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Author(s): D.A. Hartman, MST-6
D.R. DeLapp, Vanderbilt University
G.E. Cook, Vanderbilt University
R.J. Barnett, Vanderbilt University

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INTELLIGENT CONTROL IN ARC WELDING

D.A. HARTMAN

Materials Science and Technology Division
Los Alamos National Laboratory
P.O. Box 1663, Mail Stop G770
Los Alamos, New Mexico 87545
Email: hartman@lanl.gov

D.R. DELAPP, G.E. COOK, AND

R.J. BARNETT
Welding Automation Laboratory
Vanderbilt University
Box 1824 Station B
Nashville, Tennessee 37235

ABSTRACT

A unique excitation, sensing, and control system has been developed to predict and control the state of penetration during the gas tungsten arc welding (GTAW) process. Excitation of the molten pool is accomplished by synchronously modulating the arc force in phase with the weld pool's own natural frequency using a phase-locked loop (PLL) technique. A non-intrusive, non-contact, top-side sensor collects the arc light reflected from the oscillations of the molten metal's surface. Assessment of the joint geometry is performed using Rayleigh's suspended droplet analogy in which the mass, and hence the volume, of the droplet is related to the natural resonant frequency of the molten region. Finally, joint penetration is maintained constant throughout varying thermal regions by regulating the current in response to changing pool conditions.

A detailed discussion regarding the development of a self-organizing fuzzy logic controller, modeled after expert human welding knowledge and tuned on-line is provided. An in-depth comparison between various open- and closed-loop experiments of the joining process is discussed.

INTRODUCTION

The fabrication of precision components is particularly susceptible to difficulties in maintaining uniform bead geometry, in general, and consistent depth of penetration, in particular. Inconsistent root fusion using identical equipment and the same welding schedule can occur as a result of variations in (1) the process parameters, such as material dimensions and joint fit-up; (2) the welding parameters, including welding current, electrode-to-workpiece distance, electrode dimensions and tip geometry, and shielding gas composition and flow rate; (3) the material properties, involving cast-to-cast variations in material composition, surface roughness, and cleanliness; (4) heat sink variations caused by, for example, inconsistent size tack welds; and finally (5) the welder's skill.

Mechanization and tighter control of the process tolerance and welding parameters has been employed in an effort to minimize variations, improve the depth of penetration uniformity between consecutive weld schedules, and reduce the demands on the welding operator's skill. Automatic and robotic welding systems are capable of preprogrammed control of the welding parameters and the welding torch motion. Weld joint tracking systems incorporating sophisticated vision- or laser-based seam tracking are able to not only track the joint but also sense the joint size and root opening in an effort to maintain adequate root fusion.

Even under extremely stringent process tolerances and production welding conditions sufficient variations occur during the fusion process causing unacceptable welds with marked differences in penetration. Such inconsistencies can be attributed to (1) variations in the equipment performance, including power supply cooling efficiency, electrical dips and surges, and output current noise, such

as peak-to-peak ripple; (2) distortion of the components (i.e., warping) during the welding process; (3) cast variations within a given material specification; and (4) electrode deformation.

On-line feedback and control of the welding process parameters during mechanized welding is necessary to ensure high quality, repeatable welds under conditions in which unavoidable and undetectable irregularities exist. Innumerable research efforts at improving the quality and reducing the performance variation through process feedback and control have been attempted. The choice of process parameter(s) used in the feedback loop and the methods employed in the control algorithm have varied greatly with different research attempts (Cook *et al.*, 1993). In general, however, penetration is a good first order indicator of weld integrity, and most efforts at weld quality control have been concentrated on penetration (Hardt and Katz, 1984).

This research investigates the application of intelligent techniques, fuzzy logic and neural networks in particular, as a means of improving the controllability of the depth of penetration in the gas tungsten arc (GTA) welding process. A closed-loop, single variable process control system was developed to control the depth of penetration of the molten weld pool into the weldment. Both neural network and fuzzy logic methods have been employed as tools to help indirectly sense, predict, and control the state of penetration of the weld pool (Hartman, 1999).

