DESIGN AND IMPLEMENTATION OF A VIDEO SENSOR FOR CLOSED LOOP CONTROL OF BACKBEAD WELD PUDDLE WIDTH

by

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Abstract

Arc welding is one of the more common methods for metal joining. Weld quality, however, is very difficult to judge without destroying the weldment. In order to assure proper weld quality, it is desirable to implement a means of monitoring and regulating in process welding. A model describing the dynamics of a weld puddle has been derived relating the velocity of the weldment relative to the torch and the backside puddle width. A video-image processor has been designed and implemented to measure the backside puddle width. A standard digital control program and a digital model adaptive control program have been implemented to use the backbead measurement to control the width of a fully penetrated weld pool. A series of experiments were conducted to test the capabilities of the standard control system, the video sensor and the weld puddle model. The results of these experiments suggest that the standard controller can regulate the backbead width, the sensor works but can be improved and that further studies with a revised sensor will yield more definitive evidence as to the validity of the derived dynamic weld pool model.

Thesis Supervisor: Dr. David E. Hardt
Title: Assistant Professor of Mechanical Engineering

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Chapter 1

INTRODUCTION

Arc welding has long been an important means for joining metals. Proper welding technique can yield a joint which is almost as strong as the base metal. Obtaining consistent welding technique, however, is not a trivial matter. The size of the weld puddle on the underside of the weldment after the pool is fully penetrated is one means of judging weld quality. Full penetration means that the heat input to the base metal is sufficient to melt the entire thickness of the weldment in a limited area. This suggests that the joint formed from such a weld will be as thick as the base metal and will have the same area to resist shear and normal loadings. If one were able to implement an automatic control system to regulate the fully penetrated backbead width, then a means for controlling in process weld quality will have been implemented.

In an effort to regulate the backside weld pool width, a model for the weld system has been derived. This linear first order model is dependent on welding conditions. This suggests that changes to the welding process are parameter disturbances to the system model. In order to regulate the backbead width, one needs access to real-time measurement of the puddle width. A video sensor has been designed which uses the digitized picture of the underside of the weld from a video camera and searchs one line for the width of the backbead. The measurement is then used in a standard digital control program to regulate the velocity of the weldment underneath the arc and relative to it. Also, a digital model adaptive control program has been implemented to supplement the capabilities of the standard controller.

A series of experiments were conducted to explore the capabilities of the standard control program, the video sensor and the model of the weld puddle system. The results of the experiments suggest that the standard controller is capable of regulating the backbead to within a relatively small range of values about the desired width. The video sensor seems to be limited because of two conditions: 1. the focal plane of the video camera lies beneath the torch and not on the fully penetrated weld puddle, and 2. the image processing program searches one specified line of the digitized backbead image. Both of these problems contribute to sensor noise and not tracking the puddle causes the possibility of limit cycle behavior. Finally, the weld puddle system model seems to simulate the actual puddle dynamics. Because of the limit cycle problems, though, this conclusion needs to be investigated further.

Chapter 2

THEORETICAL BACKGROUND

2.1 Gas Tungsten Arc Welding

Arc welding makes use of the energy liberated from the electric ionization of the gas seperating two charged electrodes. Gas Tungsten Arc (GTA) welding, sometimes called Tungsten Inert Gas (TIG), is a form of arc welding where one electrode is the workpiece to be welded and the other electrode is a tungsten rod.

A typical GTA welding station, as is shown in Fig. 2.1, consists of a torch, a power supply and a source of shielding gas. The power supply is a constant current, DC supply connected so that the tungsten electrode is the cathode and the workpiece is the anode (known as DC, straight polarity). During welding, the tungsten electrode is not affected, so that GTA welding employs a non-consumable electrode. Filler metal, if desired, is added directly into the arc and the weldpool to replace evaporated base metal and to add structural strength. The shielding gas, most typically inert argon or helium, serves three purposes:

- The flow of gas past the electrode helps to cool the torch so that over heating does not occur. (Note that, in high current welding, the flow of gas will not be sufficient to cool the torch so that additional water cooling is employed to prevent overheating.)
- The flow of gas protects the weld pool from the atmosphere, thereby preventing oxidation of the weld.
- The gas flow aids in the transfer of energy to the workpiece.

Five factors determine the final mechanical and geometric properties of the weld. These factors include:

- The original mechanical properties of the workpiece.

- The joint geometry.
- The rate of input of heat to the workpiece.
- The filler metal used, if any.
- The mechanism of heat transfer within the workpiece metal.

Each joint design requires a specific heat input. The heat input per unit length can be determined by (see Reference 1):

$$Q_{in} = f \frac{EI}{V} \qquad (2.1)$$

where, f=efficiency, E=arc voltage, I=arc current, V=torch velocity. The arc voltage can be varied by changing the distance between the electrode and the workpiece, the current can be adjusted by simply changing the current output of the DC power supply and the torch velocity can be set by varying the travel speed of the arc relative to the workpiece. Efficiencies for the GTA welding process range from 40% to 65% and will be assumed to be 50% for our purposes.

2.2 Weld Control Hardware

Most of the equipment used in this research was designed and constructed by former researchers in the Laboratory for Manufacturing and Productivity (LMP) at MIT. A block diagram illustrating the separate components and their interconnections is shown in Fig 2.2a. The computer system consists of a Cromemco Z2-D microcomputer. The velocity servo is made up of a lag-lead compensator made by General Electric (GE); a GE pulse-width modulated amplifier; a permanent magnet, DC servomotor made by GE and a tachometer attached to the servo. The servomotor is attached to the leadscrew of a Bridgeport milling machine table through a very stiff coupling. As is shown in Fig. 2.2b, the welding hardware, the torch, and the mirror positioner are attached to the head of the same Bridgeport milling machine.

