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Fiber Optic Sensor: Feedback Control Design and Implementation

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Fiber Optic Sensor: Feedback Control Design and Implementation

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ABSTRACT

Digital feedback control of Gas Tungsten Arc Welding (GTAW) has been demonstrated on a tube sample of stainless steel and titanium alloy. A fiber optic sensor returns a signal proportional to backside radiance from the workpiece; that signal is used by the controller to compute a compensation weld current. The controller executes 10 times a second on an Intel 486 chip. For travel speeds of 3 to 6 inches per minute and thicknesses between 0.025 and 0.10 inches, constant backside bead width was maintained within 0.02 inches, from startup to tie-in.

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MASTER

* Dave Tung is now working at Quantum Electronics.

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Nomenclature

A	system identification coefficients for system + sensor
B	system identification coefficient for system + sensor
I_0	source surface characteristic
F	filter characteristic
P	power incident on fiber face
T	temperature (K)
U_i	fiber half angle of view
b	constant defined in App R
c	speed of light
h	Planck's const
n_a	ambient index of refraction
x	position vector x_f position of point on fiber face x_r position of point on source x_c position of point on collector (App R)
w	weld width
ϵ	grey body emissivity of radiation of source (backside of weld bead)
ν	light frequency
σ_{SB}	Stefan-Boltzmann constant $5.67 \times 10^{-12} \text{ W/m}^2\text{K}^4$
V_{pd}	photodetector output voltage
V_1	sensor package output voltage

FIBER OPTIC SENSOR: FEEDBACK CONTROL DESIGN AND IMPLEMENTATION

INTRODUCTION

The craft of manual welding has been developed through training and experience, so that a human welder can control one or more metrics such as bead width. Through trial and error development, such a skilled welder can determine useful open loop control settings for current, arc gap (voltage) and travel speed to achieve a desired result repeatably in an automated production fixture. Such open loop control, though, lacks the ability to respond to perturbations to the nominal job parameters, such as part thickness. To assure the desired outcome in perturbed cases, feedback control is needed.

The human welder uses very complex signal processing of images and sounds to gauge the quality of the weld, and has considerable agility in responding to perceived perturbations. However, the signals sensed come primarily from the topside of the weld, and backside conditions are only estimated from previous experience. Topside weld configuration is not uniquely coupled to fluid motions of the weld pool, so the estimates of penetration and backside width of the weld are inherently risky in this procedure. Thus, an automated welder with sensors responding to backside signals can potentially provide much better control of penetration [Hardt¹].

Rather than attempt to mimic human sensory capability and human ability to apply expertise gained from experience, the digital control developed below seeks to avoid complexity (and expense) of the sensor by use of a simple optical fiber to collect backside radiance of the workpiece following previous Sandia demonstration [Bentley²] and recent extension. This radiance is converted to a voltage signal by a photomultiplier and amplifier circuit [Stecker³]; the output voltage is strongly correlated to the actual weld pool penetration, so it serves as an ideal control signal, as discussed in Section 3.

To use the sensor for feedback control, a two-step process is used. First, a weld schedule is developed which can approximately produce the required penetration goal. The iterative process employed to obtain the schedule uses guidance from a digital model of heat conduction in the (slab) workpiece as described in [Bertram⁴]. Then, for that nominal schedule, carrying out the schedule on the welding fixture then results in a sensor output profile which provides a nominal condition for which feedback gains can be derived to maintain the stated penetration goal. The sensor output profile can also be used for self-calibration of each succeeding workpiece [Bertram et. al.⁵].

The computationally fast digital model can be useful in the controller in at least two more ways. First, it can be used to transform the sensor signal from voltage to penetration; i.e., the combination of sensor and model constitutes a "pseudosensor" of penetration. Second, it can be used to change the feedback controller setpoint for photodetector output voltage, making the simple feedback much more robust. This latter usage constitutes a hierarchical model-based scheme with the feedback

controller at the first level from the workpiece, resending rapidly (around 10 Hz), while the model occupies the second level, and responds much more slowly (1 Hz at most). This architecture has been provided but not implemented.