This paper will present the development and application of an on-line tuning fuzzy logic controller for GTA weld penetration control. The motivation behind such an implementation is explained. The results will demonstrate the robust capabilities of applying fuzzy logic to the control of ill-defined processes. Finally, this paper will demonstrate how a fuzzy tuner can monitor the controller's performance on-line and fine-tune the controller's rule base to handle specific process conditions, such as asymmetric process characteristics, and other process details that usually get lost in the translation from expert knowledge to fuzzy membership functions (MFs) and rules.

WELD BEAD GEOMETRY CONTROL

Background

Unlike sensing the bead width or the root gap opening, directly sensing the depth of penetration can be extremely difficult, if not impossible, to perform. When access to the backside of the workpiece is unavailable or when full penetration is undesirable, directly sensing the depth of penetration becomes a non-trivial task. Numerous methods for sensing penetration, directly and indirectly, are presented in (Hartman, 1999).

The method for assessing joint penetration employed in this paper is an improvement upon a method presented in (Andersen *et al.*, 1997) and (Hartman *et al.*, 1998) in which the natural mechanical frequencies of the molten material are used as an indirect means of assessing the fusion zone geometry, and hence penetration. The dynamic model used in this research employs a novel fluid droplet analogy to predict the mass of the weld pool from the fundamental mode of vibration (Hartman, 1999). An improved method of synchronously exciting and intelligently detecting the natural frequencies of the molten metal using fuzzy logic and neural networks is described in (Hartman, 1999). Improvements in monitoring accuracy, reliability, and controllability have been achieved.

In general, successful implementation of a closed-loop, single or multivariable process control system involves sensing, modeling, and control. Weld bead geometry control using the fundamental frequency of the weld pool involves (1) exciting the pool into motion, (2) sensing the pool's relevant modes of oscillation, (3) detecting the fundamental frequency, (4) relating the fundamental frequency to pool mass or volume, and (5) adjusting the total heat input (either through regulating the current or travel speed, or both). Sensing weld pool vibration involves monitoring

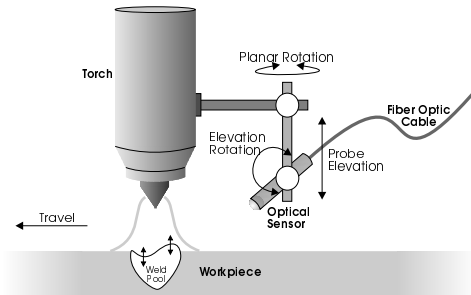


Figure 1. Weld pool oscillation monitoring using specular arc light.

at least one of the process outputs, either arc voltage or arc light. A model of the relationship between the pool's geometry and its frequency is necessary to extract useful information from the power spectral density and to properly adjust the total heat input into the weldment.

The detection of pool oscillation was accomplished by collecting the specular reflection from the weld pool's mirror-like surface. Unlike sensing the fluctuations in the arc column, either through arc voltage or diffuse arc light, specular reflection of the pool's surface has been found to provide additional modal information from the pool's vibrations, thus enhancing the detection and controllability of the process. A schematic of the optical probe relative to the GTAW torch and workpiece is illustrated in Figure 1. A sophisticated computer-based data acquisition, visualization, and control interface was developed to provide real-time feedback of the process outputs. High-performance parallel digital signal processors (DSPs) were used to perform signal processing tasks, such as filters, fast Fourier transforms (FFTs), and phase-locked loop (PLL) techniques, and to execute intelligent techniques, such as neural networks and fuzzy logic, for detection and control. The system was a critical component to the successful completion of the weld penetration controller (Hartman and Cook, 1999).

