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# Weld Pool Impedance Identification for Size Measurement and Control

*A primary indicator of weld quality is the size of the bead produced, and for full penetration welds this size parameter can be reduced to the width of the backbead. A method for determining this width in real-time is proposed that measures the natural frequency of pool motion when driven by a time varying arc plasma force. This method is developed analytically and verified experimentally for stationary weld pools. A control system based on this measurement scheme is also developed and simulation results are presented.*

## Introduction

The rate of defective welds in critical structures is high and the cost of repair is a significant portion of any high quality welding project. Implementing automatic control of weld quality would eliminate these problems and also allow reduction of fit-up tolerances and an increase in torch velocities, resulting in significant reduction in the total time to weld.

The concept of weld quality control should be differentiated from other types of welding machine control systems that are already in use. For example, there are at present systems used to regulate the conditions at the interface between the welder and the work-piece (e.g., heat output, torch to workpiece distance, wire feed rate, and torch velocity). These regulators are adjusted to fixed values based upon experience for the particular weld being produced. This results in open-loop control of the quality of the weld, which cannot deal with the wide range of output and parameter disturbances that affect the welding processes.

A second application of automatic control in welding is to seam tracking. These devices guide the torch so as to maintain a fixed position and orientation with respect to the seam. Seam tracking reperesents a great advance over preprogrammed trajectory control and is a necessary condition for automatic high quality welding, but clearly an insufficient one.

The concept of on-line weld quality control of welding is quite broad and for this work has been narrowed to full penetration control. Further, this work concentrates on thick section root passes using Gas-Tungsten-Arc Welding (GTAW) and not on the filling process using Gas-Metal-Arc Welding (GMAW). Although the filling occupies considerable time in welding thick material, the root pass requires a higher level of control and precision, and therefore can benefit more from application of control techniques. Another application area is autogenous GTA butt welds, which involve a full penetration pass and may or may not require additional fill passes.

The main problems with GTAW root pass welds are incomplete melting and burn-through. A full penetration control system would command the welding device to melt only enough material to completely fuse the joint without risking a burn-through, and then seek to maintain a specific backbead width. In this paper a measurement technique is developed and a controller scheme presented for on-line closed-loop control of full penetration in GTAW, that does not rely on access to the back side of the weldment.

Having restricted ourselves to full penetration it is important to view the role of full penetration control in improving weld quality. In controlling the quality of the welds the purpose is to achieve certain strength, toughness, and fatigue properties in the weld and the Heat Affected Zone (HAZ). These quality parameters are related to the geometry of the weld and there is a apparent correlation between them and the width of the back bead. This is clear intuitively because the extent of penetration determines the cross sectional area of the weld. With incomplete penetration the area available to support loads is less than it could be, and also may result in high stress concentrations at the joint. At the other extreme, excessive melting may result in burning through or unnecessary heating of the weldment. There are, of course, other factors that affect the quality of the weld and they cause a significant scattering in the correlation between the back bead width and the strength of the resulting weld. These factors include the thermal history in the weld and in the HAZ, the size of the HAZ, porosity, slag inclusions and undercut.

## Background

The first step toward developing a full penetration geometry control is to examine the physical phenomena that can be exploited to relate the weld geometry to measurable parameters. Katz [1] has investigated a method to sense the extent of penetration and even the puddle shape, in real-time using ultrasonic pulse echo techniques. The technique is based on the fact that the material density and its ability to sustain shear is changed at the metal-liquid interface. It has been shown experimentally that the ultrasonic rreflections can be related to the size of the puddle in a staionary rod-like geometry where the puddle is made in one end of the rod and the ultrasound tranducer is at the other end. However, the goal of two dimensioonal shape measurement has not yet been reached.

