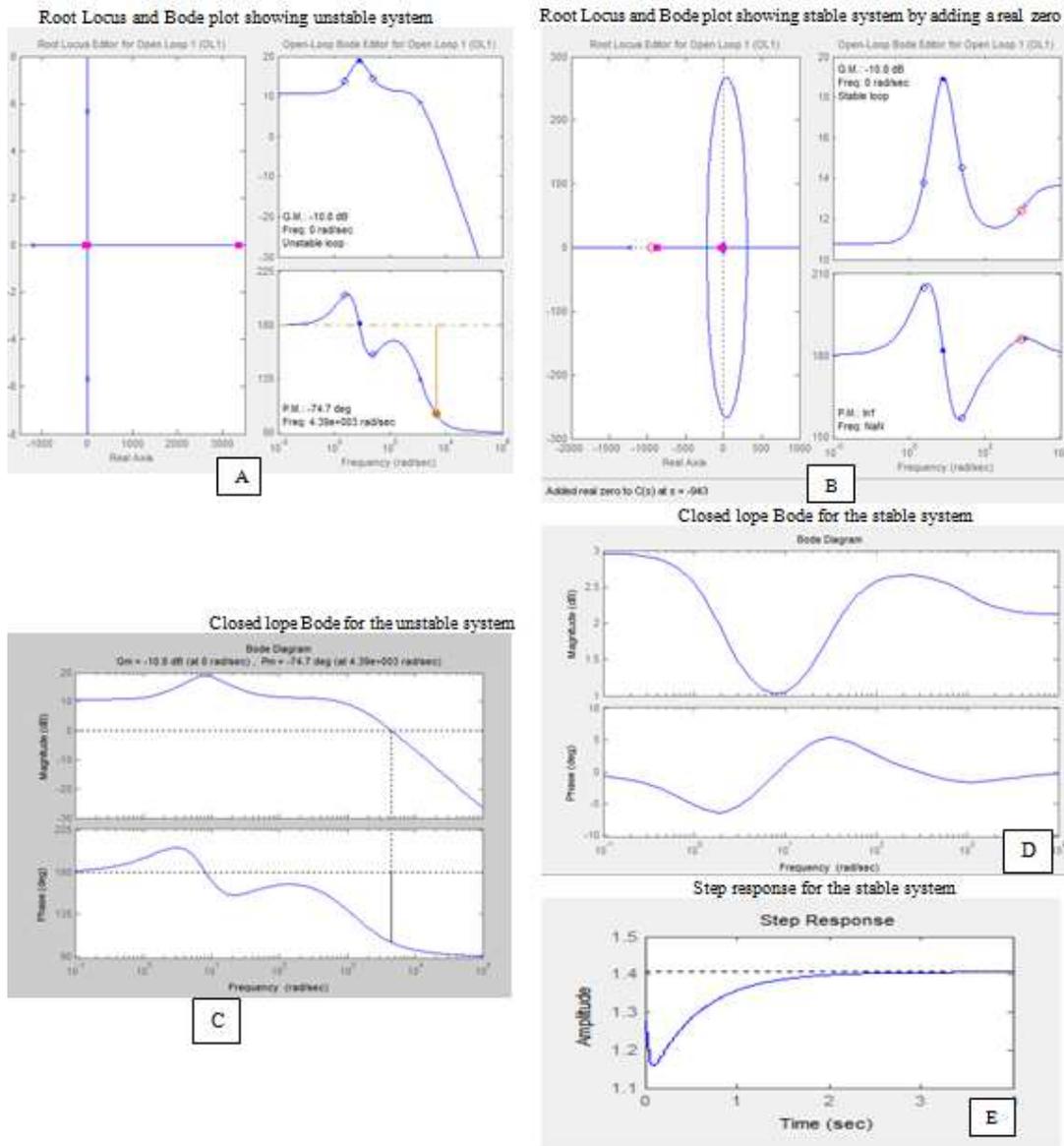


Fig. 2. Stability analysis using Bode plot, Root Locus and step response.