The approach taken in this research can be naturally broken down into three areas of interest: excitation, detection, and control. This paper will address the development of an on-line tuner for a fuzzy logic controller. Further information about this and other topics regarding penetration control can be found in (Hartman, 1999).

Fuzzy Logic Control

The control of the fusion zone size by adjusting the total heat input into the weldment is a non-linear, time-varying, asymmetric problem. A comprehensive analysis of the arc welding process is extremely complex due to the interactions between electrical, thermal, mechanical, and metallurgical phenomenon of the process. Consequently, relationships between the various process inputs and outputs are ill-defined and, oftentimes, highly coupled. Furthermore, unexpected process, environmental, and material variations that are encountered, even under extremely stringent process tolerances and production welding conditions, demand that the controller have on-line, adaptive capabilities.

Conventional methods require an analytical technique based on the fundamental laws of physics to describe the dynamic and static behavior of the process. Such an approach to the control of ill-defined or complex processes will ultimately compromise the accuracy and robustness of the controller due to necessary simplifications and assumptions that must be made on behalf of the model to ensure computational tractability.

Humans, on the other hand, are quite capable of performing control tasks on

Table 1. Regulating current while monitoring weld pool oscillations.

| Error = Setpoint - Actual | | |
|---------------------------|------------------------|----------------------------|
| Mathematical Relationship | Physical Phenomenon | Controller Action Required |
| Setpoint > Actual | The pool is too large. | Decrease current. |
| Setpoint < Actual | The pool is too small. | Increase current. |

complex processes where a thorough understanding of the process dynamics is unavailable, and hence a mathematical model is impractical. Unlike conventional control where the underlying physics are necessary in developing a controller, a human can, for example, perform complicated vertical-up shielded metal arc (SMA) welding without any mathematical understanding of the relationship between surface tension, arc force, gravity, and temperature. Although years of training and experience have provided the welder with the skill and proficiency necessary to perform complicated welds, the knowledge is not based on mathematical principles or fundamental physical understandings.

Clearly, a different approach needs to be taken in order to address control problems in which conventional techniques based on precision and certainty and governed by difference, differential, and integral equations fall short. In this research, the designer of the control strategy is the welding expert. A welder's knowledge of control can be captured through heuristics, or rules of thumb, rather than through complicated electrical and thermal models of the process. Fuzzy logic provides an ideal platform for translating this typically imprecise knowledge and qualitative information into a quantitative form. The result is a fuzzy model based on the intuitive control strategies of an expert human welder.

A commonly accepted practice in FLC design is to choose the error and the change in error as inputs and to generate an incremental variable as output. For the penetration control system developed in this research, the controller's input is frequency and its output is current. The fuzzy input variables, therefore, are the error e and the change in error Δe , while the fuzzy output variable is the change in current Δu . The control variables are normalized to a universe of discourse within the interval $[-1.0, 1.0]$ prior to the fuzzification process.

The strategy employed to regulate current is presented in Table 1. A weld pool that is too large will have a fundamental frequency that is less than the setpoint frequency thus resulting in a reduction in the welding current by the controller. Conversely, a weld pool that is too small will have a fundamental frequency that is greater than the setpoint frequency thus resulting in an increase in the welding current by the controller.

Based on this high-level understanding of the relationship between pool size and frequency, the following linguistic labels were defined for the three fuzzy sets:

$$\begin{aligned}
 e &= \{ \text{NL, NM, NS, ZE, PS, PM, PL} \} \\
 \Delta e &= \{ \text{NL, NM, NS, ZE, PS, PM, PL} \} \\
 \Delta u &= \{ \text{NL, NM, NS, ZE, PS, PM, PL} \}
 \end{aligned}$$

where NL, NM, NS, ZE, PS, PM, and PL are negative large, negative medium, negative small, zero, positive small, positive medium, and positive large, respectively. Each fuzzy label is described using simple triangular or trapezoidal membership functions.