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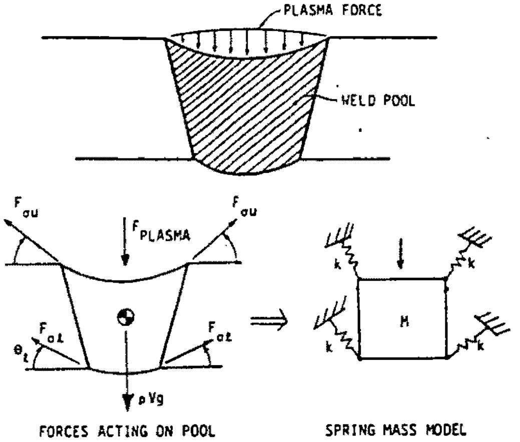


Fig. 1 Model of a completely melted weld bead

Vroman and Brandt [2] used a line scan camera to measure the width of the top side of a weld to allow closed-loop regulation of that variable. The width to depth ratio of a weld remains nearly constant under fixed welding conditions, as long as the puddle penetration is small compared to the thickness of the workpiece. Under these conditions, controlling the top weld width results in a regulated penetration. However, Vroman and Brandt experienced controller problems associated with pure delays introduced by their measurement technique and the true promise of this approach remains to be realized. This problem has been recently resolved by the on-electrode axis measurement technique developed by Richardson et al. [3]

Another approach involved sensing the back bead radiation. Nomura et al. [4] measured the infrared radiation from the back side of the weld for partial penetration submerged-arc welding, and succeeded in regulating the intensity of this radiation by varying the current. However, penetration and back side thermal radiation are not simply related, and other factors such as weldment thickness and preheat can drastically change this relationship as was shown in their results.

Garlow [5] has used a single phototransistor to directly sense the back bead width of full penetration welds by measuring the amount of visible light radiated from the liquid surface. Since this is a single variable analog measurement, the bandwidth problems associated with scanned arrays are avoided. Also, this measurement method appears to be insensitive to material thickness and preheat, but it is sensitive to the emissivity of the materials being joined. He has used this measurement technique along with a computer based controller to successfully regulate the back bead width in bead on plate experiments using simple linear compensation techniques.

## The Puddle Impedance Technique

In this work a method for sensing extent of full penetration was sought that did not rely on access to the backside of the weldment. The method explored below takes advantage of the mechanical changes in a weld puddle when the transition from partial to full penetration takes place.

As full penetration is reached there is no longer any solid material to support the puddle and the weight of the puddle is supported mostly by surface tension. As the puddle moves vertically the angle of these forces changes providing a position-dependent vetical force, that is, a spring (see Fig. 1). The resulting mechanical impedance of this system determines the response of the puddle to periodic forces, and can be characterized by the natural frequency and damping ratio of the puddle mass-surface tension system. This natural frequency will be shown to be related to the size of the puddle, and can be used to indirectly sense the back bead width.

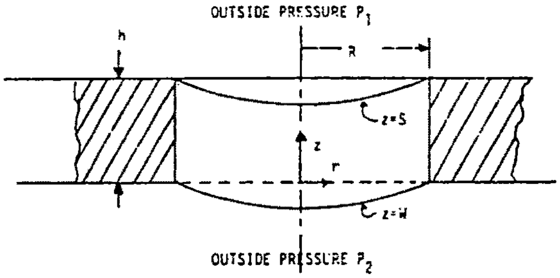


Fig. 2 Model of a weld puddle at full penetration

The proposed measurement technique based on the impedance of the puddle involves exciting the puddle with a vertical force (originating, for example, from the torch plasma jet momentum), measuring the puddle motion, and then calculating and regulating the natural frequency. Once excited, the vertical position of the top surface of the weld must be measured. An attractive method to do so uses the fact that the puddle motion changes the arc length, which in turn changes the arc potential. Consequently, arc voltage measurement is sufficient and no additional instrumentation is needed. However, interpreting the arc voltage is very difficult, since there are many other factors influencing this potential, and this difficulty suggests that other methods of measuring puddle motion from the puddle surface may need to be studied. In the work described below both the arc potential method and a laser shadowing technique were used to measure puddle motion, but only the latter gave unequivocal results.

## Puddle Impedance – Theory

The purpose of the following analysis is to identify the main parameters that influence the puddle motion and to get an estimate of the natural frequencies of that motion. The analysis is carried out for a simplified case to gain insight into the problem, and absolute accuracy is not citical.

The surface motion can be investigated in at least two ways. Using fluid mechanics, the surface motion can be developed as part of a velocity-potential problem. This method clarifies the theoretical distinction between the partial and full pentration cases, and is detailed in [6]. However, since only the puddle surface motion is of interest (and not the value of the velocity-potential function throughout the puddle) a slumped parameter approach is presented here since it gives similar results and is more intuitive.

