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Prepared by
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Albuquerque, New Mexico 87185 and Livermore, California 94550
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Control of Resistance Plug Welding Using Quantitative Feedback Theory

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Abstract

Resistance welding is used extensively throughout the manufacturing industry. Variations in weld quality often result in costly post-weld inspections. Applications of feedback control to such processes have been limited by the lack of accurate models describing the nonlinear dynamics of this process. A new system based on electrode displacement feedback is developed that greatly improves quality control of the resistance plug welding process. The system is capable of producing repeatable welds of consistent displacement (and thus consistent quality), with wide variations in weld parameters. This paper describes the feedback design of a robust controller using Quantitative Feedback Theory for this highly complex process, and the experimental results of the applied system.

Acknowledgments

There are many people who have contributed to this work. The authors wish to thank Dr. Isaac Horowitz of The University of California at Davis who developed "Quantitative Feedback Theory" (QFT)—which made this design both practical and understandable. The talents of Gene Angvick are responsible for implementation of the control system in software, and its flawless performance. Technical assistance was provided by Scot J. Marburger, Sam B. Johnson, John A. Brooks, Rich H. Campiotti and Gordon Gibbs—and a special thanks to Antonio J. De Sousa who spent many hours making and evaluating the welds. The contributions of all these people are sincerely appreciated. This investigation was carried out at Sandia National Laboratories in Livermore, CA. The support of the United States Department of Energy under contract DE-AC04-76DP00789 is gratefully acknowledged.

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Introduction

Plug welding is a solid-state resistance welding process used to attach stainless steel plugs or stems to pressure vessels. It is one of the last steps in the fabrication of complicated and expensive reservoirs that must be highly reliable. Since there are currently no nondestructive evaluation techniques available to completely verify weld quality, the welds must be cut open and evaluated under the microscope.

The weld (illustrated in Figure 1) is made by passing a high current through the parts to be joined. Prior to the flow of current, a large force (typically two to four thousand pounds) is applied by the welding electrodes to the parts. Because of the resistance at the interface (between the two parts), current flowing across the interface generates heat. The combination of elevated temperature and electrode force causes the plug to *slide* into the hole, and a metallurgical bond develops at the interface. The resulting weld quality is a complicated function that depends on a number of weld and material parameters, the most significant of which are: current, weld duration, force and part cleanliness.

Figure 1. Schematic Illustration of Resistance Plug Welding

a. Class 1: Interface not visible when etched—grain growth across interface.

b. Class 2: Discontinuous interface visible—grain growth across interface.

c. Class 3: Continuous interface when etched—faintly visible unetched.

d. Class 4: Interface clearly visible unetched condition—no grain growth.

Figure 2. Photomicrographs (500x) for Evaluating Plug Weld Bond Quality.

Modern resistance welding equipment operate under the direction of a welding operator who determines proper machine settings. In more advanced systems, individual weld parameters (weld process inputs) such as weld current, force and/or power are held reasonably constant with feedback control loops; however, set points for the individual weld parameters are selected based on the results of narrow experimental parameter searches. These tests are expensive even for statistically designed experiments. Weld characteristics (weld process outputs) such as bond length, and microstructure are used as acceptance criteria during the parameter selection process. Plug welds are slit longitudinally, etched (to enhance grain boundaries) and classified as to the amount of grain growth across the interface (among other things). An ideal weld interface (class 1 bond) is shown at 500X in Figure 2a along with the more typical interface (class 2 bond) in Figure 2b. Poor quality welds are either class 3 and class 4 (also shown in Figure 2.) Along the weld interface there typically exists bond sections of all four classes—with class 3 or 4 at the ends of the weld and class 1 or 2 in the middle.

The challenge associated with quality control of plug welding is the large amount of uncertainty in the relationship between weld quality and weld parameters. That is, weld quality often varies in unpredictable ways—even while welding parameters are held reasonably constant. Prototype plug welds are developed at Department of Energy design laboratories but weld parameters cannot be successfully transferred to the production agencies because of the difficulty in calibrating development welding equipment with production equipment. Calibration between production welders is a tedious process.

Once a system is properly calibrated, factors such as electrode wear and oxidation, can cause the relationship between weld parameters and bond quality to shift over time. Furthermore, weld current is difficult to control due to power surges and dips created by other high-power equipment on the same circuit and is also difficult to accurately measure because of its non-sinusoidal, large magnitude.

Presently, the only way to completely determine plug weld quality is the above mentioned microstructure evaluation. Production welds are randomly sampled and destructively tested to *infer* weld quality of the untested parts. While these methods are useful, they do not **improve** weld quality, only **inspect** quality, and add tremendous costs to the product.

The goal of this work is to reduce the need for post weld inspection and equipment calibration by implementing automatic, real-time quality control. That is, by utilizing feedback control, weld quality variation can be minimized to the point that inspection becomes unnecessary. Achieving this requires sensor systems capable of appraising weld quality in real-time. A recent study at Sandia demonstrated a correlation between plug weld quality and electrode displacement, (see Figure 3) suggesting that displacement could be used as a real-time quality measurement for feedback control.¹ The objective of the study reported herein was to develop a feedback control system to produce plug welds of consistent weld quality, with wide variations in welding power.

---

1. Johnson, S. B., "A Characterization of the Side Bonding, Upset Plug Welding Process," *Sandia Report*, August 1989, SAND89-8242 UC-13, Sandia National Laboratories, Livermore, California.