2. Welding Experimental Configuration

The welding task chosen for prototype testing was an autogenous girth weld on a (nominally) circular tube rotated by a stepping motor driven chuck (Fig. 1). The goal is to produce, under digital control of the power supply current output at fixed voltage, a full penetration weld with uniform backside width. A second performance test will be to hold constant partial penetration. The combination of the capabilities provides for control of multipass welding of a joint.

For feedback control, a sensor is required which will produce a signal strongly correlated to the quantity which is to be controlled (backside width), and an actuator which can effectively change that quantity. Here, the actuator is to be the power supply current output (at constant voltage), which is to be digitally controlled by software running on the 486 CPU, which sends signals to the power supply. Similarly, shield gas flow is turned on and off, and the chuck rotation speed is controlled by this software (App. S).

A robust, economical sensor is described next.

3. BACKSIDE FIBER OPTIC SENSOR

The backside sensor consists of an optical fiber in a holder tube coaxial with the rotating chuck (Fig.2). The fiber has end face area A_f and acceptance angle U_f ; its output passes through a high-pass filter, with spectral response $F(v)$ at frequency v ; the radiance from the filter falls on a photodetector (PD) fitted with an amplifier circuit such that the final output $V_1(t)$ is in the range 0-5 V, as described in App. S. and [Stecker³].

The power incident on the PD will be [e.g.,6,7, summarized in App.R]:

$$P = \int_{A_s} \int_0^\infty \int_{A_f} \{F(v) I_v \cos \theta_f / |\mathbf{x}_f - \mathbf{x}_s|^2\} dA_f dv dA_s \quad (1)$$

in terms of the intensity I_v emitted by the source area element dA_s and the filter characteristic $F(v)$, where v is the frequency of the light. If it collects light from a grey body source of emissivity ϵ , the intensity function is $I_v = [h/2 (\pi c)^3] v^3 / (\exp(b v) + 1)$, and the integration can be done explicitly to give [App.R]:

$$P = \sigma_{SB} \int_{A_s} \int_{A_f} \{\epsilon T_s^4 \cos \theta_f / |\mathbf{x}_f - \mathbf{x}_s|^2\} dA_s dA_f \quad (1a)$$

for the unfiltered signal with $F \equiv 1$. When a filter is used, the the more general (1) must be used to calculate P .

This power P from (1) or (1a) is incident on the photodetector array, which produces a voltage output $V_{pd}(t)$; that output is in turn amplified to serve as the signal $V_1(t)$ at time t . If the amplifier transfer function can be taken as a real multiplier C_{amp} in the time domain and the photodetector device which takes in light radiation power $P(t)$ and puts out voltage $V_{pd}(t)$ is also characterized by a single multiplier C_{pd} , then the signal can be written as:

$$V_1(t) = C_{amp} C_{pd} P(t) \quad (2)$$

This value is to be input for the feedback control of weld width w .

Fig.1. Schematic of prototype weld setup. Numerically controlled stepping motor rotates chuck holding the workpiece (tube). Welding torch supplies arc with digitally controlled current $I_a(t)$.

Fig.2. Sensor elements of backside radiance. Angle of acceptance U_i defines fiber's field of view, and the axial weld-to-fiber tip distance x_f determines the fraction of the weld emissions captured. Conversion of fiber optic output to voltage by photodetector and amplifier is described in App. A. Transform of signal $V_1(t)$ into a digital data file in real time is described in App. S.

The dependence of (2) on the geometric factor $\cos \theta_f / |\mathbf{x}_f - \mathbf{x}_s|^2$ which appears in (1) is, of course, basically an inverse- r^2 decrease in signal strength with distance, and an explicit dependence on the angle θ_f between the fiber axis and the fiber-to-weld vector ($\mathbf{x}_f - \mathbf{x}_s$). For the limiting case of a small source at distance r from the sensor, (1) takes the form:

$$P = \frac{A_f}{r^2} \cos \theta_f \int_{A_s} \{ \} dA_s \quad (1b)$$

which is equivalent to Lenef and Gardner's⁸ form because $\cos \theta_f / r^2 = (\mathbf{x}_f - \mathbf{x}_s) \cdot \mathbf{n}_f / r^3$. Since the fiber has a limited view characterized by its numerical aperture $n_a \sin U_i$ where n_a is the ambient (air+ fumes) index of refraction and U_i is the fiber's "acceptance angle", it follows that detector placement can be a matter of crucial importance in its successful use.