The analysis is performed for a stationary puddle of cylindrical shape. (See Fig. 2). The cylindrical shape is similar to the actual shape of a stationary puddle at extensive full penetration. However, it does not accurately describe either a stationary puddle at partial or slightly full penetration (when the back bead radius is small compared to the upper bead radius), or the puddle shape under a moving torch.

The molten metal is nearly incompressible and is assumed to be inviscid. Furthermore the molten metal is assumed to be homogeneous: the surface tension ($N$) and the liquid density ($\rho$) are constant and independent of the temperature. (It is reasonable to assume that the fluid flow inside the puddle will result in a small gradient of temperature). At full pentration, the surface tension at the interface between the weld puddle with the surrounding atmosphere supports the molten metal and prevents burn-through. Surface tension at the metal-liquid interface is not considered.

In the lumped parameter approach the puddle is modeled as a mass-spring system. The surface tension behaves likes a nonlinear spring, which for small motions can be approximated by a linear spring. Using a Newtonian approach

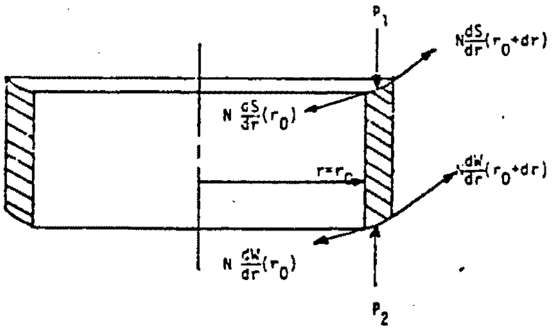


Fig. 3 Forces on an isolated ring of a cylindrical puddle

the momentum equation for the lumped system at full penetration can be derived. However, to evaluate the resulting time varying surface shape description we must first determine the equilibrium surface shape. The equilibrium equations for a $\theta$-independent, symmetric puddle (shown in Fig. 2) are:

$$\frac{N}{r}\frac{d}{dr}\left(r\frac{dS}{dr}\right)-\rho g S=P_1-P \tag{1}$$

$$\frac{N}{r}\frac{d}{dr}\left(r\frac{dW}{dr}\right)+\rho g W=P_c-P_2 \tag{2}$$

Where $P_1$ and $P_2$ are the outside pressures above and below the puddle, $S$ and $W$ are the upper and lower surface shape, $N$ and $\rho$ are the constant surface tension and density, and $P_c$ is a constant that represents the pressure in the puddle at some constant $z$ (e.g., $z=0$).

For constant $P_1$ and $P_z$, and boundary conditions $W(r=R)=0$ and $S(r=R)=h$, the steady state surface shapes are:

$$S_0=\left(\frac{P_1-P_c}{\rho g}+h\right)\left(\frac{I_0(er)}{I_0(eR)}-1\right)\cdot+h \tag{3}$$

$$W_0=\left(\frac{P_c-P_2}{\rho g}\right)\left(1-\frac{J_0(er)}{J_0(eR)}\right) \tag{4}$$

where $e=g/N$. $R$ and $h$ are the radius and height of the puddle-cylinder. and $I_0(er)$ and $J_0(er)$ are the Bessel functions of order zero and parameter $e$. $P_c$ can be calculated from the mass conservation condition:

$$\int_0^R W(r)rdr=\int_0^R (h-S(r))rdr$$

When equations (3) and (4) are added and the result integrated, the result is the expected macroscopic equilibrium equation:

$$2N\pi R\left(\frac{dS}{dr}\bigg|_{r=R}+\frac{dW}{dr}\bigg|_{r=R}\right)=mg+F_1+F_2 \tag{5}$$

Tension Force = Gravity + Outside forces

The puddle dynamics result from the combination of the surface tension, gravity, and outside forces. Isolating a circular ring, (see Fig. 3) the free body equation of motion is

$$N\frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}(S+W)-eg(S-W)=P_1-P_2\right.$$
$$\left.+\frac{1}{2}\rho(S-W)\frac{d^2(S+W)}{dt^2}\right. \tag{6}$$

Since the solution of this equation (the time varying surface shape) can be considered an infinite summation or integral of weighted sine functions at all frequencies, we can assume a solution of the form

$$S=S_0+S_1\sin(wt) \tag{7}$$

and

$$W=W_0+W_1\sin(wt) \tag{8}$$

for the surface shapes, and then use these to find the characteristic frequencies, $w$. For small deviations from flat surfaces the term $(S-W)\,d^2(S+W)/dt^2$ in equation (6) can be approximated by $h\,d^2(S_1+W_1)/dt^2$, and $\rho 3\,(S-W)$ can be approximated by $\rho g(S_1-W_1)$, if gravity forces are neglected compared with surface tension forces.