Figure 3. Plug Weld Quality Vs. Displacement

Currently there is considerable interest, among welding and material science engineers, in the area of feedback control of welding processes. This work is largely concentrated on developing new sensors to monitor weld quality for use in feedback systems.² Many promising techniques have been developed for real-time measurement of weld quality. Unfortunately, most welding engineers find control theory too theoretical for their backgrounds³ and typically resort to empirical methods of feedback design—utilizing such tools as Proportional-Integral-Derivative (PID) with or without auto tuning capabilities, Bang-Bang, Adaptive, Fuzzy etc. This regrettable situation has led to some strong statements such as: "In developing welding control, system theory is not of much help."⁴ Another strong conclusion is offered below:

-
2. Madigan, R. B., and H. R. Castner, "Survey of Weld Penetration Techniques," *Edison Welding Institute Research Report*, MR9002, January 1990.
  3. Morari, Manfred, "Control Theory and Process Control Practice," Plenary Session 2, *American Control Conference*, Boston, June 28, 1991.
  4. Schumacher, B. W., J. C. Cooper and W. Dilay, "Resistance Spot Welding Control that Automatically Selects the Welding Schedule for Different Types of Steel," *Society of Automotive Engineers Technical Paper Series*, 850407, (1985).

Unfortunately, the development of reliable [weld] penetration sensors cannot at this time be considered to be broadly successful. This is certainly related to shortcomings of current sensor technologies themselves, but also to the lack of knowledge of how to control [weld quality] once detected. That is, we do not have a good **quantitative** understanding, in engineering terms, of how control is achieved by manipulation of process parameters in the face of a multiplicity of disturbing variables.⁵

Engineers often spend more time tuning feedback parameters than testing their new sensors. The power of ordinary feedback—even when designed empirically—is so tremendous that impressive benefits are achieved in the laboratory by such designs—once they have been carefully tuned. However, empirically designed feedback systems have often caused **more** uncertainty in the processes they are trying to control when they are implemented on the factory floor. As a result, feedback control has developed a bad reputation for itself throughout the manufacturing community.

Dr. W. Edwards Deming, the internationally renowned consultant whose work directly led Japanese industry to revolutionize their quality and productivity, said the following about feedback control: "Gadgets and servomechanisms that by mechanical or electronic circuits guarantee zero defects will destroy the advantage of a beautiful narrow distribution of dimensions. They slide the distribution back and forth inside the specification limits, achieving zero defects and at the same time driving losses and costs to the maximum."⁶ (In recognition of Dr. Deming's "contribution to the economy of Japan", the *Union of Japanese Science and Engineering* now gives annual prizes in his name for contributions to product quality and dependability. In 1960 the emperor of Japan awarded him the *Second Order Medal of the Sacred Treasure*. Dr. Deming has also received numerous other awards including: the *Shewhart Medal* from the American Society for Quality Control in 1956; the *Samuel S. Wilks Award* from the American Statistical Association in 1983; and several LL.D. or Sc.D. *honoris causa* degrees from the University of Wyoming, Rivier College, Ohio State University, University of Maryland, Clarkson College of Technology, and the George Washington University.⁷)

Why is such an unfortunate impression prevalent among manufacturing engineers? One explanation has to do with the complicated dynamics of most manufacturing processes. Welding processes, for example, are highly nonlinear systems with large uncertainties. Obtaining reliable models that can be used for control design is for all practical purposes a non-option. Modern control methods, (such as H^∞ , H^2 and their derivatives) require some form of plant model with a very generalized uncertainty structure. In addition, modern control design methods typically result in overly conservative controllers which require the engineer to reevaluate the plant model. This design by iteration process, a fact of life in real world applications, must be as short as possible.

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5. Richardson, Richard W., and Paul Taylor, "An Experimental System for Full-penetration Gas Tungsten-Arc Welding," *Edison Welding Institute Research Brief*, B9007, September 1990, p. 1. (Emphasis Added.)
  6. Deming, W. Edwards, *Out of the Crisis*, Massachusetts Institute of Technology Center for Advanced Engineering Study, Cambridge, Ma, 1982, pp. 141-142.
  7. *Ibid.* p. vii.

Contrasting modern control methods, in terms of their applicability to manufacturing processes, is *Quantitative Feedback Theory* (or QFT). QFT is a rigorous engineering design method for robust performance specifications, and is applicable to large classes of nonlinear and/or time-varying systems as well as to linear systems. QFT is a valuable design tool for the following reasons: (1) it does not require identification of plant dynamics with uncertainty models—can use input/output data directly without fitting the data to mathematical models; (2) it employs classical frequency domain concepts with which most engineers are familiar—but it is emphasized that QFT is nevertheless mathematically precise (no approximations), for large classes of highly uncertain nonlinear, time-varying plants; and (3) the design process is highly transparent so that the "cost of feedback" in terms of compensator complexity, gain and bandwidth, number of sensors needed, sensor accuracy, sensor noise effects and design effort are clearly seen by the engineer—empowering him or her to make the necessary performance tradeoffs throughout the design cycle.

If an accurate model (including uncertainty) does exist of the nonlinear plant, one can design the closed loop system to meet pre-defined performance specifications.⁸⁻⁹ Another great advantage of QFT is that it allows the engineer to apply feedback theory to a wide variety of complex, ill-behaved systems,* without requiring extensive new design skills. The same techniques learned in classical control theory can be reapplied to complicated and challenging systems—thus liberating the engineer to concentrate on his or her conflicting design requirements and control strategies, rather than learning new mathematics.