To characterize the general sensor of Eq.(1), one must know

Detector position x_f

Detector const $\equiv C_{det} \equiv C_{amp} C_{pd} A_f$ (a single calibration scalar)

Source surface characteristic $I_v (v, \theta, \phi, x_s)$

Source geometry $dA_s (x_s)$

Filter response $F(v)$

when the source (workpiece backside) has a characteristic I_v given as in (1).

To assess the utility and sensitivity of the fiber, consider an idealized sensor. Let this sensor respond only to the radiance from the melted zone on the backside, and let it have a sharp cutoff of sensitivity at an angle of 45° (the nominal U_i value for the optical fiber used). Suppose that no reflected radiation in its band $F(v)$ is present, so that only the pool acts a source for the fiber. Further, let the fiber be at sufficient axial distance x_f that the inverse- r^2 approximation applies. If the radiation which it senses is uniformly distributed over the backside pool, and is isotropic, then I_v depends only on v , and the integration over dv gives the same result regardless of geometry, so the form of Eq.(1b) applies to characterize the source geometry and surface characteristics. From this form, the idealized response of such a sensor can be written down as a function of axial position x_f . That is:

$$V_1 = \begin{cases} 0 & x_f < x_U \\ A_s(x_f)/A_s \cdot C_o (r_o/r)^2 & x_U < x_f < x_U + W \\ C_o (r_o/r)^2 & x_U + W < x_f \end{cases} \quad (3)$$

With the value r_o defined as the distance from the pool centroid to the fiber tip when the full pool is just barely within the acceptance angle; i.e.,

$$r_o = \sqrt{(x_U^2 + r_i^2)} \text{ where } x_U = x_w + 0.5 \cdot w + r_i / \tan U_i \quad (3a)$$

and the constant C_o fitted to the data at the position nearest $x_f = x_U$, Eq.(3) produces the solid curve shown in Fig.2.2. The degree to which the actual sensor performs in this idealized manner is apparent for the data points plotted in the figure. These were obtained by manually withdrawing the fiber as welds progressed. Clearly, the dominant response of the sensor is described by the idealized case, and its sensitivity to positioning (x_f) and pointing (θ_i) is captured by (3).

Fig. 3. Sensor signal V_1 dependence on axial position x_f . Solid curve is Eq.(3), response of idealized sensor with acceptance angle $U_i = 45^\circ$, when no reflections or scattering reach the fiber. Plot symbols are data obtained from the setup in Figs.1,2 by manually withdrawing the fiber during welding, with stops at 0.5-in intervals. This strong response to the pool radiation indicates that signal should be strongly correlated to backside weld bead width w . If the fiber were put at the peak position, risk of complete loss of signal due to small placement error would be unacceptable. At large x_f , signal attenuation would be unacceptable, so practical compromise favors distances $1.5 < x_f < 2.5$ for robust control of this weld. Working value $x_f = 2.125$ in was used in all cases below.

Fig.4. Correlation between dynamic sensor output $V_1(t)$ and instantaneous backside bead width $w(t)$. Width estimated by borescope and edge-detection software. This case displays ideal behavior of sensor for width control in this full penetration case.

The sensitivity of the sensor signal to fiber tip placement can be reduced somewhat by providing software evaluations of the calibration constant C_0 in Eq.(3) from data during the open-loop heat-up phase of welding. The same statement applies for the optimum placement x_f --a range of values can be made acceptable by software adjustments, removing the burden of precise (mm accurate) positioning which would be required for 10% precision in reproducing signal magnitude from one production workpiece to another. The feasibility of such software is assured by the simple form of (3) with its few parameters to characterize the sensor. It remains to establish the adequacy of the correlation between $V_1(t)$ and $w(t)$ for control purposes. This is addressed next.