Using these approximations, substituting equations (7) and (8) into equations (5) and using equations (3) and (4) to eliminate $P_1$ and $P_2$ we get:

$$\frac{N}{r}\frac{d}{dr}\left(r\frac{dU}{dr}\right)=\frac{eh}{2}(-w^2)U;U\equiv S_1+W_1$$

or

$$r^2\frac{dU^2}{dr^2}+r\frac{dU}{dr}+\frac{w^2eh}{2N}r^2U=0 \tag{9}$$

which is a Bessel equation of order zero with parameter $k$, $k^2=w^2\ (\rho h/2N)$. The solution to equation (9) is the Bessel function $U=CJ_0(kr)$. From this result we can solve for the parameter $k$ by applying the boundary condition $U(kR)=0$. Thus the zeroes of $J_0(kR)$ define the discrete frequencies of oscillation according to $k=b_{0n}/R$, where $b_{0n}$ is the nth zero of $J_0$. For this work it is assumed that the first or fundamental frequency will dominate, so $b_{00}$ is the only solution that is needed. With this, we get that the natural frequency of the puddle surface motion is given by:

$$w=\frac{b_{00}}{R}\sqrt{\frac{2N}{\rho h}} \tag{10}$$

From this equation we can see that the natural frequency will vary inversely with the puddle radius and will vary as the square root of the material property descriptor $N/\rho h$.

A numerical estimate of the expected natural frequencies can be calculated based on the above analysis. The values of the parameters used in this example are:

$\rho$ = $7.8\times10^{-6}$ Kg/mm$^3$ (density of iron or steel). See [7]
$N$ = 1 N/m (Surface tension). See [8]
$g$ = 9.8 m/sec
$b_\infty$ = $.765\pi\cong2.4$, the first solution of $J_0(b)=0$
$h$ = 2.5mm (0.1 in), a typical root pass weld thickness material = steel
$R$ = 3mm (for continuous welds)
$R$ = 6mm (for stationary welds)

Given these values, the predicted natural frequencies are 40 Hz and 20.4 Hz for the 3mm and 6mm radius respectively.

Since only the first mode of vibration of the puddle is being considered, a second order transfer function relating output motion to input force can be defined:

$$\frac{A}{s^2+2\xi wnS+Wn^2}$$

where $A/w_n{}^2$ is the low frequency gain.

In the frequency domain such a system can be identified by a low frequency or DC gain asymptote, and by a −40db roll-off line. If the system is underdamped (damping ratio less than .707) there will be a peak at $w_r$ $(w_r=w_n\ (1-2\xi^2)½)$which will help in identification.

## Puddle Excitation

As discussed in [6] and [9], the pressure the arc exerts on the puddle is proportional to the square of the current. If the current has an AC component the resulting force will have corresponding AC components. For $I=I_0+I_a$ Sin$(wt)$ the force is

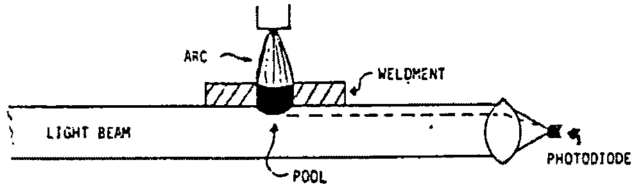


Fig. 4 Schematic of the laser shadowing puddle motion measurement technique

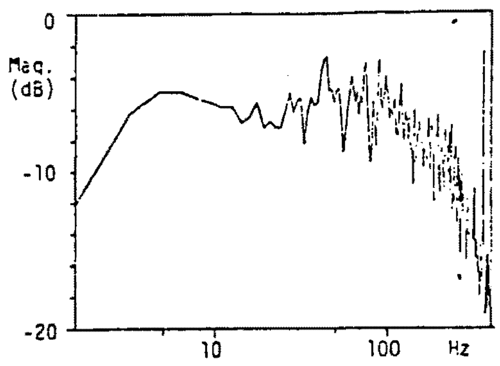


Fig. 5 Frequency spectrum of the current; no weld puddle present

$$F=\frac{\mu}{2\pi}\left(I_0{}^2+\frac{I_a{}^2}{2}+2I_0I_a\sin(wt)+\frac{I_a{}^2}{2}\cos(2wt)\right) \tag{11}$$