This transfer function is used as the plant model in the control system. The transfer function is the relationship between the arc current and CTWD. The transfer function of the system is unstable but can be adjusted by adjusting the position of the poles by adding a real zero. This is done by

the implementation Table. 1 of the following algorithm below. The SISOTOOL in MATLAB helps us to adjust the position of the poles or zeros in the Root Locus. The Bode plot Fig. 2 shows the relationship between the output signal $I(S)$ and the input signal $H(S)$ that describes the linear system. The Bode

plot for the transfer function of the plant shows that the system is unstable. The closed loop Bode plot in Fig. 2A has a gain margin of -10.8 dB at 0 rad/sec and phase margin of 74.7 degrees at 4390 rad/sec shown in Fig. 2C. This means that for the system to be stable, we need to decrease the gain by 10.8 dB. However adding a real zero at $s = -943$ shown in Fig. 2B will make the transfer function of the system stable. The closed loop Bode Fig. 2D of this system has a peak response of 2.96 dB at a frequency of $3.71e-008$ rad/sec. The step response Fig. 2E of the stable system has input amplitude of 1.4. The output response follows closely the input response without an overshoot.

Table 1. MATLAB implementation

NUM=-3.46*[0.01685 0.4575 1]
DEN=[1.28e-5 1.576e-2 1.776e-1 1]
sys=tf(NUM,DEN)
sisotool(sys)

5. Controller for Underwater Wet Welding Process

Fuzzy controller: This control system is a fuzzy logic controller that controls the plant which is the welding machine. The SMAW and FCAW mostly used in underwater welding are dependent on several process parameters that usually vary over a wide domain. Fuzzy logic technique is able to learn the relationship between the welding process input variable and output variable. Fuzzy set theory application is valuable in experimental data modeling which involves unpredictability between the relationships of the welding process input variables and the subsequent bead geometry output. The fuzzy model is used to analyze the appropriateness of the fuzzy relations in predicting the characteristics of the weld bead geometry profile. Fuzzy control is effective for systems which have dissimilarities of system dynamics. The model of the system can perform well for processes that are not precisely defined unlike PID controller. Fuzzy controllers are suitable in achieving a decreased rise time and slight overshoot [12]. The structure of the two inputs (error e and error change Δe) and three output (proportional gain K_p , integral gain K_i and derivative gain K_d) are designed for the fuzzy rules used in the hybrid fuzzy controller. The structure for the fuzzy logic controller designed for this research paper is two inputs (error e and error change Δe) and single output of the error and error change. The linguistic variables defined are sentences in normal English language such as negative big (NB), negative small (NS), zero (Z), positive big (PB), positive small (PS), which are expressed by fuzzy sets. The fuzzy sets are characterized by fuzzification (assigning input variables), membership functions (mapping of the input space to a membership value), fuzzy rule (IF-THEN conditional statements), inference system (mapping inputs to outputs) and defuzzification (quantification of expressions). The outputs of the fuzzy sets are obtained in crisp form. The Fig.3

summarizes the operations that are carried out in a fuzzy logic controller. In this research, the output from the defuzzifier which is a proportional, integral and derivative gain is fed into the input signal of the transfer function of the welding machine. The aim of the fuzzy logic in the controller design is to tune the parameters of the PID controller. This will significantly improve the performance of the system as compared to the conventional PID controller.

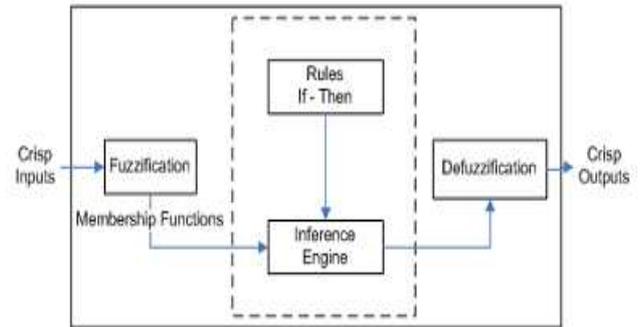


Fig. 3. Fuzzy logic controller block diagram [13].

5.1. Rules

The fuzzy control rule is a collection of fuzzy IF-THEN rules in which the preconditions are the error and error change variable and consequents are the output from the fuzzy logic variables which involves linguistic variables. The fuzzy control rule for the hybrid fuzzy PID controller have preconditions as the error and error change variable and consequence as gain parameters

5.2. Defuzzification Process

The defuzzification process converts the fuzzy output into a crisp using a defuzzification approach that relates the membership functions in Fig. 4 with the fuzzy rules [14]. In this paper, the centroid defuzzification technique is used. The defuzzification process is shown in the Fig. 5 is as a result of the assumptions reached for membership function and fuzzy rules. From the figure, it can be found that as each individual set of input parameters are changed, a subsequent change in the output parameter is effected.