3a. PERFORMANCE TESTING OF SENSOR

When a borescope CCD camera view of the weld in Fig.1 is provided as well as the sensor output, it becomes possible to log the instantaneous variations of the backside bead width $w(t)$ while a weld is being made. The test weld can be made with varying current levels and durations, to characterize the primary dynamics of the system as well as to "stress test" the sensor.

A test weld was made here by providing a pseudorandom sequence of current levels, changed at pseudorandom times. Ideal durations of each current fall in the range $0.316 t_1$ to $3.16 t_1$, where $t_1 = w^2/(4 a)$ is the characteristic thermal diffusion time of the weld width.

The degree to which the sensor can provide a signal correlated to the backside width is obvious in Fig.4. The sensor output tracks the vision-derived pool width so faithfully that it is very well approximated by $0.55*w$. This simple proportionality, however, does not apply when the weld fails to penetrate fully, as seen in Fig.5. In that plot, the disappearance of liquid from the backside does not result in a zero signal from the sensor, indicating that its response to the thermal emissions of the solid is still detectable, and therefore, usable for partial penetration control.

4. SYSTEM IDENTIFICATION AND CONTROL

The control problem becomes single-input, single-output (SISO) when only the voltage $V_1(t)$ is provided as a measure of 'plant output', and only the welding current $I_a(t)$ is varied by the controller, with all other welding variables (gap, voltage, gas flow, travel speed) being held constant. In the case of arc gap, constant conditions are only approximately maintained by a separate control [Richardson,Hillaire,⁹] or by open loop positioning of the torch.

For the SISO case, system identification (i.e., construction of a correlation model) can be carried out by standard methods^{10 11 12}. Specifically, 'system ID' means correlation of the sensor output $V_1(t)$ to experimentally imposed arc current $I_a(t)$. To carry it out in a state space formulation, suppose the infinite number of degrees of freedom of the welding arc and workpiece can be approximated by a finite number, m ,

of "state variables", written as the vector $\mathbf{v} = \{v_1, v_2, \dots, v_m\}$, and that the sensor voltage $V_1(t)$ is a linear combination of these state variables and the control variable $la(t)$:

$$V_1(t) = \mathbf{C} \mathbf{v} + \mathbf{D} la \quad (4)$$

These state variables, for the actual system, satisfy linear evolution equations

$$\dot{\mathbf{v}} = \mathbf{A} \mathbf{v} + \mathbf{B} la \quad (5)$$

where the dot overscore indicates time derivative. The data in Figs.4 and 5 above is to be reproduced by Eqs.(4,5) when the coefficients $\mathbf{A}, \mathbf{B}, \mathbf{D}$ and the variables $\mathbf{v}$ are chosen by a least squares process when the data sets and the relations (4,5) pass some observability tests¹².

The result of that process for our data set is a 7th order model ($m = 7$) which produces the fit to the $V_1(t)$ history shown in Fig. 6, with the errors shown in Fig. 7.

Fig.5. Correlation between $V_1(t)$ and backside width $w(t)$ for intermittent-penetration case. Note that sensor signal does not go to zero when penetration fails. This case indicates capability for sensing and control of partial penetration operation.

Fig.6. System ID for state space model of weld on 0.065 in thick stainless steel tube.

Fig.7. (a) The set of components of state vector $\mathbf{v}$ for the model of Fig.6. (b) The error between estimator (5) and the data for the components of (a).

The system can be controlled to a setpoint V_{set} for the sensor output by using the estimator (4) to evaluate the error between the present state of the system and the desired state

$$\hat{e}(t) = V_1(t) - V_{\text{set}} \quad (6)$$

where the caret indicates an estimated value. The next current value is selected by the control form

$$I_a = K_s \hat{e}(t) + K_i \int_{t_0}^t e(\tau) d\tau \quad (7)$$

with the gains K_s and K_i being chosen from the Bode plots in Fig.8^{11,12}. A similar feedback is used to update the estimator

$$\dot{\hat{v}} = A\hat{v} + B I_a + L(V_1 - B\hat{v}) \quad (8)$$

with L designed to provide stable rapid convergence of $\hat{v}$ to v^{12} . Thus, (7) and (8) make up the control, as indicated schematically in Fig.9.