Where $\mu$ is the magnetic permeability of the molten metal and is approximately the same as the permeability of air. The puddle can be forced at any desired frequency by adding an AC component to the current at this same frequency. To avoid the nonlinear effects the AC component should be small compared to the DC component of the current, so that $I_a{}^2/2$ can be neglected compared to $I_0I_a$. If this is the case, the amplitude of the A.C. force $F$ is given by:

$$F=\frac{\mu}{2\pi}I_0I_a \tag{12}$$

(In experiments that were performed to identify the transfer function the AC component was kept at less than 10 percent of the DC value.)

**Steady Versus Continuous Case.** The model developed above was for a stationary puddle with a cylindrical shape. The actual shape of the puddle in a continuous weld is different. Furthermore the torch-puddle topology is different, and during a continuous weld the torch is not necessarily directly above the full penetration region. As a result, the motion resulting from the arc force may not be parallel to the torch and may instead have some inclination.

The experiments detailed next investigate the puddle impedance concept using a stationary puddle. Apart from the fundamental differences between a stationary and a continuous weld, there are some practical considerations that involve the evaluation of the experiments. With a stationary torch the level of the DC current used is much lower than the one used during a continuous weld. With continuous welds the current level is determined by the required heat input per length of weld, which is inversely related to the torch velocity, therefore high torch-velocities require large DC currents and vice versa. On the other hand, with a stationary puddle the heat input should be such that full penetration can be held long enough (about 5 minutes) to take data. The stationary experiments described here were performed on 2.5mm (0.1 in.) thick steel at about 60A DC (using a 3/32" diameter 30° tip angle tungsten electrode). On the same kind of plates, continuous welds are made with about 125A DC (at 3 in/min) and higher currents are common at higher torch velocities.

The low level of the current has two important consequences: First, the resulting arc-force is much lower. Second, at low current the voltage-current relationship for the arc is quite nonlinear, and this nonlinearity affects the attempts to interpret the arc-voltage in order to detect the puddle motion.

On the other hand, a stationary weld is much larger in diameter then a continuous one. A typical diameter of a stationary puddle is 12mm, while a typical width of a continuous weld is 6mm. This difference coupled with the shape difference will affect the value of the natural frequency (probably higher for a continuous weld, since the puddle size, hence the mass, is smaller), and the magnitude of the motion under the same force (higher for stationary puddle, since the spring constant is slightly smaller for a larger puddle).

## Experiments

The purpose of these experiments was to perform a frequency response test on a fully penetrated weld puddle to identify the natural frequency of the puddle motion. The equipment used included a custom built solid-state current regulator with a 0-50 kHz bandwidth (for details see [9], a water cooled TIG torch, an FM tape recorder for recording output data and an Hewlett-Packard 5423A Structural Dynamics Analyzer, which was used to compute the frequency spectrum information. In these experiments the arc pressure was used as the force input, and initially the puddle motion measurement technique was based on shadowing a laser beam by the back side of the depressed puddle.

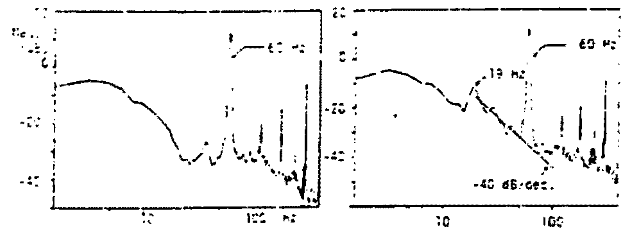
In this measurement technique, a Ne/He laser beam is expanded through two lenses to a 1 cm diameter beam. After passing beneath the puddle the beam is concentrated (through a lens and a laser filter) into a photodiode (a HP PIN Photodiode model 5082-4220). See Fig. 4 for a schematic of the measurement system. As full penetration is reached the puddle is depressed and blocks part of the laser beam. In response to a varying force the puddle moves up and down according to its dynamic characteristics, creating a shadow in the beam. The laser beam is then detected by the photodiode and its output varies according to the puddle motion.