The design of the controller's rule base was guided by a conventional phase-plane understanding of the error and the change in error, justified through expert welding control knowledge, and verified on-line as an adequate solution to the

problem. The following rules summarize the thinking process involved in tracking a setpoint using the error and the change in error:

1. If both the error e and the change in error Δe are zero, then maintain the present control setting, i.e., let $\Delta u = 0$.
2. If the conditions are such that the error e will go to zero at a satisfactory rate, then maintain the present control setting, i.e., let $\Delta u = 0$.
3. If the error e and the change in error Δe indicate departure from the setpoint or approach the setpoint at unsatisfactory rate, then set the controller output Δu to a value which depends on the sign and magnitude of e and Δe .

Using the three metarules listed above, the phase-plane mappings developed in (Hartman, 1999), and assuming a symmetrical response from the process, a generic rule base can be naturally mapped into a grid-like format.

The predefined linguistic variables, their membership functions, and the untuned rule base produced adequate results for slow process and environmental variations. The translation, however, from expert human knowledge to a set of fuzzy variables and an accompanying rule base inevitably results in a loss of details. Consequently, this generalization almost always requires the control engineer to manually tune, or tweak, the fuzzy controller in an effort to improve the transient and steady-state performance of the system. Manually tuning a fuzzy logic controller is time consuming, and hence costly; ill-defined and oftentimes subjective; and unsystematic thus resulting in inconsistent outcomes from one tuning run to the next. It is, therefore, highly desirable to automate this stage of development to ensure reproducible results, enhance the details of the process that were lost in the translation from expert knowledge to fuzzy variables and rules, and reduce the development time.

Adaptive Fuzzy Logic Control

In general, the tuning process of most control systems involves a trial-and-error period in which the control engineer monitors the transient response to a unit step input. Typical performance criteria that are used to characterize the transient response include overshoot, delay time, rise time, and settling time.

Although the controller's performance was acceptable for our initial trials, improvements in tracking accuracy, increased travel speeds, and larger variations in both the process and the environmental conditions necessitated a more accurate description of the fuzzy control laws. Consequently, an on-line adaptive tuner was developed to modify the initial membership functions and/or linguistic rules. The on-line tuner enabled the penetration control system to accommodate different welding materials and conditions, to adjust to asymmetric response characteristics of the process, and to continually adapt to changing heat capacity conditions in the workpiece.

The approach taken in this research to develop an on-line FLC tuner was consistent with the reasoning and methodology inherent in modeling ill-defined processes using fuzzy logic. Rather than relying on an inverse mathematical model to evaluate controller performance and facilitate controller tuning, this research employed a model-independent, self-tuning scheme. Controller performance and rule-base tuning was accomplished in the traditional spirit of fuzzy logic, i.e., through human experience and precedents that can only be expressed in a vague, ambiguous, and qualitative way.

No assumptions were made about the process. Instead, the only knowledge required to evaluate the controller's performance and modify the control laws was based on a human expert welder's expectations of the process response, and hence the controller's performance: rise time, overshoot, and steady-state oscillation. Consequently, the model-free tuning method required no additional knowledge

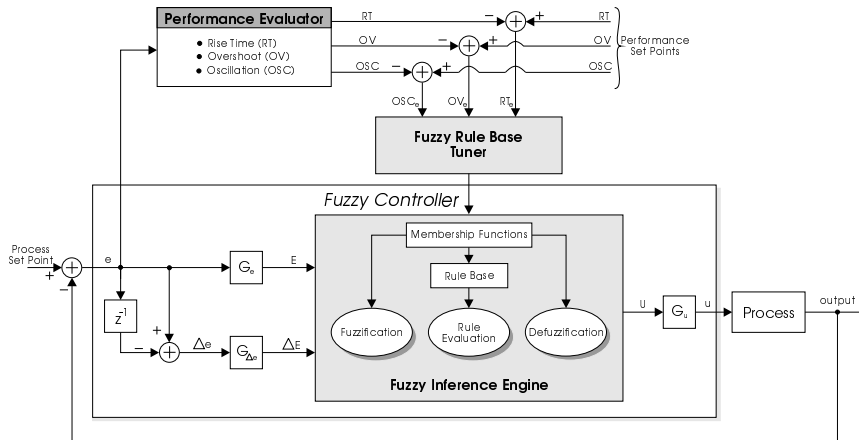


Figure 2. Fuzzy logic control system with on-line tuning.