Fig.8. Bode diagrams connecting output $V_1(t)$ to control input $I_a(t)$ for the model of Fig.6. Half power point is at 0.6-0.7 rad/sec, corresponding to dominant time scale of 1.4-1.7 sec. The heat diffusion time $t_1 = w^2/(4a) = 1.2$ sec here.

Fig.9. Schematic of state variable control scheme for welding. Voltage signal $V_1(t)$ from the sensor is digitized as $V_1(k)$ at time $t(k)$ in a rotating buffer. At 100 msec intervals, control commands are issued according to (7,8).

5. CONTROL PERFORMANCE

To test the robustness of the controller, several different thicknesses of stainless steel tubes and some Ti-6V-4Al tubes were tested. The travel speed was held at about 3 ipm, so durations were around 65 sec. Ar gas was used for shielding of both topside and backside (the greater reactivity of Ti required additional shielding of the hot bead behind the pool). For the SS tubes, a setpoint $V_{\text{set}} = 0.5 \text{ V}$ was prescribed, and resulted in the history plotted in Fig. 10 when the startup and weld of a tube of 0.077 in thickness was carried out under the control (7,8). The sensor output overshoots the setpoint by about 10% during the step-function startup, indicating a slightly underdamped control. After the first 10 seconds, the data settle on V_{set} with only minor fluctuations, of the same 5% scale as the error in the model fit; apparently these reflect the general noise level in the system. A possible source of this noise was investigated in the run depicted in Fig.11, where the shielding of the backside was absent. The control again produced a slight overshoot followed by successful tracking of V_{set} , but with an increase in the noise level. Since the backside was vulnerable to oxidation in this case, it is plausible that the presence of oxides in the pool, with their greatly increased emissivity, account for these fluctuations.

Fig.10. Control of current I_a (top curve) when sensor voltage $V_{set} = 0.5$ V is prescribed on 0.077 in thick stainless steel tube of 1.3175 in dia. Initial arc gap was 0.070 in, but noncircular tube resulted in gap variations since weld torch was held fixed.

Fig. 11. Control of weld as in Fig.10, but without backside shielding. Successful control shows greater scatter in sensor output, presumably due to more emissive oxides in backside of weld pool.

6. SUMMARY AND CONCLUSIONS

An extremely economical sensor has been developed for control of weld penetration. Its performance has been demonstrated in holding a setpoint for welding on thin SS and Ti tubes. In the stand-alone mode reported here, it has displayed its sensitivity to positioning and to the emissivity changes which will be encountered in most production settings. With enough care, the stand alone mode of feedback control can be used to greatly improve weld quality.

The potential pitfalls of the stand alone mode can be countered by combining it with model-based software⁵, so that the sensor can be calibrated with little effort for a girth weld with startup, running weld, and tie-in. An iterative schedule development guided by such software moves toward precision by incremental adjustments, until the result is suitable to the user's goals. Once a successful weld has been made, production welds of the same quality can be generated even when power supply, sensor and workpiece variations would have caused part rejection in stand-alone feedback or open loop control. As a rule, the greater the welding expertise of the user, the faster the development will go. Even a professional welder will many times profit from the systematic reminders provided during the steps of the guided development process.

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APPENDIX A

Operation and Description of Fiber Optic Sensor Amplifier Box

This describes and documents the design and operation of a fiber optic sensor and associated signal conditioning developed to sense light emitted from the back side of a welding operation. The intent is to control welding parameters based on the measured intensity of the light.

The first element is a photodetector sensitive to the wavelengths of interest and capable of generating a usable level of output for the relatively low levels of input transmitted through the fiber optic probe. A literature search found a photodetector with good characteristics from UDT Sensors, Inc. The part selected was the PIN-HR040. It is a silicon based photodiode with a high responsivity (typical responsivity 0.52 A/W at 830 nm) and wide bandwidth. The active surface of the die is 0.8 mm², a collection area providing good coverage for the fiber optic interface. Another important feature is low cost at \$17.50. There is also a spherically lensed version available at \$27.50 that would provide a more efficient coupling between the fiber optic probe and the detector. Initial tests have shown this to be unnecessary for the light levels being measured.