Initially, the frequency of a 60A (peak to peak) sinusoidal component on a 62A DC current was varied in steps from 4Hz to 35Hz, and the photodiode voltage was recorded on a chart-recorder. The resulting photodiode voltage (which was sinusoidal and of the same frequency as the input), increased in amplitude until about 14Hz, beyond which the output rapidly dropped off. (Phase angle was not measured.) This behavior suggests the existence of a resonance near 14Hz and indicates that the puddle acts like an underdamped dynamic system.

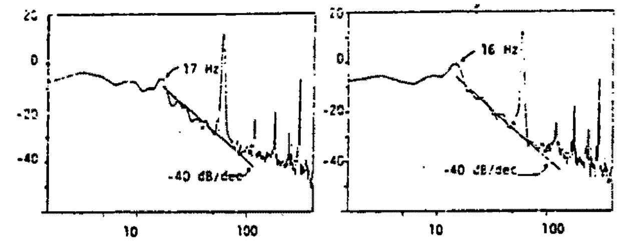
To permit a more exact determination of the puddle transfer function a broadband current control signal was constructed. A typical frequency spectrum of the resulting current is shown in Fig. 5. In all cases the amplitude of the AC component in the current is kept at about 10 percent of the DC level (i.e., 12A peak-to-peak when the DC current is 60A). In this way the linearity of the system is maintained.

During the experiments both the photodiode voltage output and the current measurement signal were passed through first order low pass filters at 200 Hz. before being recorded and the current signal (derived from the voltage drop across a resistor in series with the welding torch) was amplified by a factor of 100. The recorded data were then used as input to the HP Structural Dynamics Analyzer and the frequency domain information was obtained.

Typical results for the transfer function between the current input and the photodiode voltage output are shown in Fig. 6. Each transfer function was computed from data taken during the same experiment (same puddle), at different times after the initiation of the arc, and the plots are arranged in



a) Immediately After Arc Start b) 1.3 Minutes After Arc Start



c) 2.3 Minutes After Arc Start d) 3.4 Minutes After Arc Start

**Fig. 6 Transfer function (impedance) of a single puddle at different times**

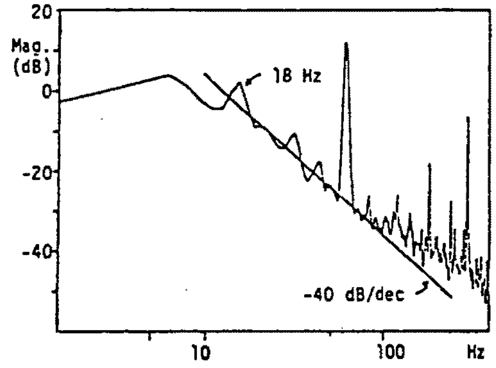


**Fig. 7 Puddle impedance; second puddle**

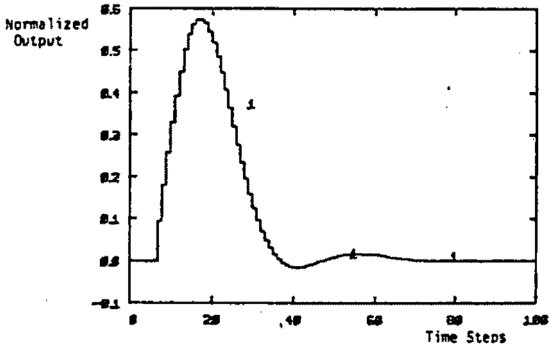


**Fig. 8 Step disturbance reponse of the system using pole-zero cancellation. The output is normalized to the plant gain.**

chronological order. The elapsed times after arc initiation for Fig. 6(*a*), (*b*), (*c*), and (*d*) are 0,1.3, 2.3, and 3.4 minutes, respectively. A peak at around 15-20Hz, and a −40db roll-off are apparent in most of the graphs. The puddle grows slowly with time, and according to Eq. 10 the natural frequency is expected to become smaller. This phenomenon is demonstrated by the results since the magnitude peak clearly shifts to the left with time.