about the process other than what a typical control engineer would expect in evaluating a controller.

Just like a control engineer would watch the time-base, transient response between the process's actual value and its setpoint, a performance evaluator was developed to monitor the rise/fall time, the over/undershoot, and the steady state oscillation of the system. The error between the actual performance values and the set of performance criteria is calculated to assess the extent of deviation from the actual and the desired for each of the criteria. A second fuzzy logic inference engine assesses the deviation in performance and adjusts the membership functions and/or the rule base appropriately. The integration of a performance evaluator as an on-line tuner to a FLC is illustrated in Figure 2.

Automated FLC tuning was accomplished in a manner similar to manual tuning. For example, if the rise time performance of the controller is inadequate, then the control engineer would adjust those membership functions of the output fuzzy variable to encourage a quicker response. In general, the control engineer would "strengthen" or "weaken" those membership functions that exhibited poor performance either due to inadequate rise time characteristics, excessive overshoot, or unacceptable oscillation during steady state.

Unlike self-organizing techniques which rely on adding or replacing rules based on a reward system (Procyk and Mamdani, 1979), (Langari and Tomizuka, 1990) (Vijeh, 1993), and (Singh, 1998), FLC tuning techniques assume that some initial rule base has already been established. Consequently, tuning methods exploit the fundamental advantage of fuzzy systems by incorporating a vague, yet intuitive, human-based model of the system. Once the fuzzy system is established, the evaluation of the controller's performance and the modification of the controller's fuzzy variables and rule base can thereby deepen the controller's knowledge of the process dynamics, and hence improve its performance.

Adaptive techniques in which an initial rule base is tuned either on- or off-line is similar in concept to auto-tuning of a PID controller in which an approximate controller is designed off-line followed by an on-line tuning of the gain coefficients. Most attempts at tuning a fuzzy controller involve the modification of the weighting coefficients, or scaling factors (SF), for the input and output variables of the FLC (Abdelnour *et al.*, 1991), (Daugherty *et al.*, 1992), (Li and Gatland, 1995), and (Oh and Park, 1998). Adaptive gain adjustment of the input/output fuzzy variables enables a fuzzy variable to have either coarse or fine MFs depending upon the state of the process. In general, large errors in the transient state require coarse control,

| Δe | NL | NM | NS | ZE | PS | PM | PL |
|------------|----|----|----|----|----|----|----|
| PL | ZE | NS | NM | NL | NL | NL | NL |
| PM | PS | ZE | NS | NM | NM | NL | NL |
| PS | PM | PS | ZE | NS | NS | NM | NL |
| ZE | PL | PM | PS | ZE | NS | NM | NL |
| NS | PL | PM | PS | PS | ZE | NS | NM |
| NM | PL | PL | PM | PM | PS | ZE | NS |
| NL | PL | PL | PL | PL | PM | PS | ZE |

Labels: "fall time" on the left, "Rise Time" on the right.

| Δe | NL | NM | NS | ZE | PS | PM | PL |
|------------|----|----|----|----|----|----|----|
| PL | ZE | NS | NM | NL | NL | NL | NL |
| PM | PS | ZE | NS | NM | NM | NL | NL |
| PS | PM | PS | ZE | NS | NS | NM | NL |
| ZE | PL | PM | PS | ZE | NS | NM | NL |
| NS | PL | PM | PS | PS | ZE | NS | NM |
| NM | PL | PL | PM | PM | PS | ZE | NS |
| NL | PL | PL | PL | PL | PM | PS | ZE |