Quantitative Feedback Theory has been successfully applied to both the resistance and arc welding processes at Sandia National Laboratories. In both cases, the "robustness" of the welding process was tremendously improved—far above any work previously published.¹⁰

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8. Horowitz, Isaac, and M. Sidi, "Synthesis of Feedback Systems with Large plant Ignorance of Prescribed Time Domain Tolerances," *International Journal of Control*, vol. 16, pp. 187-309, (1972).

9. Horowitz, Isaac, *Quantitative Feedback Design Theory*, vol. 1, QFT Publications, 1993, (4470 Grinnell Ave., Boulder, Co., 80303), Chapter 11.

* Such as unstable and/or non-minimum-phase plants (time-delays), multiple-loop plants with a variety of available internal sensing points—how to divide up the feedback burden between them, multiple-input multiple-output plants (for example in a 3 by 3 plant, the nine closed-loop system response functions to commands and disturbances, can be individually controlled despite large uncertainties).

10. Bentley, A. E., "Quantitative Feedback Theory with Applications in Welding," *International Journal of Robust and Non-linear Control*, Vol. 4, Issue 1, January 1994.

Process Characterization

In this section we describe the characterization of the plug welding process from the viewpoint of control design. That is, we identify the relevant input, disturbance, and manipulated variables, along with output or regulated variables.

Input and Output Variables

Under certain conditions, maintaining a constant electrode displacement from weld to weld can greatly decrease undesired variations in weld quality. Therefore we select electrode displacement, a measurable quantity—in real time, as the regulated variable. A typical electrode displacement curve for a nominal weld is shown in Figure 4 superimposed with the current used to make the weld.

The manipulating input variables are weld time, electrode force, power and transformer tap setting. Most important to the transient weld dynamics are weld time and power. Weld time is specified in cycles—meaning the number of 60 Hz power cycles used to make the weld. Welding power was selected as the control input which will respond dynamically to the feedback. Welding power is controlled by modulating the duty-cycle of the 60 Hz input current. The duty-cycle is specified in units of "percent heat". That is, a 50 percent heat setting delivers half of the *available* power to the part. As the available power changes due to voltage transients, welding power will likewise vary. Weld power may also be throttled by selecting different tap settings on the primary of the welding transformer. Thus weld power is a function of the primary line voltage, transformer tap setting and percent heat setting. While, percent heat and weld time are used as the manipulated variables in this study, electrode force, primary line voltage and transformer tap setting are treated as disturbances to the process.

Figure 4. Plug Weld Input (current) and Output (displacement) Waveforms.

A few words are in order regarding the effect of electrode force on weld quality. The weld quality vs. displacement correlation is shifted when the electrode force is varied—hence it is important to maintain consistent force in order to use displacement as a weld quality feedback measurement. A previous study¹¹ showed that the effect of electrode force on weld quality was insignificant (for the range used in that study) when compared to variations in welding current, and weld duration (Figure 5).

The measure of weld quality used in Johnson's study was the total length of acceptable bond quality (class 1 and 2). A more accurate weld quality measure was desired for this study, since Johnson's method did not discriminate between class 1 and 2 bond quality, neither did it take into account the poor quality welds (classes 3 and 4). The welds evaluated for Figure 5 (from Johnson's study), were re-evaluated by a certified welding inspector* and a weld quality number was calculated as follows: At 500x magnification, the total number of microscopic fields-of-view⁺ with class 1 bond (n_1) was quantified for each weld along with the total number of fields-of-view of class 2 bond (n_2) and so on. This was done on both sides of the sectioned plug weld and the assigned quality measure was calculated as per equation 1 below:

$$\text{Weld Quality} = 4 \cdot n_1 + 3 \cdot n_2 + 2 \cdot n_3 + n_4 \quad (1)$$

The nominal weld is approximately 0.13 inches long (or nine 500x fields-of-view). Therefore, the maximum weld quality number for a class 1 weld 0.13 inches long on both sides would be $4 \cdot 9 \cdot 2 = 72$, however it is not possible for a solid-state weld to be class 1 the entire length of the bond, and thus all welds of nominal length will have a quality number less than 72. (Of course, welds with more than nominal length, could exceed this maximum.) Applying the weld evaluation of equation 1 to the welds of Figure 5, manifests the effect of electrode force on weld quality. See Figure 6.

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11. Johnson, *Ibid*, pp. 25-27.

* Because the classification of weld quality is a highly subjective process, it is influenced largely by the eye of the classifier. Classes 1 and 4 are easily distinguishable even to the untrained eye, however the distinction between class 2 and 3 is much less obvious, and requires much skill and experience to accurately evaluate. (See Figure 2.) Therefore in order to accurately compare the results of this study with those of Johnson's study, the welds from both studies were evaluated by the same welding inspector.

+ At 500x magnification each field-of-view is 0.014 inches.

Figure 5. Length of Acceptable Bond Vs. Weld Duration and Force.

Figure 6. Weld Quality Vs. Duration and Electrode Force

Input/Output Dynamics

The resistance plug welding process is highly uncertain, non-linear and time varying in nature. Several examples follow that demonstrate each of these behaviors. The data for these examples come from the study conducted by Sam Johnson at Sandia—(reference 1).

The displacement curves of four different welds are shown in Figure 7. All four welds were made with identical force, percent heat, and tap settings. The only quantifiable difference between the welds was the length of time that current was applied, for example, the heat input for the "10 cycle weld" was shut off after 10 cycles, etc. For all welds, current was initiated at time zero.

The welding process has time varying dynamic behaviors that can be divided into three periods. The first period is a "temporary saturation" noticeable in Figures 7 through 9, and less so in Figure 10. In the second period, all transients seem to be dominated by an exponential growth along with some higher order dynamics. In the third period, we generally notice a sudden transition to steady state (after the power is shut off at the end of the weld).