The dynamics of the velocity servomotor and the milling table will be included with the model used to describe the plant (see section entitled Weld Puddle Model). As will shortly become clear, the dynamics of the servo and table will be insignificant when compared to the weld pool dynamics. The time constant of the servo is about 0.02 seconds. This, compared to the time constant of the weld puddle (approximately 3.0 seconds), will have no effect on the dynamics of the model for the plant and can be safely ignored.

The puddle width sensor consists of a mirror positioned under the workpiece. The mirror is adjusted so that the electrode is visible from a 90 degree viewing angle. This configuration is illustrated in Fig. 2.2c. The Panasonic CCD video camera is positioned so that the focal plane of the camera lies on the bottom of the workpiece. The image output of the camera is fed into a North Star microcomputer image processor. The video signal is then digitized and stored. Albert Tam has developed an algorithm (see Appendix A) which checks one line of the digitized signal and determines the width of the weld in picture elements (pixels). This number is then passed to the Cromemco Z2-D microcomputer for scaling and use in the control program. The sensor dynamics consist of a pure delay and a gain for the signal. That is:

$$G_D(s) = K_d e^{-Ts} \qquad (2.2)$$

where, K_d=sensor gain, T=sensor delay time. The sensor gain, K_d, needs to be determined each time the camera is setup and focused. This can be done by placing a ruler on the backside of the workpiece and dividing the width of the camera monitor by 256. This is because 256 is the number of pixels which make up the entire picture width. The sensor delay time, T, has been estimated to be approximately 20 hertz (cycles/second).

2.3 Weld Puddle Model

Dave Garlow (see Reference 2) developed a model for the GTA welding system described above. A relationship between the torch velocity and backside weld puddle width as a function of the welding parameters and weld metal characteristics was determined from an analytic analysis of the welding process. This model was verified with experiments by Garlow and has been assumed correct in the present work.

In order to derive an analytic model of the weld pool, the following assumptions have been made:

- The weld puddle is constant in temperature.
- The weld puddle is cylindrical, symmetric and fully penetrated.
- The temperature contours at the weld pool-base metal interface are continuous.

Using these simplifications and some heat transfer theory, one can derive (see Reference 2) the following equation which approximates the heat transfer characteristics of the weld puddle as:

$$\dot{Q}_{in} = 2\pi r \ell \left(r h \rho \frac{dr}{dt} + K \frac{dT_{ml}}{dr} \right) \tag{2.3}$$

where, $\dot{Q}_{in}$=rate of heat input per unit length, r=puddle radius, l=puddle thickness, p=puddle density, K=thermal conductivity of base metal, T_{ml}=temperature near the puddle, h=latent heat of fusion of base metal. Equations (2.1) and (2.3), when combined, rearranged and transformed into the frequency domain (Laplace transform), yields the following relationship between the inverse velocity and weld puddle width (see Reference 3):

$$G_p(s) = \frac{W(s)}{\frac{1}{V(s)}} = \frac{K_p}{T_p s + 1} \tag{2.4}$$

$$K_p = \frac{f E I}{\pi \ell K \frac{dT_{ml}}{dr}}$$

$$T_p = \frac{r h \rho}{K \frac{dT_{ml}}{dr}}$$

where, $G_p(s)$=transfer function of weld puddle, K_p=gain of the weld puddle, T_p=time constant of the weld puddle. Garlow conducted open loop weld experiments to determine the gain of the plant to be 0.015 inches/second and the time constant to be 3.0 seconds. Recent open loop experiments were performed and the plant gain for the base metal thickness (13 gauge) used was determined to be about .01 inches/second and the plant time constant was measured to be approximately 4.0 seconds. As can be seen from Equation (2.4):

- Changes in plant gain are directly related to changes in welding current, voltage and workpiece temperature.
- The plant gain varies inversely with workpiece thickness and puddle width.
- The plant time constant varies proportional to puddle width and workpiece temperature.

This suggests that changes in the weld system are parameter disturbances to the weld puddle model. Further, these parameter disturbances—suggest the possible need for a parameter adaptive control system to account for variations in welding parameters.

The complete system dynamics are shown in Fig. 2.3. Figure 2.3a shows the theoretical control loop and Figure 2.3b is the control loop with the appropriate transfer functions substituted into the proper block. $G_c(s)$ is the controller for the weld system. From Rieff's work and programs which simulate dynamic systems (see Figs. 2.4 a-h), it was determined that a proportional-integral (P-I) controller would provide the most desired system response. Then,

$$G_c(s) = \frac{K_c}{s}(T_i s + 1) \qquad (2.5)$$

where, K_c=controller gain, T_i=controller time constant. The controller gain, K_c, was chosen to be between 700 and 750 because of the results of the simulations. Also, T_i, the time constant, was fixed to be 2.0 seconds.

2.4 The Control Program

A FORTRAN program which digitally implements the control system shown in Fig. 2.5a was developed by John Rieff (see Reference 1). This control program was the result of the analysis of numerous different control options. The model adaptive controller was chosen because disturbances to the physical plant translate into changes in the plant gain and time constant. The standard controller was chosen to be a proportional-integral (P-I) controller because simulations of the weld system suggest that this controller would provide the smallest overshoot, the quickest 2% settling time and zero steady state error.