Labels: "Undershoot" on the right, "Overshoot" on the left.

| Δe | NL | NM | NS | ZE | PS | PM | PL |
|------------|----|----|----|----|----|----|----|
| PL | ZE | NS | NM | NL | NL | NL | NL |
| PM | PS | ZE | NS | NM | NM | NL | NL |
| PS | PM | PS | ZE | NS | NS | NM | NL |
| ZE | PL | PM | PS | ZE | NS | NM | NL |
| NS | PL | PM | PS | PS | ZE | NS | NM |
| NM | PL | PL | PM | PM | PS | ZE | NS |
| NL | PL | PL | PL | PL | PM | PS | ZE |

Labels: "Undershoot" on the right, "Overshoot" on the left, "Steady State" at the bottom.

Figure 3. Areas of the control rule base and their effect on different states of the control process.

whereas small errors in the steady state require fine control. Consequently, variable control resolution facilitates improved performance over a larger range of process conditions.

Although similar to adjusting the SF of the input or output fuzzy variables in which the effect is felt globally across all output MFs, the method implemented in this research is able to affect only those output membership functions that need tuning, thereby leaving all other membership functions unchanged. Locally adjusting the scaling factor of only certain membership functions, i.e., by shifting their centroid, is equivalent to having a separate gain variable for each rule in the fuzzy rule base. Most importantly, unlike modifying a global gain variable, localized adjustments enable the controller to adapt to asymmetric process characteristics and further enhances the non-linear tracking capabilities of the controller.

| Δe | NL | NM | NS | ZE | PS | PM | PL |
|------------|---------|---------|---------|---------|---------|---------|---------|
| PL | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 |
| PM | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 |
| PS | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 |
| ZE | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 |
| NS | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 |
| NM | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 |
| NL | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 | 1.0e+00 |

Figure 4. Rule base gain matrix.

Knowledge about which rules from the rule base are responsible for certain performance characteristics of the process is facilitated by an understanding of the phase-plane relationship. Conceptually, the phase-plane helps the control engineer map the desired system performance of the process to the FLC rule base. However, when the desired system performance is inadequate a phase-plane understanding can help identify which area of the control rule base grid must be modified.

The areas of the control rule base responsible for the system's transient and steady state performance are illustrated in Figure 3. Each rule within the rule base grid is initialized with a gain equal to 1.0, see Figure 4. Modification of the gain for an individual rule or a group of rules is performed by the tuner when the controller exhibits unacceptable performance during the rise-time, overshoot, or steady state oscillation.

Performance expectations of the time-response characteristics from the controller are defined a-priori by the control engineer. Criteria for the acceptable rise/fall time, over/undershoot, and steady state oscillation must be provided. In order to establish when the process should have reached steady state, an additional process characteristic, the settling time, must also be furnished. The performance tuning criteria can be modified and monitored in real-time (Hartman, 1999).

Adjustment of the gains for each rule within the rule base is accomplished with a one input, one output proportional fuzzy logic controller. The input is the error between the actual process response and the desired response and the output is the percent adjustment. Two fuzzy membership functions, error and adjustment, were defined for both the input and output tuning components, respectively. Three membership functions, small, medium, and large were used to quantify both the error and the adjustment. The fuzzy tuning variables are normalized across a universe of discourse within the interval [0.0, 1.0].

Tuning is initiated after the process is brought close to the desired operational condition by manual control. Steady state operation is, therefore, assumed to be achieved at this time. A detailed presentation of the tuning procedure, including a flowchart and algorithm of the process, is provided in (Hartman, 1999).