The detector is installed in an SMA style adapter to provide easy coupling to the fiber optic probe. The SMA style connection provides an efficient, repeatable way of establishing the coupling between the detector and the probe.

The detector is used in photovoltaic mode in which the detector photocurrents are amplified by an operational amplifier circuit. This mode requires no bias supply and provides an excellent signal-to-noise ratio. It also provides a highly linear response to input irradiance.

This amplifier circuit feeds an inverting variable gain amplification stage to provide output level control. The output is adjustable with a dial-pot potentiometer so that the output can be optimized for the recording or control instrumentation. The output voltage is zero based and can be scaled to provide full-scale voltages up to 12 V. The low dark current of the detector and offsets of the amplifiers were negligible for the levels used. The addition of an offset nulling potentiometer to this output amplifier stage would remedy this, if it becomes necessary in the future.

The circuit requires external power supplies of ± 15 V for operation.

A schematic (Figure 1) and data sheets for major components follow.

A set of gel filters could be used to tailor the response of the circuit to a particular range of wavelengths in the blue to ultraviolet regions of the spectrum. The filters reduce the system transmissibility and this required a substantially higher gain setting than that used previously.

Should it be required, UDT makes a series of Blue and UV enhanced detectors that could provide additional response at those wavelengths. Responsivity at other wavelengths would be similar to the existing detector. It should also be noted that the quality of the filter elements could be improved and pass bands narrowed, if desired.

The fiber optic probes have a high Numerical Aperture (NA) of 0.48 yielding an acceptance half angle of 28.7° . As supplied, these probes have a polished male SMA proximal termination and a simple cleaved probe at the distal end. If desired, the acceptance angle could be increased by the addition of a ball lens that would enlarge the acceptance half angle to 90° . These enhanced probes can be purchased from the same supplier, Pioneer Optics Company.

Below is a listing of the major sources used for this project:

Sensor/Detectors	UDT Sensors, Inc.	310-978-0516
Fiber optic Probes	Pioneer Optics Co.	203-292-8705
SMA Sensor Adapter	Fiber Optic Center	800-473-4237

- U1 - PIN-HR040 - UDT Sensors Inc
- U2, U3 - AD711 Operational Amplifier
- R1, R2 - $402K\Omega$
- R3 - $4.22K\Omega$
- R4 - $10.0K\Omega$
- Rg - 0-100K Ω Potentiometer (Dial-Pot)
- C - $.01\mu F$ Ceramic Cap

Note: U1 is mounted to the breadboard using a female SMA style fiberoptic adapter model 698-AR1.

Figure A.1. Fiber optic Amplifier Schematic

APPENDIX R

Radiation

The source is an area A_s , radiating to a collector with area A_c . These elements are at positions $\mathbf{x}_s$ and $\mathbf{x}_c$, and have outward normals $\mathbf{n}_s$ and $\mathbf{n}_c$, respectively; see Fig. R.1. Then, if the source radiates with specific intensity $I_v(\nu, \theta, \phi)$ from the infinitesimal area dA_s , into a solid angle $d\Omega$, that "pencil" of radiation contains power

$$dP = I_v d\nu dA_s d\Omega / 2\pi \quad (R.1)$$

in the frequency band ν to $\nu + d\nu$. From the geometry of the collector, the solid angle $d\Omega$ corresponding to an element dA_c of collector area is:

$$d\Omega = \cos \theta_c dA_c / |\mathbf{x}_c - \mathbf{x}_s|^2 \quad (R.2)$$

so that the collector receives power

$$dP = d\nu dA_s \int_{A_c} I_v \cos \theta_c dA_c / |\mathbf{x}_c - \mathbf{x}_s|^2 \quad (R.3)$$

in the band $d\nu$. If this band is filtered by $F(\nu)$, the net signal power will be:

$$P = \int_{A_s} \int_0^\infty \int_{A_c} \{ F(\nu) I_v \cos \theta_c / |\mathbf{x}_c - \mathbf{x}_s|^2 \} dA_c d\nu dA_s \quad (R.4)$$