The first order system represented in Fig. 2.5a as:

$$G_m(s) = \frac{K_m}{T_m s + 1} \qquad (2.5)$$

is simply the transfer function, $G_m(s)$, of the adaptive loop puddle reference model. Here, K_m is the average value of K_p and T_m is the average value of T_p. This adaptive loop compares the output of the the plant with the output of the reference model which simulates the dynamics of the plant. This signal, then, is used to modify the command given to the actual plant so that this command is compensated for the varying plant parameters.

The present study considers the control system shown in Fig. 2.5b. The only change between this figure and the corresponding diagram in Rieff's work (Fig. 2.5a) is the substition of the delay and gain associated with the video sensor for the feedback loop filter. In order to digitally implement this system, difference equations for the P-I controller and adaptive loop need to be derived. The equivalent Z transform of the continuous P-I controller (see Reference 1) is:

$$G_c(z) = \frac{K_c(T_i + T) - T_i z^{-1}}{1 - z^{-1}} \qquad (2.6)$$

which becomes the following difference equation:

$$\left[\left(\frac{1}{V}\right)_c\right]_n = \left[\left(\frac{1}{V}\right)_c\right]_{n-1} + K_c(T_i + T)E_n - T_i E_{n-1} \qquad (2.7)$$

The continuous reference model becomes:

$$G_A(s) = G_m(s)\,G_d(s) \qquad (2.8)$$

which is simply the model used by Rieff, minus the feedback loop filter and multiplied by the transfer function of the video width sensor. The Z transform of this can be derived as:

$$G_A(s) = \frac{K_m K_d}{T_m} \frac{z^{-1}}{1 - e^{-T/T_m} z^{-1}} \qquad (2.9)$$

which can be represented as the difference equation

$$[W_{ms}]_n = \frac{K_m K_d}{T_m} \left[\left(\frac{1}{v}\right)_c\right]_{n-1} + e^{-\frac{T}{T_m}} [W_{ms}]_{n-1} \qquad (2.10)$$

As in Rieff's program, limits are placed on the inputs to both the plant and reference model so that they cannot become values less than .781 seconds/inch. Also, the reference model output is limited such that its value does not attain a value greater than a specified (in the program execution) number added to the measured puddle width.

The modified control program listing is shown in Appendix B. The program is organized into three sections:

- input of control data
- the control calculations
- the storage of every fourth point on disk

Chapter 3

CONTROL EXPERIMENTS AND RESULTS

3.1 Experimental Procedures

Control experiments were performed to test the ability of the P-I controller to control the backside puddle width. This would effectively check the controller as well as the model used for the weld puddle. Then, after some indication of the sucess of the controller, it was decided that the controller should be tested to see how it behaves in typical tests of standard controllers (i.e. step input changes). The results of these experiments indicated how, if at all, the controller operates. Finally, to test the limits of the system, a series of experiments were performed with parameter disturbances to see if and when the controller is able to compensate for the changes.

All of the welding experiments were performed with the above described LMP welding system. The weld torch was secured perpendicular to the workpiece for all of the experiments. The video camera was positioned so that its focal plane lay on the bottom of the workpiece. The camera lens (a Tokina 80-200 mm zoom lens with 55 mm of extension tubes) was fitted with three neutral density filters (0.2, 0.4, 0.9). Finally, the lens aperture was placed to the smallest possible opening setting (i.e. 22) and the camera output was connected to the image processor. Additionally, the following weld parameters were used:

- The weld metal was low carbon steel (1020).
- The weld metal plate dimensions were 13 gauge thick and 6.0 inches wide by 8.0 inches long.
- A 1/8 inch diameter, 2% thoriated tungsten electrode was used.
- The electrode was positioned with 1/8 inch stickout and 1/8 inch standoff.

- The shielding gas was inert argon and the flow rate was set to 30 CFH.
- The digital controller described above was used with a sampling frequency of 20 hertz.

The experiments were run with the weld conditions and initial control characteristics shown in Fig. 3.1. WD1 is the initial desired backside puddle. WD2 is the desired backside puddle width after 4.0 inches into the weld. I1 is the initial current and I2 is the current after a disturbance in weld amperage put into the system. K_c and T_i are the control system gain and time constant respectively. Preheat YES refers to the condition of welding a plate which has a temperature greater than room temperature. This was accomplished by making two welds next to eachother on the same plate. The first weld served to preheat the welding metal for the second weld. Preheat NO simply means that the base metal was initially at room temperature.

The procedure to run the experiments was as follows:

- start the arc (making sure that the electrode is positioned properly, that the gas was turned on and that the proper current was set on the power supply)
- observe the underside of the weldment until burn through occurred
- start the image processing program
- start the control program
- release the inhibit on the table so that the control program can begin to regulate the table velocity

3.2 Results

The results of the above experiments are shown in Figs. 3.2 through 3.16. The results are in the form of graphs of the measured backside puddle width vs time. The data was collected by saving every fourth sample from the control program and plotting the results using a Varian plotter.

3.3 Observations and Discussion

The measured backbead puddle width graphs seem to fall into two separate categories: 1. those results with a characteristic limit cycle, and 2. those results with a backbead width within a small range of the specified value. Obviously, two separate physical mechanisms are causing the vastly different performance of the controlled weld puddle system.