Figure 7. Plug Welds Made at 40% Heat and 3,200 lbs. Force.

In the first period, there is a small immediate response in the output (displacement) corresponding to the instant that the input (power) is applied. However, shortly afterwards the system reaches a *plateau* where the process is temporarily saturated. Figure 8 shows that the displacement at which this temporary saturation occurs is uncertain. This saturation time is variable, and presently cannot be correlated to any quantifiable parameter variation. In the second period, the process dynamics are generally more repeatable, and as shown later, can be described with linear models. However, although a simple first-order damped exponential growth model fits the processes in Figures 7 through 9, higher-order dynamics are present in Figure 10, indicating nonlinear/time-varying behavior. The nonlinearity of the steady state response is clearly seen in all four Figures, and more especially in Figure 8 where a lower total heat input (40 weld cycles) resulted in a larger displacement than a higher total heat weld (50 cycles). In addition, Figure 10 shows that at higher heat levels, increasing the weld time does not increase weld displacement proportionally. This leveling-off (as shown in Figure 10), however, is not a true saturation—the process is fully capable of achieving much higher displacements if the percent heat is significantly increased.

Figure 8. Plug Welds Made at 50% Heat and 4,100 lbs. Force.

Figure 9. Plug Welds Made at 51% Heat and 3,200 lbs. Force.

Figure 10. Plug Welds Made at 67% Heat and 3,200 lbs. Force.

Naturally, one cannot derive a single *linear time-invariant* process model that characterizes these dynamics to any degree of confidence. This fact has been the single most limiting factor for analytical design of feedback control for this welding process. Note that these nonlinearities and uncertainties* are commonplace in the world of manufacturing. Resistance plug welding is one of the least complicated welding process in use today.

With this in mind, it is not surprising that control theory has not played a significant role in the manufacturing industry—for until recently, modern control theories did not explicitly deal with the problem of uncertainty—that is, all but one. Over thirty years ago Dr. Isaac Horowitz of Hughes Aircraft, building on the work of H. W. Bode, developed the first feedback theory that allowed the engineer to design feedback systems with large uncertainties to *quantitative* performance specifications.¹²⁻¹³

Though originally developed for linear-time-invariant, Single-Input-Single-Output (SISO) processes, over the years Dr. Horowitz has extended QFT to *non-linear*, time-varying, and Multiple-Input-Multiple-Output (MIMO) systems.¹⁴⁻¹⁵ The QFT design process is simple and yet precise—even for nonlinear system design.

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* Assuming a linear-time-invariant model for such a *non-linear*, time-varying process increases the amount of uncertainty in a system. Thus non-linearities and time-varying characteristics can be viewed as uncertainties. For simplicity in the text that follows, the authors will lump all three behaviors into one category, and collectively refer to them as *uncertainty*.

12. Horowitz, Isaac, "Fundamental Theory of Linear Feedback Control Systems," *Transaction of Institute of Radio Engineers on Automatic Control*, AC-4, December 5, 1959.
13. Horowitz, Isaac, *Synthesis of Feedback Systems*, Academic Press, 1963.
14. Horowitz, Isaac, "Synthesis of Feedback Systems With Nonlinear Time-varying Uncertain Plants to Satisfy Quantitative Performance Specifications", *Proceedings of IEEE*, vol. 64, No. 1, (January 1976).
15. Horowitz, Isaac, "A Survey of Quantitative Feedback Theory," Invited Paper, *International Journal of Control*, Vol. 53, 1991, pp. 255-291.

Process Identification for Control Design

A typical feedback system is shown below in Figure 11. The weld process (open-loop plant in control terminology) consists of both the welder $w(t)$ and the hardware controller $h(t)$. The hardware controller $h(t)$ is a closed architecture system which is not easily modified. It controls the triggering of the SCR's which provide current to the weld transformer as shown in Figure 12. The outputs of the controller are the SCR firing pulses, while the input is the percent heat control signal $x(t)$. Varying only the percent heat while holding all other inputs constant, reduces the system to a single-input/single-output system. For this class of processes, the most intuitive control design approach for an industrial control engineer is the one afforded by Quantitative Feedback Theory. With QFT, the engineer can readily apply well understood classical design techniques and achieve robustness against process nonlinearities, disturbances and uncertainties.

Figure 11. Block Diagram of Feedback Control System

Figure 12. Schematic Diagram of Welding System

The first step towards a QFT design would be to derive a representation for the process dynamics. Clearly, there are no mathematical models that accurately describe the dynamics of the plug welding process, which are also adequate for control design. Therefore, one must perform welding system identification empirically. In particular, we identify a linear time-invariant (LTI) process that equivalently characterizes each input/output time series. For example, consider a *nonlinear* time invariant plant $w(t)$, which requires input $x_i(t)$ in order to produce output $y_i(t)$. Now consider a *linear time invariant* plant $P_i(s)$ which is equal to $Y_i(s) / X_i(s)$ —where $Y_i(s)$ is the Laplace transform of $y_i(t)$, and $X_i(s)$ is the Laplace transform of $x_i(t)$, and the only input allowed to $w(t)$ and $P_i(s)$ is $x_i(t)$. Under these constraints it is impossible to distinguish between $w(t)$ and $P_i(s)$, and it is reasonable to define $P_i(s)$ as the LTI equivalent of $w(t)$ with respect to the output $y_i(t)$.