EXPERIMENTAL RESULTS

Having realistic performance expectations is critical to the success of the tuning process. Otherwise, unrealistic performance criteria will result in a conflict of objectives and will ultimately cause the tuner, and hence the controller, to fail. Therefore, sufficient insight into the process is necessary to establish realistic tuning parameters which will, in turn, provide achievable controller performance.

Customization of the tuning parameters will vary due to the nature of the process and the control engineer's requirements. Certain processes are naturally quiescent such that disturbances to the process and changes to the setpoint are uncommon. Consequently, long rise times and non-aggressive response characteristics involving minimal overshoot and short settling times are desirable. On the other hand, other processes demand aggressive action which minimizes the rise time at the expense of possible overshoot error and subsequent oscillations. In any event, the ideal performance criteria is dependent on the process; therefore, performance expectations must be resolved prior to enacting the tuner.

The primary objective in this research was to maintain constant fusion zone geometry throughout varying thermal regions. The depth of penetration is typically used as a first-order approximation of the quality of a welded joint. In the event that the weld is inadequate in penetration, the possibility exists for a weld of insufficient strength and possible failure of the weld during service. If the weld penetration is too great, poor weld quality results, with the possibility of catastrophic melt-through, thus ruining the product during the assembly process and prior to any possible use. Consequently, quick response times to changing thermal conditions at the expense of small overshoots and minor oscillatory conditions was determined in advance to be the performance objective of the tuner.

Tracking limitations of the probe restricted the scope of testing to underdamped systems. Drastic variations in the pool size prevented the probe from tracking the specular reflection of the pool's surface. An operating window between 45 Hz and 60 Hz of the pool's fundamental frequency was determined to be within the limitations of the probe's tracking capabilities. Under this operating window, the welding conditions provided partial to near full penetration welds. Details about the experimental setup, including the welding process and apparatus, the welding parameters and materials, and the computer-based control system, are provided in (Hartman, 1999).

Three systems were tested: excessively underdamped, underdamped, and acceptable. The gain matrix was initialized to unity prior to each run. The output of the controller was configured in such a manner as to simulate excessively underdamped, underdamped, and acceptable response conditions. The desired criteria for the controller's performance was a 5 second rise or fall time, a 15% over or undershoot, a steady state oscillation of 15%, and a settling time of 8 seconds.

Arc initiation and steady state welding conditions were first accomplished by manual control. Automatic control was established approximately within the first 30 seconds of the welding run. Tuning was initiated shortly thereafter. Finally, step changes to the system were imposed by manually changing the controller's setpoint.

In the two underdamped cases, the rise and fall time response to a step change improved over the length of the run (refer to Figure 5). The increased slope during the time history plot of the controller's response, illustrated in Figures 5(d) and 5(e), demonstrates the tuner's capability of adjusting the gain matrix to improve the controller's performance. The gain matrices, illustrated in Figures 5(g) and 5(h), clearly demonstrate proper tuning correction when the system exhibits poor rise and fall time performance. In an effort to accommodate the desired performance characteristics, minor adjustments to the gain values associated with the overshoot were made in response to the increased gain adjustments for the rise time area of the rule base.

The third system, which exhibited acceptable rise/fall time response, required only minor modifications. In particular, a reduction in the rise time gain was made in order to accommodate smaller overshoots. This can be seen in the resulting weight matrix illustrated in Figure 5(i). Increased oscillatory behavior was expected due to the stringent rise and fall time requirements.