The characteristic limit cycle appears in the figures representing the backbead width for experiments 2,3,4,5,6,8 and 12 and can best be seen in Fig. 3.4. As is shown in Fig. 3.4, the characteristic limit cycle is an oscillation starting from a puddle width which is very small compared to the desired width. This large error is used by the controller to determine a small table velocity to compenstate for the small puddle measurement. As the table velocity decreases, the puddle size increases to a level between the upper and lower bounds on the cycle. This width is then maintained for a short while until the weld puddle fully burns through to the underside of the weldment. At this point, since the backside of the weld puddle turns liquid, there is an instantaneous change in the emissivity of the puddle and, therefore, the amount of light detected by the camera. Because of this increase in light intensity, the video sensor measures a distinctively larger puddle width in a very short time. To compensate for the large puddle width measured, the controller outputs a very large table velocity. This large velocity moves the table so quickly that the puddle is no longer under the arc and all that the sensor measures is the intensity of light from the very hot, but not liquid, backbead. At this point, the controller again sees a very large error because of the small width measurement and will determine a very small table speed to compensate. Then, the cycle is repeated. The cycle is refered to as a limit cycle because the largest and smallest possible table speeds are commanded by the controller which means that the upper and lower bounds (limits) in puddle width error have been recorded.

This limit cycle behavior seems to be the result of a flaw in the measurement system.

The system was designed to measure a backbead puddle which always remains under the torch and never exhibits any large excursions from this point. Also, the image processing program tests only one line of the digitized signal to determine the backbead width. The sensor should always be focused on the backside of the puddle regardless of the torch position. The image processing should check the entire puddle for the widest point so that if small excursions in puddle position do occur, they will not drastically effect the width measurement.

The second category of results suggest that the control system designed for the first order system model of the weld is performing as expected and that the linear model is a reasonable approximation to the actual dynamics of the weld pool. Fig. 3.2 shows an experiment attempting to control a constant backside weld puddle width with no preheat. As in most of the experiments of this category, the beginning of the measured backside puddle width graph is moderately random. This is due to the start up procedure. While waiting for the puddle to burn through to the underside of the weld metal, the sensor was turned on. The time between when the control program was turned on and the table was allowed to be controlled by the computer accounts for the randomness of the measurement. During this time, the control program was running and recording data, but the table speed was not regulated by the controller. Hence, the typical increase in puddle width until the table was uninhibited. After the table speed was allowed to be regulated, the width measurement came down to the setpoint value. All of the measured widths after this point in time lie within a range of values about the desired value. This band is most likely due to noise in the sensor signal. Changes in the number of picture elements (pixels) separating the two puddle edges will cause the contoller to respond appropriately. These changes in the number of pixels can be the result of minor backside puddle movements relative to the camera focal plane.

Experiment 15 is a system with a controller gain which is smaller than that in Experiment 1 (700 vs 750) and a smaller current than the same experiment (100 amps vs 125 amps). Fig. 3.16 shows the same characteristic start up for the first 10 seconds and then a measured weld puddle width which again lies in a band about the setpoint value. It seems, though, that the decrease in current caused a slightly larger range of width values. This can be due to the smaller amount of heat available to the system. It seems that with the smaller amount of available energy (limited by EI as defined in Eqn. (2.1)), the system does not behave as well as it did with the larger available energy (with the larger current). This change in performance is suggested by the weld puddle model because changes in weld parameters are changes to the gain and time constant of the plant.

The performance of the controller to a step change in setpoint width is shown in Fig. 3.17. As the graph shows, the characteristic startup variation as mentioned before is apparent and then the controller settles the backbead puddle width to the desired value. When the step arrives, the puddle width increases with small overshoot and a short settling time, 40% and 9 seconds respectively. Due to the limit cycles present in all of the other responses to step inputs, solid observations considering the effect of preheat on the system response cannot be made.

The last set of experimental results consider the response of the controlled weld puddle system to step changes in current. These results are shown in Figs. 3.10 through 3.15. These figures suggest that the controller had no problem adjusting to the in process change in current. One cannot even guess where the current step occurred in all but one experiment from the backbead puddle width data. After reviewing the velocity as a function of time during these experiments, obvious changes in table velocity occurred to compensate for the change in available energy for the system. Increasing the current caused the table speed to increase while the decrease in current caused the velocity to decrease. After the initial drastic change in velocity, the table velocity returned to a relatively stable appropriate value and controlled the backside width to the setpoint value.

Chapter 4

CONCLUSIONS AND RECOMENDATIONS

Based on the results of the control experiments performed, it can be seen that the first order system model of the weld pool is a reasonable approximation to the actual dynamics of the welding system. The ability of the designed control system to regulate the actual backside puddle width as well as it controls the simulated system is a good indication that the approximate transfer function (relating backside puddle width to the inverse table velocity) used in the simulation is very close to the actual system dynamics. Also, the results which indicate that the controller can respond to step changes properly, suggest that the closed-loop system behaves like a second order system. One of the integration terms for the second order system is contributed by the controller and the second integration is from the plant. If the plant were of higher order, the closed-loop transfer function would suggest higher order response characteristics which were not evident in the results. This again leads to the conclusion that the plant behaves like a first order system.