For a QFT design in general, the first step in deriving the plant representation is to formulate the set of plant outputs Y_a considered as *acceptable*. (A set rather than a single acceptable output response, is needed because it is generally impossible to achieve a single, unique output over a finite time range, throughout a range of plant uncertainty. In any case there will always be tolerances on any output—it is in fact impossible to measure anything absolutely precisely.) Due to plant uncertainties there exists similarly, a set of possible plants W . Now, imagine for the moment, that the plant model of W is known. Pick any output signal $y_i(t)$ from the set Y_a and any plant $w_j(t)$ from the set W . Given $y_i(t)$ and $w_j(t)$ one can find the corresponding input $x_{ij}(t)$ needed to produce $y_i(t)$ from $w_j(t)$. The ratio of Laplace transforms $Y_i(s) / X_{ij}(s)$ can be defined as the equivalent LTI plant $P_{ij}(s)$ for that input/output pair.

This process is repeated for all outputs in the set Y_a and for all plants in the set W to produce a set P of LTI plants, and this set can exactly replace the original set of nonlinear plants W . If W has 10 elements, and Y_a has 20, then P has 200 elements. We now have an LTI problem which can easily be solved using LTI QFT design techniques. That is, one can find the feedback compensation functions in a LTI feedback system, which guarantee that the output belongs in the set Y_a , no matter which p_{ij} in the set P is the actual plant. Then for a very large problem class, it is guaranteed that these same compensation functions achieve this same result: the output will be in the set Y_a , no matter which w_j in the set W is the actual nonlinear plant. It is emphasized that this is an exact replacement; not an approximation of the nonlinear plant set, nor a linearization about some nominal operating point. The equivalence of P to W is only with respect to the set Y_a —but that suffices, because it is guaranteed (if the LTI problem is correctly solved), that the actual nonlinear plant output is a member of the set Y_a for which the equivalence applies.

But suppose we do not have a model of W —as is usually the case in manufacturing applications. The actual nonlinear plant is however, available, and input/output data can be generated directly from the plant. LTI equations can be identified, that characterize the nonlinear system. However, it is not necessary to use *all* data sets possible, only those with acceptable outputs. In this case, approximation is involved—but only in the characterization of the input/output data. If an accurate model (including uncertainty) does exist of the nonlinear plant, then no approximations are needed for a QFT design.

It is important to include in the plant set, transfer functions that correspond to input/output relations that might exist in the actual feedback system. What appears to be the intuitive approach—open-loop experiments—is actually not the ideal approach. When one employs open-loop data for identification, one must decide first what set of input signals $x(t)$, to use. The most commonly used signals such as steps, ramps, sinusoids and noise, poorly represent (in general) the class of signals that will occur in actual closed-loop operation. The results will be that our identified set of transfer functions will be true for a different set of operating conditions, and the closed-loop performance may not be as expected. Indeed, as a first try, we used only open-loop identification for an initial control design. This provided us with a closed-loop design from which we generated a more realistic set of input/output data. As expected, the transfer functions derived from closed-loop data were significantly different than those derived from open-loop data. (See Figure 13.)

Figure 13a. Plant Representations From *Open-Loop* Input/Output Data.

Figure 13b. Plant Representations From *Closed-Loop* Input/Output Data.

In the above, it is necessary to find the ratio $P_{ij}(s) = Y_i(s) / X_{ij}(s)$, given the time signals $y_{ij}(t)$ and $x_{ij}(t)$. A technique has been developed for this purpose by Golubev and Horowitz, in which it is not necessary to obtain $Y_i(s)$ and $X_{ij}(s)$ separately.¹⁶ The novelty of this approach is the use of *integration* in contrast to *differentiation* as used in most identification techniques. This approach achieves improved robustness against noise and works effectively even when only small portions of the transient response are used.

Because the closed-loop operation was to start only after the initial period is completed (see next section), neither the electrode force input nor the initial conditions were considered—that is, a single input/output transfer function with zero initial conditions was identified. The electrode force input was considered as a disturbance since we did not attempt to control the force in real time. The identification results are illustrated for a single input/output set in Figure 14.

There exists some practical constraints on successful identification which had to be accounted for here. (1) A finite sampling rate limits accuracy of the transfer function at high frequency, (2) a finite record length limits accuracy at low frequency and (3) the discrete quantization of the data limits over-all accuracy. In special cases the LTI plant set may emerge with members of different relative degree, which is associated with nonlinear differential equations in which the highest derivatives of output and/or input appear in nonlinear form (such as the square root of dy/dt , etc.) This is the case here as seen in Figures 15 and 16. There are QFT techniques for coping with this problem by inserting a suitable nonlinear pre-filter in front of the plant. Another means, adopted here, is to limit the system bandwidth below the point where the uncertainty—due to this anomaly of different relative plant degree—becomes unmanageable (as discussed later in connection with Figures 18 and 19).

Figure 14. Identification Results Using the Golubev Method.

16. Golubev, B., and Isaac Horowitz, "Plant Rational Transfer Function Approximation From Input-Output Data," *International Journal of Control*, Vol. 36, 1982, pp. 711-723.

Figure 15. Three Unique Identifications for One Input/Output Data Set.

Figure 16a. Magnitude of Bode Plots of the Three Models in Figure 15.

Figure 16b. Phase of Bode Plots of the Three Models in Figure 15.