Figure 7 represents a second puddle produced in a similar experiment. There is a clear peak in the amplitude at 18 Hz, and this peak is about 5.0 db. higher than the low frequency response. This corresponds to a damping ratio of about 0.3 and the natural frequency can be calculated from $w_n = w_r\ (1-\xi^2)½$. With $w_r = 18$Hz this results in $w_n = 18.9$Hz. Comparing with the numerical example given above for $R = 6$mm there is a good agreement between this experimental value, 18.9Hz, and the predicted value (for $R = 6$mm and $k = b_{00}\ R$) at 20.4 Hz. A −40db line is shown in Fig. 7 to be a good match to the roll-off after the 18Hz peak. This is in agreement with the expected second order system behavior.

From these results it can be concluded that the laser-based experimental technique is capable of detecting the puddle motion and that ther is good agreement between the experimental results and the model of the puddle dynamics.

## Discussion

With the existence of the puddle resonance confirmed it is possible to attack the problem of devising a practical means for detecting puddle motion. This was attempted here by using the same conditions as listed above, but in addition to recording the photodiode output, the arc potential was also recorded. However, before recording this voltage the variation in voltage caused by the sinusoidal component of the current was subtracted from the current signal to improve the arc-length change related signal to noise ratio.

With this procedure it was possible to get frequency spectra from the arc voltage that suggested the second order characteristic detected earlier, however, these results were not consistent. The major problem was the fact that the DC arc current had to be maintained at a low level because of the stationary puddle geometry and this necessarily keeps the arc force low as shown by eq. 12. Furthermore, the arc voltage-current relationship at low DC currents is highly non-linear, which makes interpretation of the voltage measurement more difficult. It is expected that with the higher current typical of moving torch welding that the resulting arc-length related voltage variations will give more consistent frequency response data. (For more details on the arc-voltage measurement problem see [6].)

## Implications for Control System Design

The weld puddle size measurement method developed here is intended for use in a real-time feedback regulator. Accordingly, the feasibility of such an application must be addressed. Since the proposed measurement technique involves identifying low frequency resonances, the time required for such a measurement will be long relative to the desired response time of the system. This presents the classical problem of large measurement delays in the feedback path.

To investigate the effect on a weld puddle frequency (size) regulator, a discrete controller was designed based upon a first order model for the weld ment melting dynamics and using a proportional plus integral (PI) control strategy. The frequency measurement was modeled as a delay of n time steps of the controller where n is governed by the required resolution of the frequency measurement. For a frequency resolution of 1 Hz, a plant time constant of 1 sec. (as reported by Garlow [5]) and a sample time of 0.1 s, the PI controller was designed using *Z*-plane root locus techniques.

The feedback measurement delay caused most designs to be marginally stable, but one in which the controller zero cancelled the plant pole gave acceptable performance. The disturbance response of this design for a value of the controller gain that gave the smallest settling time is shown in Fig. 8. This illustrates a 5 percent settling time of 30T or 3 seconds. For a puddle length of approximately 6mm this settling time suggests a maximum velocity change of 6mm/3s or about 6 in/min, which is a reasonable velocity for thick sectin GTAW. Therefore for a first order performance evaluation we can conclude that the torch will not overrun the weld pool during the disturbance settling time.

It must be noted that the pole cancellation design will have some severe limitations when applied to the real system, since the plant pole is a highly variable parameter. Consequently this problem is an ideal candidate for parameter adaptive control.

## Conclusions

A technique for measuring the size of a fully penetrated weld puddle has been presented. It requires that the frequency of oscillation of the puddle-surface tension system be identified in real-time and then regulated using the torch velocity as the control input. The basic ability to excite and detect the puddle natural frequency has been demonstrated, however, this has only been done for the case of a stationary weld puddle. It remains to be seen if similar results occur when a moving torch is used. Also, the essential relationship between natural frequency and puddle size has yet to be examined experimentally.

Preliminary controller designs based on real-time FFT identifcation of the puddle natural frequency indicate that satisfactory response can be obtained despite the long time delays involved in the sampling-transformation process, but the use of adaptive control schemes may be necessary.

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