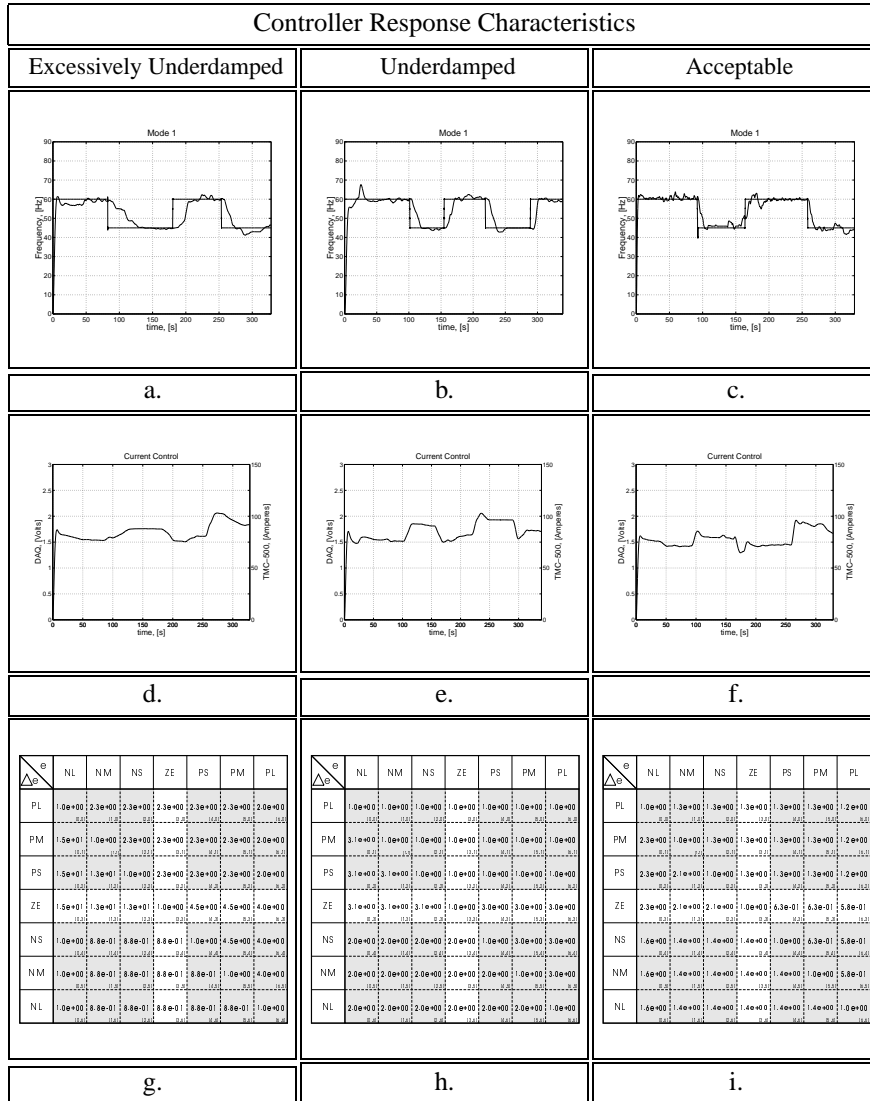


Figure 5. Rule base tuning results for different controller response characteristics.

CONCLUSION

Manually tuning a fuzzy logic rule base is considered by some to be the greatest drawback to using fuzzy logic for control purposes. In addition to the inherent time consuming and tedious nature of the task, manual tuning is unsystematic and error prone. This paper attempts to address this shortcoming in FLC by presenting a fuzzy tuning method.

The method presented incorporates the flexibility and power of fuzzy logic to

overcome one of its largest drawbacks, i.e., tuning. The method assumes that a general, yet non-optimal, control rule base has already been established. Relying on this assumption, the tuning strategy observes the time-domain tracking performance of the controller to make localized adjustments to the rule base gain matrix.

The tuning technique has been demonstrated on a real-world application under industrial manufacturing conditions in which process disturbances, such as noise, material impurities, varying thermal conditions, etc., are commonplace. The intelligent adaptive controller has improved the response time of the system without jeopardizing other controller performance characteristics. Furthermore, it has enhanced the non-linear tracking capabilities in addition to incorporating asymmetric response characteristics which were lost during the translation from human expert knowledge to fuzzy variables and rule definition. Most importantly, in the spirit of fuzzy logic, the tuning approach is simple, robust, and easy to explain.

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