Comparing the ability of the controller to regulate the backside puddle width under varying welding parameters suggests that there is a qualitative difference in the response of the closed-loop system. Changing the current and the desired backside puddle width effect the response of the controller to measurement noise and the range of measured values changes accordingly. This variation in response is likely due to the fact that altering welding conditions result in parameter disturbances to the dynamics of the system plant model. This is suggested when one studies the derived plant dynamic model. The plant gain and time constant are dependent on welding conditions (i.e. arc voltage, arc current, preheat, puddle width and base metal) so that changing any of these parameters will qualitatively change the system response and the ability of the controller to regulate the backside puddle width.

The characteristic limit cycle oscillation which is apparent in many of the experimental results is probably caused by the sensing mechanism. The sensor should track the puddle and not the torch. This would cause the sensor to always measure the backside puddle width and not the puddle width under the torch. This would provide a more reliable backbead measurement. Another way to decrease the effect of measuring beneath the torch is to limit the possible acceleration of the table. If this limit functions properly, it will prevent the puddle from wandering too far from the torch location. Also, to decrease the noise due to small excursions from the exact backside of the torch, it is suggested that the image processing program scan the entire puddle image to find the largest puddle width in the picture.

Finally, it is recommended that the ability of the designed model adaptive controller to regulate the backside weld pool width be explored. This will allow further verification of the derived system model and should also provide a closed-loop system with improved response characteristics.

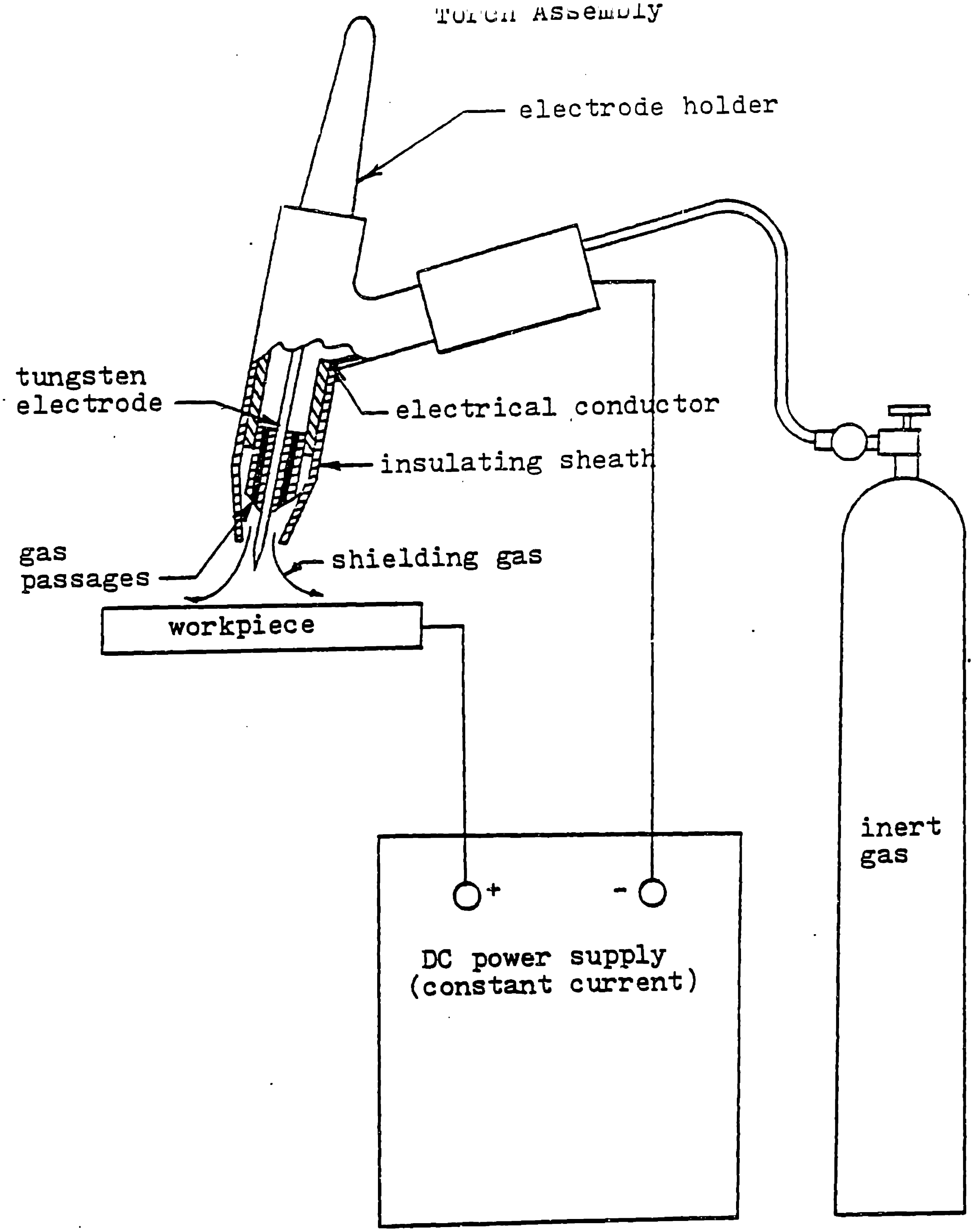


Figure 2.1 A GTA welding system.