For isotropic radiation, I_v is independent of θ, ϕ . For a black body, the radiation is isotropic, and I_v is proportional to $\nu^3 / (\exp(b\nu) + 1)$ [6; Callen, 13], so that the quadrature over frequency gives the Stefan-Boltzmann flux if $F(\nu) = 1$ at all ν :

$$P = \sigma_{SB} \int_{A_s} \int_{A_c} \{ \epsilon T^4 \cos \theta_c / |\mathbf{x}_c - \mathbf{x}_s|^2 \} dA_s dA_c \quad \text{Grey Body} \quad (R.4a)$$

It is also useful to note that the general relation (R.4) can be specialized to the case where both source and collector are small compared to the separation distance $r = |\mathbf{x}_c - \mathbf{x}_s|$ of their centers; i.e.,

$$A_s \ll r^2 \quad \text{and} \quad A_c \ll r^2 \quad \text{both hold.}$$

In that case, which would be typical for a fiber sensor viewing the weld arc at distances greater than 10 cm, the geometric quantities are all constant over the quadrature with respect to dA_c , and can be factored:

$$P = \text{const} \int_{A_s} \int_0^\infty \{ I_v F(\nu) d\nu \} dA_s \quad (R.4b)$$

where $\text{const} = A_c \cos \theta_c / r^2$.

Fig.R.1 Radiation of frequency ν emanating from source area dA_s in pencil of solid angle $d\Omega$ falls on collector area dA_c . The pencil makes angle θ_c with the normal n_c of the collector area element, and has length $|x_c - x_s|$. Power collected by A_c , when filter $F(\nu)$ is applied to collector signal, is given by Eq.(R.4).

Calibration: Start time for the rotating data buffer precedes the arc-on trigger by 't_{lag}' msec in order to provide an uninterfered-with signal for calibration purposes; t_{lag}=1000 msec is presently implemented. Similarly, at power-off time, the cooling of the part provides an independent check on model parameters, so a time 't_{delay}' of data is recorded beyond the power-off signal.

APPENDIX S

Real Time Software

Hardware

IBM PC or compatible with 486 processor
DOS operating system
LabPC + board for data acquisition and control from National Instruments
Floppy disks A and B with 'AWQC' software on them

Software

Modular units written in 'C'
Compile and build uses Microsoft NMAKE utility
Compiled with Nmicrosoft Visual C++ version 1.5. (Use of a more recent version of the Visual C++ compiler may require changes to the project makefiles.)
High level routines in directory \AWQC\PROJ
Service level routines under director \AWQC in subdirectories CONTROL, INFOTEXT, INTERFACE, RECORDS, SDEV, SENSORS, TABLE, TIMER, and WELDER.
Service routines may be compiled and tested independently of main program

Install and Build

The system is contained on two backup disks—disk A and disk B.
The system is installed by inserting disk A and running the program
a:\awqc\bin\rcvr_a and then inserting disk B and running the program
a:\awqc\bin\rcvr_b.

The PATH environment variable must be set so that NMAKE and the C compiler are executable from any directory. The INCLUDE environment variable should have an entry for the compiler header files and for the AWQC header files. For example, ...;c:\MSDEV\include;c:\MSDEVSTD\include;c:\awqc\include;...
The LIB environment variable should have an entry for the compiler libraries. For example, ...;c:\MSDEV\lib;c:\MSDEVSTD\lib;...

Build the system by moving to directory c:\awqc and running the command
nmake all

This command will cause the high level routines in the proj directory and the service routines to be compiled with all object and header files copied to the proj directory for linking to the executable file. This assumes that a suitable compiler is available and that the environment variables for path, include, and lib are set correctly. The resulting executable file awqc.exe will be found in the awqc\proj directory.
Change 'awqc.exe' to 'weldit.exe' and move it to working directory.

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