Because of these limitations there is no single mapping that accurately describes the process over the entire frequency spectrum. This shows up as additional uncertainty. While all three models in Figure 15 accurately describe the system in the time domain, they differ significantly at high and low frequencies, as shown in Figure 16. Which of the three is the most accurate? From the data given, it is not possible to determine. Therefore all three equations must be used to represent the plant. That is, we must assume that at any given time the plant may *take on* the characteristics of any of the three plant models, and we must develop a feedback system that will be stable and meet the quantitative performance requirements for all cases at once. This may seem like a great challenge, however, handling uncertainties such as these is fairly simple by means of QFT, which is based on the work of Bode, the great pioneer of genuine (i.e. quantitative) feedback theory.¹⁷

Similar equations were generated to characterize other welds made under different operating conditions that span the range of desired operation. In this manner the system uncertainty, nonlinearities and time-variances were quantified together. However, it was not necessary to model every weld, only those that were of acceptable quality. Once the feedback system is properly designed, only outputs within the range of desired operation will be present. Therefore, it is not necessary to include in the model plant equations corresponding to all possible input/output relations, only those within the *desired* range.

17. Bode, H. W., *Network Analysis and Feedback Amplifier Design*, (Van Nostrand, 1945).

These equations constitute a set of plant transfer functions, that span the range of uncertainty in the welding system. As argued by Horowitz, the uncertainty in $P(s)$ is precisely the justification of the use of feedback—without uncertainty one has no need for feedback. It was due to this observation that led Horowitz to develop QFT over thirty years ago.¹⁸ The goal of this project is to design one compensator, $g(t)$ that will produce good welds for any plant in the set. That is: at any time the weld may *take on* the characteristics of any one of the plants in the set, and the feedback system must adjust the percent heat to arrive at the desired displacement.

The controller— $h(t)$, provides a digital input signal for external control of percent heat. Since the SCR's can only be fired once every half-cycle, the welding system cannot change percent heat more often than 8 milliseconds—the controller will not respond to the control signal $x(t)$ between pulses. This was characterized as time delay of 11 milliseconds. (The actual time delay ranges from 2 to 11 milliseconds depending on when a change in $x(t)$ occurs relative to the timing of the SCR pulses.) Though not true in general, for this design it was sufficient to consider the worst case delay of 11 milliseconds. Thus we have for the plant (welding system): $P(s) = W(s) \cdot H(s) = W(s) \cdot e^{-s\tau}$ Where: $\tau = 11$ milliseconds, and $W(s)$ is the set of LTI transfer functions identified above.

Following the process identification, the block diagram in Figure 11 is replaced with the LTI equivalent (shown below in Figure 17).

Figure 17. Block Diagram of Linear-Time-Invariant Equivalent System.

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18. Horowitz, Isaac, *Synthesis of Feedback Systems*, Academic Press, 1963.

QFT Design Procedure

Any analytic design method should provide the ability to meet specific *quantitative* design requirements. In actual industrial applications, design requirements are most often *unquantified*—leaving it up to the engineer to invent practical *qualitative* design specifications. When explicit design requirements are specified by the customer, QFT is the ideal tool to ensure that all specifications are precisely met. In this case however, no such requirements were provided. Because the QFT design procedure is highly transparent, and not steeped in complex mathematics, it is also the ideal tool for making *qualitative* design tradeoffs to optimize the *benefits of feedback* while taking into account the *costs of feedback*. For example, in this design the objectives were to maximize disturbance attenuation, while minimizing sensitivity to process variations, overshoot* and controller complexity. Clearly, these design requirements are in conflict with each other, and the engineer must employ a design method that will allow him or her to clearly see the relative effects of each objective on the other objectives and make engineering tradeoffs to obtain the best compromise of performance objectives. This is the greatest advantage of QFT—that it provides an "honest price list" of each design objective—enabling the engineer to make the *optimum* tradeoff between conflicting design goals.

At each frequency ω , a plant p_i in the set P has the value $p_i(j\omega)$ —a *point* in the complex plane. If P has 10 possible plants, then $P(j\omega)$ is a *region* in the complex plane defined by the points $p_i(j\omega)$ for $i=1$ to 10. This region is called a "template," which is the geometrical characterization of the plant uncertainty at the frequency ω . The frequency information for the several welds was plotted in Nichols chart form for a discrete set of frequencies. This produced a *set* of plant templates, five of which are shown in Figure 18. These templates give a *quantitative* measure of the amount of uncertainty in the plant $P(j\omega)$. For each frequency, there are several points plotted (one for each plant in the set), and they are clustered together by straight lines. Any plant not represented by one of the several points, but within the range of weld uncertainty tested, should fall inside the area bounded by the lines clustering the several points.

The plant templates were then superimposed onto a Nichols chart of the same scale, using a QFT CAD program designed by Dr. Oded Yaniv of Tel-Aviv University. The magnitude and phase of the closed-loop transfer functions $T(j\omega)$ can be read directly from the Nichols chart. This makes it possible to design for all plants in the set at the same time. To guarantee closed-loop stability, it is necessary to ensure that the compensated plant $L(j\omega)$ stays away from the region on the Nichols chart about -180° , until the gain is well under 0 dB.

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* Minimum overshoot is required because the process is only controllable in the positive direction. That is, once the desired displacement has been surpassed, there is no mechanism to cause the plug to back-out of the hole. Therefore, overshoot cannot be compensated for and must be minimized.

Figure 18. Plant Templates for $\omega = 0.1$, to 20 radians/second.

By insuring that the magnitude of the closed-loop transfer function $|T(j\omega)|$ (where: $T(j\omega) = L(j\omega) / [1 + L(j\omega)]$) is less than some value γ for all plants in the set, one can control the amount of overshoot in the output responses. A typical practice is to design for $\gamma = 2.3$ dB—which is often used for conservative designs. The frequency bounds for the compensator $G(s)$ (which guarantee a stable closed-loop system with $|T(j\omega)| \leq \gamma$ for all plants in the set) can be determined by moving the template over the range of the Nichols chart. This process was automated using Dr. Yaniv's computer program.