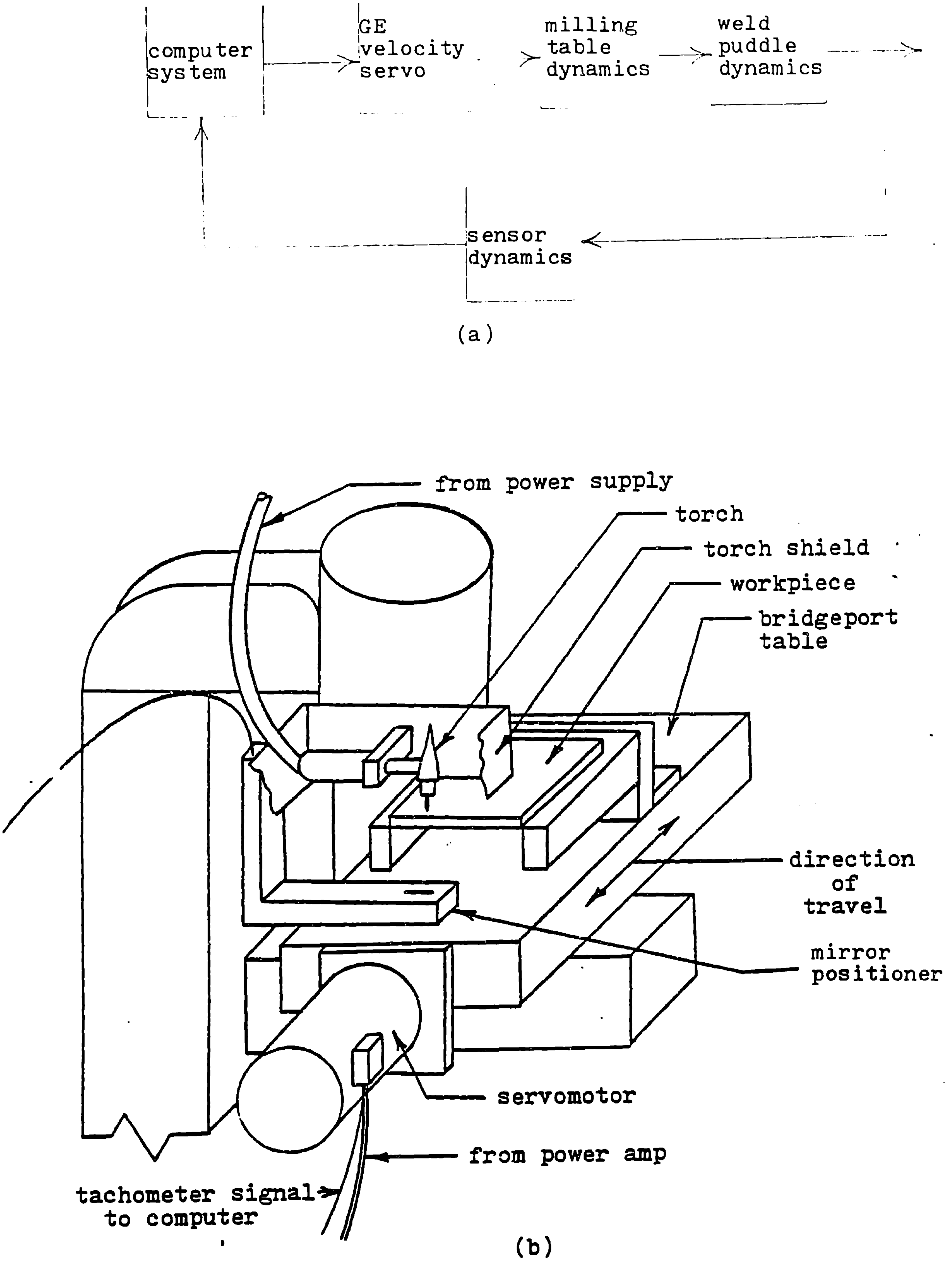


Figure 2.2 (a) Block diagram of the LMP welding system; (b) configuration of equipment mounted on the bridgeport.