PID controller: PID controller is widely utilized industrially for control applications. This controller is suitable in improving a systems transient response and steady state error simultaneously [15]. The control logic of the PID controller is implemented by finding suitable gain parameters K_p , K_i , and K_d . The transfer function of the PID controller is obtained by adding the terms of the proportional, integral and derivative controller (Equation 10). One major setback of a PID controller is that it does not effectively control a system having big lag, uncertainties and parameter variations. This makes it necessary for a fuzzy-PID hybrid control system [16].

$$PID(s) = K_p + K_i/s + sK_d$$

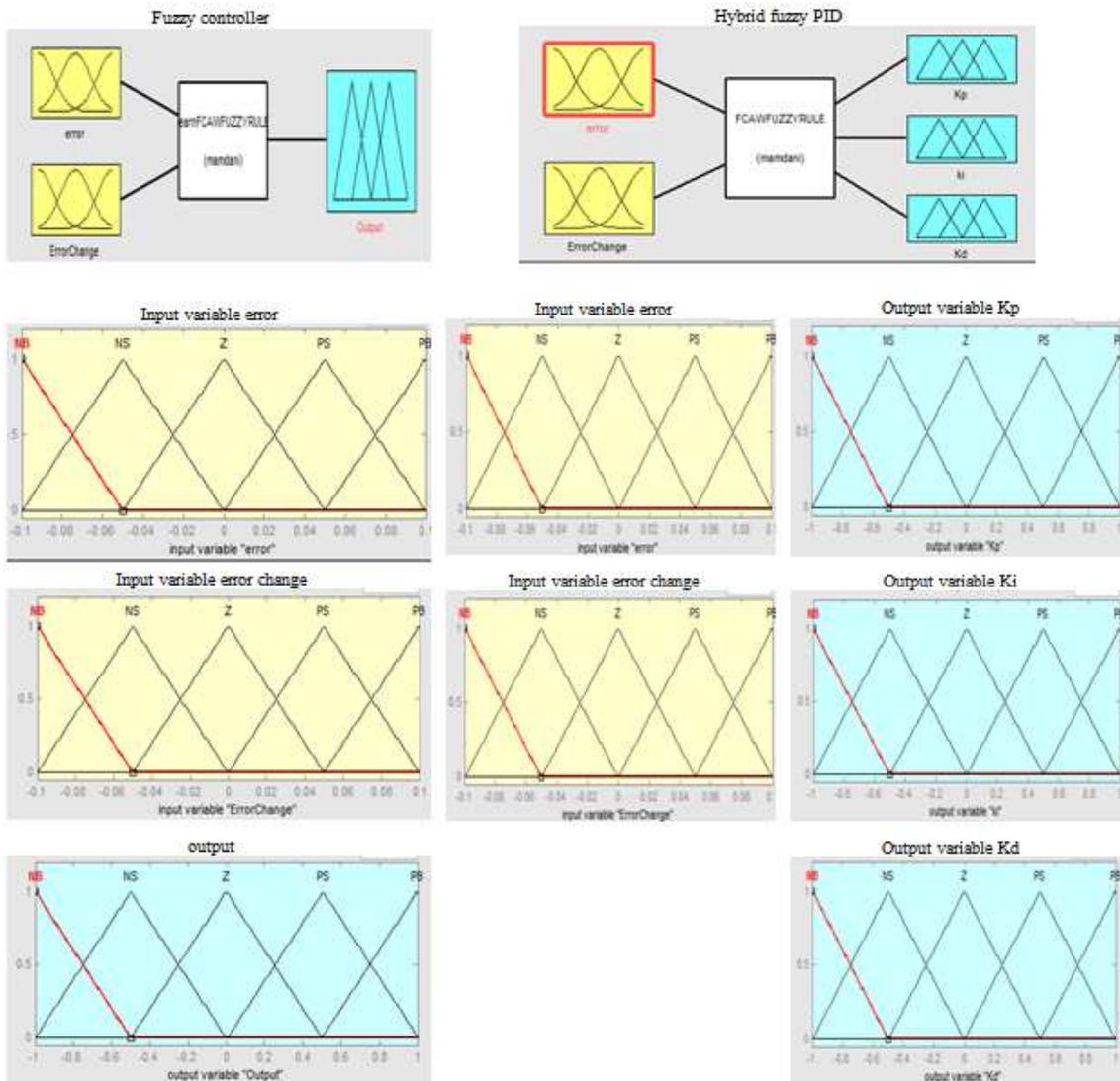


Fig. 4. Membership function diagram

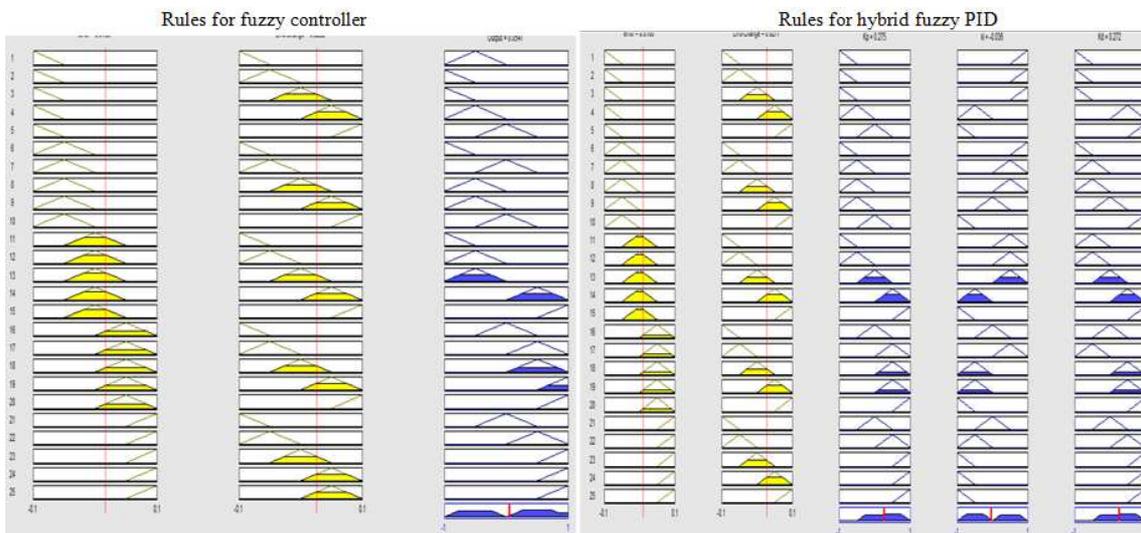


Fig. 5. Centroid defuzzification using max-min inferencing.

Hybrid fuzzy PID controller: The control system is a typical fuzzy-PID hybrid control system. It utilizes the advantages of a fuzzy controller and a PID controller. This controller is capable of overcoming the presence of nonlinearities and uncertainties in a system. Tuning of the different parameters of the PID controller is executed with the fuzzy logic controller. Fuzzy rules are designed for effective tuning of the parameter K_p , K_i , and K_d according to functions of the actuating error signal. The proportional term

is responsible for the entire control process that is proportional to the error. The aim of the integral term is to help in reducing the steady-state error through low frequency compensation with the aid of an integrator. While the derivative term helps in improving the transient response through high frequency compensation [16]. The design and implementation of the control system uses efficient technique that can achieve performance requirement in the presence of disturbances and uncertainty [17]