Shown in Figures 19 and 20 are the Nichols chart frequency bounds (marked in *italics*). The boundary where $|T(j\omega)| = \gamma$ is marked on the Nichols chart at discrete frequencies so that if the compensated nominal plant falls outside of the bound at each frequency, then $|T(j\omega)| \leq \gamma$ for all plants in the set. Because our set of plant models included transfer functions of varying relative order, these bounds became quite large at high frequency—so that it was not possible for the compensated system to cross 0 dB at a frequency higher than about 20 radians/sec., and still satisfy the stability bounds.

Also shown in Figure 19 is the "trajectory" of the uncompensated nominal plant $P_n(j\omega)$ (marked with +') as the frequency is varied from 0.01 to 20 radians/sec. The uncompensated system is stable and satisfies all of the bounds, however, it has not enough gain to make a significant improvement in eliminating low-frequency disturbances. The purpose of $G(s)$ is to "shape" or compensate the open loop system response so that the

closed-loop system meets all design objectives. The trajectory of the compensated nominal plant $L_n(j\omega)$ is also shown in Figure 19 where: $L_n(s) = P_n(s) \cdot G(s)$, and:

$$G(s) = \frac{815 (s + 0.5) (s + 2.5) (s^2 + 7s + 7^2)}{s(s + 0.1)(s^2 + 18s + 13^2)(s + 20)(s + 30)} \quad (2)$$

Assuming the significant process disturbances are primarily low frequency, insensitivity to process disturbances is maximized by minimizing steady state error (that is: minim variation in magnitude of the closed-loop transfer functions $|T(s)|$ at zero frequency. By studying the Nichols chart it is clear that the region that is most insensitive to plant variation is the region associated with high gain and -90° of phase. Thus, the first element of the compensator $G(s)$ was an integrator. A phase-lag filter with a pole at 0.1 and a zero at 0.5 radians per second was then added to more rapidly descend down the Nichols chart. A phase-lead filter (with zeros at 2.5 and 7, and poles at 13 and 20) was next added to satisfy the stability bounds. Finally a pole at 30 was added to lower the bandwidth.

A less cluttered version of Figure 19 is shown in Figure 20. As can be seen in Figure 20, the compensated system meets the stability bounds comfortably. The Bode plot of the compensator $G(s)$ is shown in Figure 21 and that of the compensated nominal plant $L_n(s)$ in Figure 22. The closed-loop Bode plot for the several plants is shown in Figure 23. Note that the 2.3 dB design criteria was satisfied at all frequencies.

Figure 19. Frequency Bounds for $L_n(j\omega)$ With Trajectories of $P_n(j\omega)$ & $L_n(j\omega)$.

Figure 20. Frequency Bounds & Trajectory of $L_n(j\omega)$.

Figure 21. Bode Plot of the Compensator $G(s)$.

Figure 22. Bode Plot of Compensated Nominal Plant $L_n(s)$.

Figure 23. Bode Plot of Closed-Loop Transfer Functions.

Implementation Results

The control system was implemented in software on an industrial PC. It works as follows: The welding operator selects the desired weld parameters (total displacement and electrode force) then starts the welding sequence as he or she would if there were no feedback system connected. Once started, the controller opens a valve allowing pressurized air to enter the pneumatic cylinders which in turn apply force to the electrodes. As the pressure builds, the electrode force is monitored by the computer, and the air pressure is adjusted to reach the desired force. When the force has stabilized at the desired value, the computer measures the *cold displacement* (d_c)—that is, the displacement due only to the applied force.

At this point several calculations are necessary. *Total* part displacement (d_t)* is the output variable we desire to control, yet d_c is a function of electrode force, part cleanliness, fit-up (the difference in diameter between the plug and the hole) material hardness, etc. Electrode force is set by the operator, while part fit-up, cleanliness and hardness are only partially controllable. Because of these uncertainties, and the necessity to maintain consistent electrode force, d_c is not controllable. Therefore, the computer subtracts the measured d_c from the desired d_t to calculate the desired *hot* displacement (d_h). The reference signal (or command input) $r(t)$ is an actual displacement profile from an ideal weld—stored in an array. This signal (which is stored as the command input) is then scaled up or down so that the last data point in the profile is equal to the desired hot displacement.

Another calculation is needed to determine when to shut-off welding current. Because of heat build-up in the part, it continues to displace for a time after welding current is shut off. Since the process is only controllable in the positive direction, (as noted previously) it is necessary to shut off control *before* the desired displacement is reached. Along with the ideal weld profile, the displacement at which the current was shut-off is also stored. For future reference this value will be referred to as d_s . If the control system is properly designed, then at the end of the weld, under nominal conditions, the *slope* of the electrode displacement will approximately be that of the ideal weld. Therefore if current is shut-off when the displacement reaches d_s —the displacement at which the ideal weld was shut-off, then it should end up at approximately the same final displacement as the ideal profile. Since the weld profile is scaled to end up at d_h , d_s must also be scaled accordingly. This simplistic method worked quite well for small disturbances (as illustrated in Figure 24), and was sufficient for welds made with more significant disturbances (Figure 25).

Note that the steady-state error shown in Figure 25 is due to the combination of two system nonlinearities mentioned earlier—namely: (1) that the process is only controllable in the positive direction, and (2) that the process must be shut off *before* the desired hot displacement is reached. Without these two nonlinearities, the process would have no steady-state error since the compensator included an integrator.