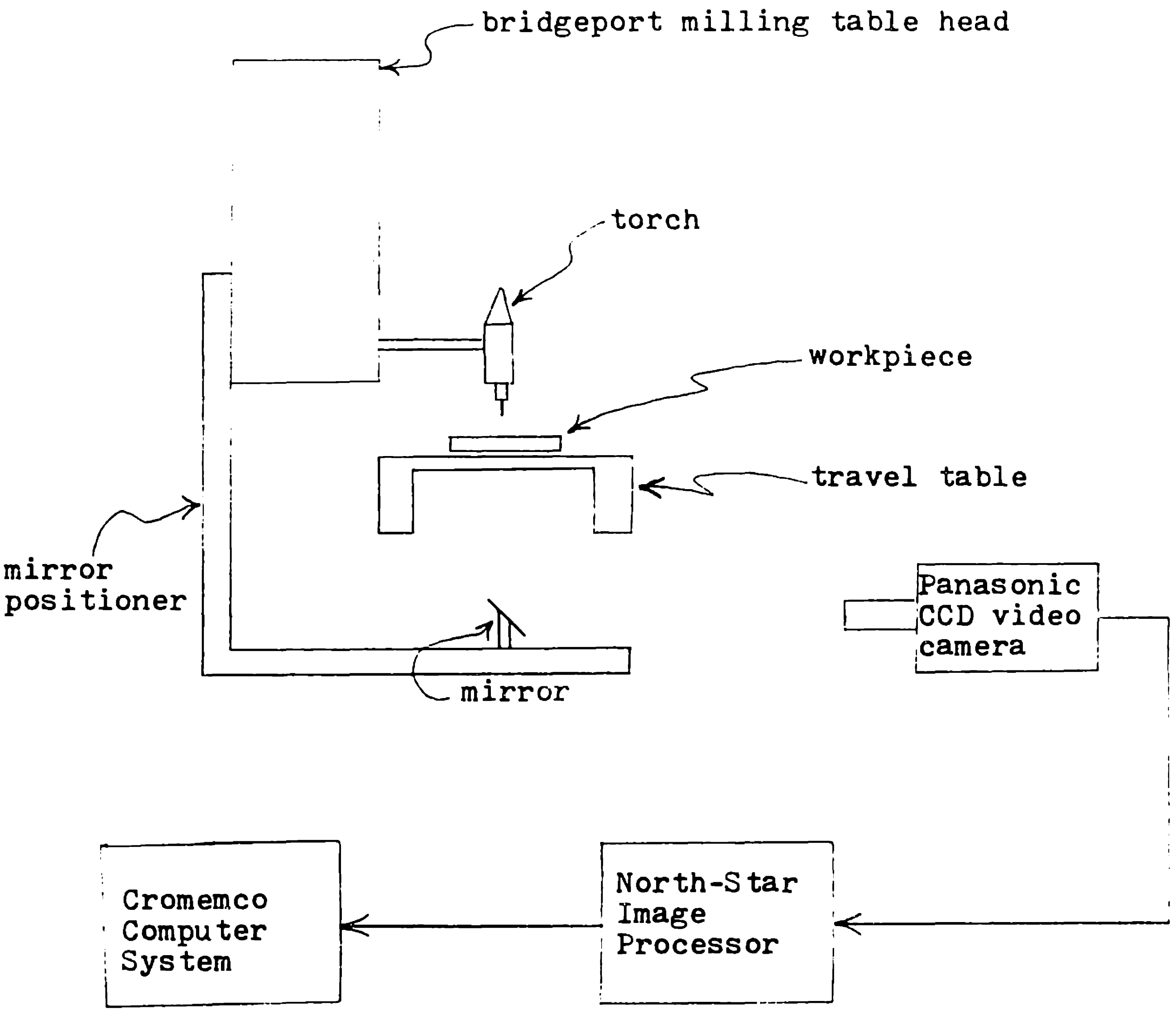


Fig. 2.2(c) Weld Width Video Sensor

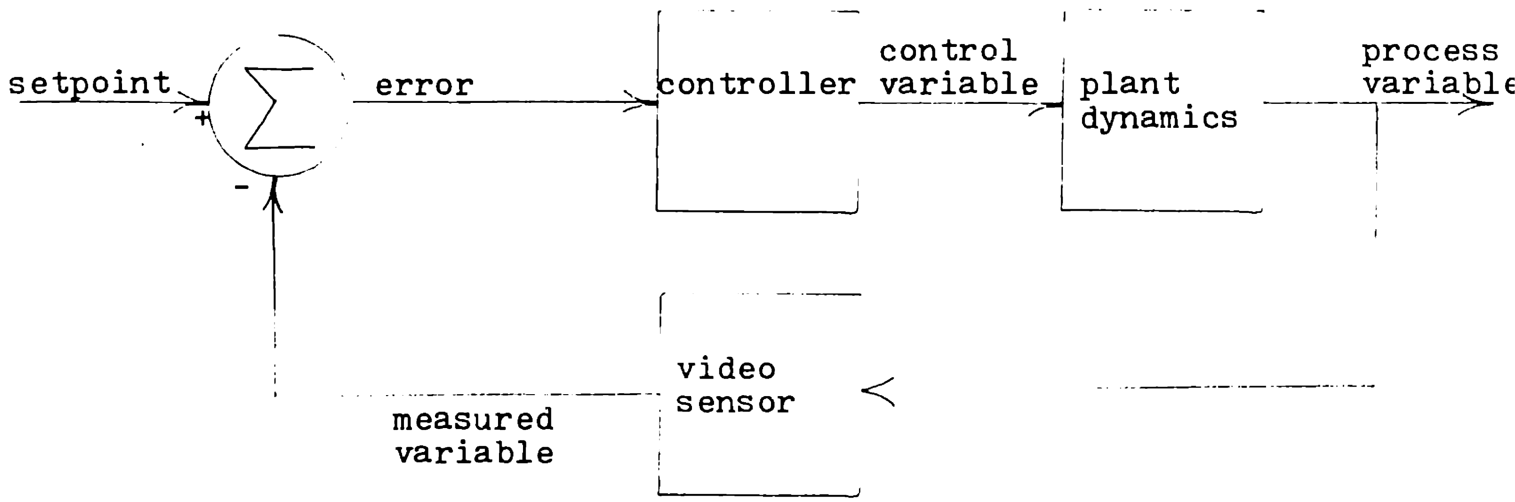
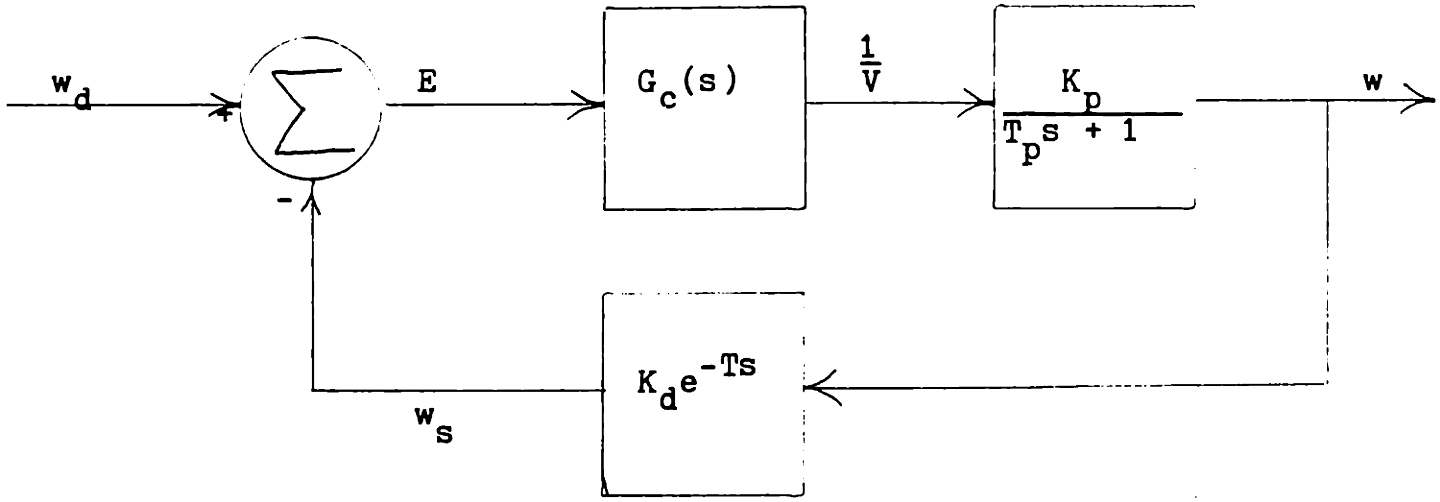