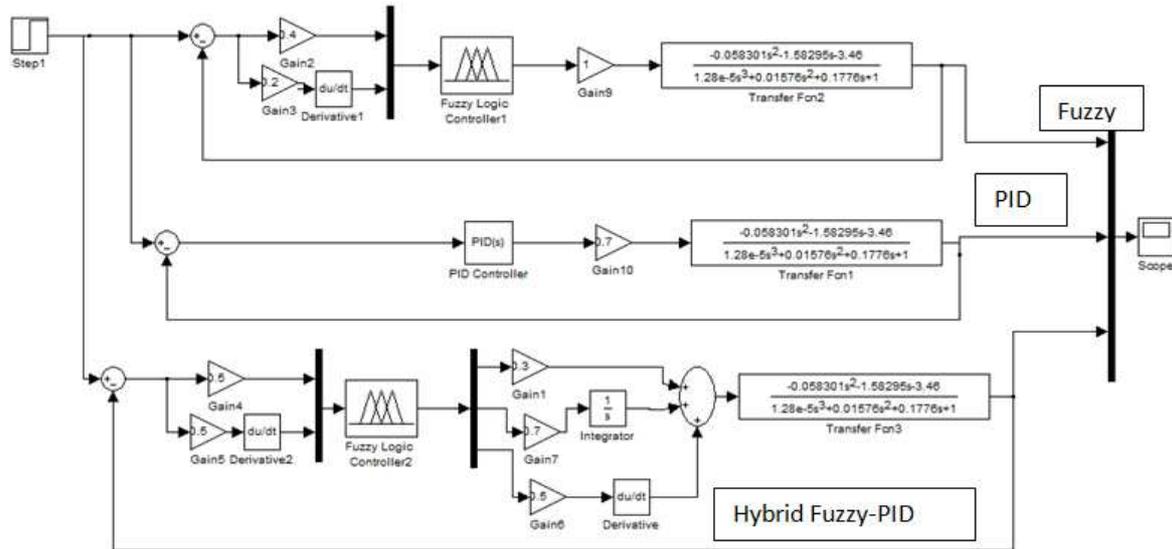


Fig. 6. Control system for underwater FCAW.

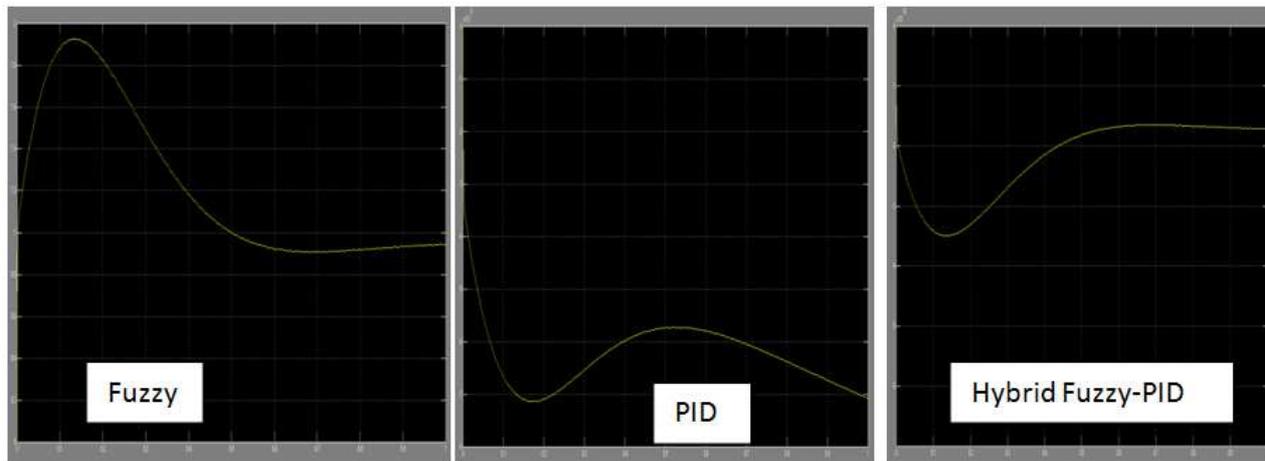


Fig. 7. Matlab simulation results of PID, Fuzzy and hybrid fuzzy PID controller.

6. Results and Discussion

The plant model executed in this paper (Figure 6) made use of the application of the control dynamics of PID, fuzzy and hybrid fuzzy PID. The performances for the different control systems were compared as can be seen in the simulation results in Fig. 7. The system response was tested using a step input signal. From the analysis of the dynamic response of the various control system indicate that fuzzy controller produces a more suitable result compared to the

PID controller. From the results, it is evident that the fuzzy controller exhibits a faster response than the PID controller. Results from the PID controller gave rise to overshoot. However, results from the hybrid fuzzy PID controller gave a more satisfactory result of overshoot, rise time and steady state error. The proposed hybrid fuzzy PID controller demonstrates the advantages of fuzzy and PID controller. Application of the hybrid fuzzy PID controller is suitable for FCAW process used in underwater welding since the input current and output CTWD can be predicted and controlled.

7. Conclusion

The control of welding arc current in relationship to CTWD of FCAW for underwater welding application is effective way of ensuring the desired heat input and arc length during welding. The application of a hybrid fuzzy PID controller has the potentials of eliminating the effect of uncertainties and disturbance during underwater welding. A properly control underwater welding process will result bead geometry that is favorable for a sound and reliable weld for welding of offshore structures underwater.

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