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* *Total displacement* (d_t) is equal to the sum of d_c and d_h where d_h is the *hot displacement* due to the current.

Figure 24. Feedback Controlled Welds with Small Disturbances.

Figure 25. Feedback Controlled Welds with Large Disturbances.

Once these constants are calculated and the ideal weld profile has been properly scaled, the computer initiates the weld with a step function input to the controller. This starts the weld current flowing at the nominal percent heat—that is the percent heat that would under nominal conditions yield the desired hot displacement. The electrode displacement is measured and compared to the reference signal $r(t)$, to become the error signal. If the welding process had no uncertainty, the error signal would be small and the compensator will not change the specified percent heat. However, when process disturbances change the behavior of the welding process, (as is usually the case) the compensated error signal adds an offset to the controller input signal, changing the percent heat. The duration of the weld is also shortened or increased as needed to drive the displacement to the specified value. When no disturbances are present the system responds the same as it did without feedback.

The system was tested, and found capable of controlling the final displacement to ± 3.5 percent with large disturbances in welding power. As mentioned previously, the welding current may be throttled by changing the tap settings on the welding transformer. Feedback controlled plug welds were made with tap settings that cut the available power roughly in half, and others were made with triple the normal input power, yet the feedback system was able to compensate and bring the welds to the proper final displacement. (See Figure 25.)

The system was further tested with a *Box-Behnken* statistically designed experiment as shown in Table 1.

In order to make a straight-forward comparison between open and closed-loop control, it was necessary to reduce the tap setting disturbance from that used for the welds in Figure 25. Without feedback control, the high tap setting in Figure 25 would have likely caused an eruption of molten metal, likewise, the low tap setting used in Figure 25 would have not produced a weld. Thus the High and Low tap settings shown in Table 1 were selected to cause a much smaller disturbance on the process. The effect of this tap setting disturbances was quantified by measuring the initial power into the part—that is the power going into the part before the feedback system had made any corrections to the percent heat.

One set of welds was made under normal operating conditions, and another was made with feedback control. The order in which the welds were made (including whether or not feedback was used) was randomized to unbiased any effects of slow process variations. The target displacement for all feedback controlled welds was 95 mils. The resulting welds were then cross-sectioned, etched, and evaluated by a certified welding inspector. Each weld was assigned a quality number as defined in equation 1 and shown in Table 1. This data was analyzed by a statistician to determine the effectiveness of feedback control on improving weld quality control. His results are summarized in Figures 26 through 28. The experimental data of Table 1 is plotted with +’s—for the results without feedback, and X’s—for the results with feedback, along with curve-fits to the experimental data—shown as a solid line in Figure 26 and mesh plots in Figures 27 and 28.

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* Note, the feedback computer has no knowledge of the transformer tap settings—corrections to the percent heat are made solely on the displacement error signal. An obvious improvement to the robustness of the process would be to give the computer access to the primary line voltage and use that knowledge to modify the percent heat to further compensate for improper settings. However, in order to fully test the feedback capability of the system, this information was withheld from the computer. The final application could, however, incorporate this improvement.

INPUT PARAMETERS			OUTPUTS (Results)			
			(W/O Feedback)		(With Feedback)	
Tap	Force (lb.)	Fit*	Displ. (mils)	Quality	Displ. (mils)	Quality
low	1800	0	46	10	97	57
high	1800	0	99	66	97	62
low	2400	0	49	11	95	51
high	2400	0	101	65	95	40
low	2100	-3	44	10	93	67
high	2100	-3	98	61	95	62
low	2100	3	51	12	96	49
high	2100	3	107	56	96	46
med.	1800	-3	60	31	94	79
med.	2400	-3	66	18	92	67
med.	1800	3	62	31	97	58
med.	2400	3	70	19	95	54
med.	2100	0	72	24	95	72

Table 1. Box-Behnken Experimental Test of Feedback Design.

The analysis showed that without feedback control, the main factor influencing total part displacement, and also weld quality, is the power setting as shown in Figures 26 and 27. Figure 26 shows that for total displacement, this was effectively canceled-out through feedback control. There was also a slight interaction between part fit-up and force on weld quality as shown in Figures 27 and 28.

Figure 26. Disturbance Effects on Displacement With and W/O Feedback.

* Interference fit is defined as the relative difference between the diameter of the plug and that of the hole. Since the hole tapers in, the diameter of the hole is taken at the top surface. The units of *fit* is mils—1/1000 of an inch.

Figure 27. Disturbance Effects on Weld Quality Without Feedback.

Figure 28. Disturbance Effects on Weld Quality With Feedback Control.

Conclusions and Future Work

Quantitative feedback theory provided a simple, yet powerful philosophy for designing the feedback control system—allowing the designer to optimize the system by making design tradeoffs, without getting lost in complex mathematics. Overall, the feedback system worked well in reducing the process sensitivity to changing weld parameters and disturbances. Displacement was accurately controlled and bond quality maintained, with large variations in available welding power, force and part fit-up.

The next step will be to determine the ability of a control system to compensate for other parameter variations. Specifically, we will assess what would be the effects of variations in part hardness, cleanliness, electrode wear and alignment, etc.

Many of the problems encountered in welding are related to variations in temperature caused by changes in energy input, heat sinking, displacement of energy source, etc. This feedback control technique has the potential to reduce or eliminate a number of these and other problems because it tends to maintain the weld at a constant temperature. However, additional studies are required to determine what effect the control technique will have on internal voids, the propensity for cracking, cold shunts, and other welding problems.

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