Fig. 2.3(a)



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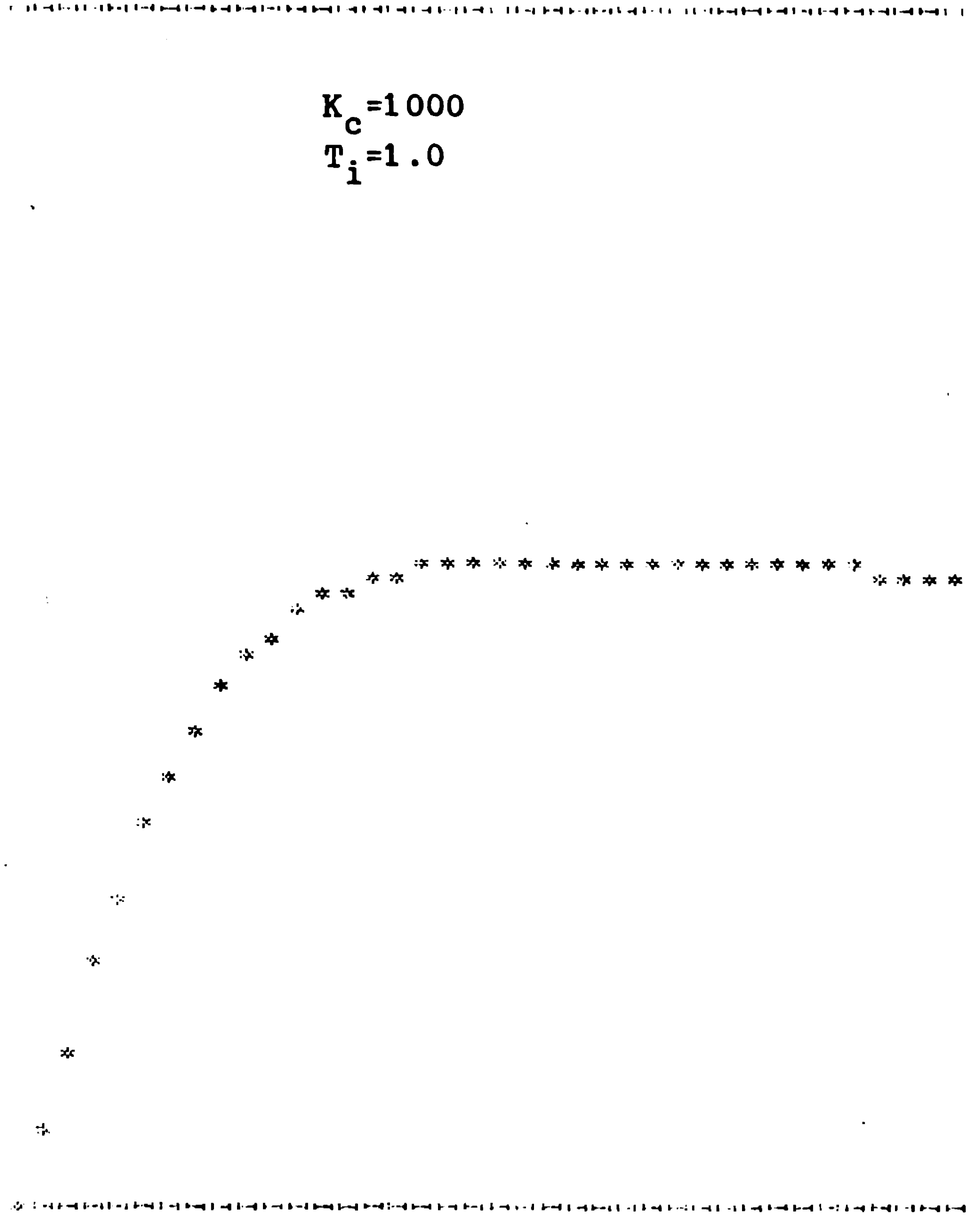


Fig. 2.4(a)

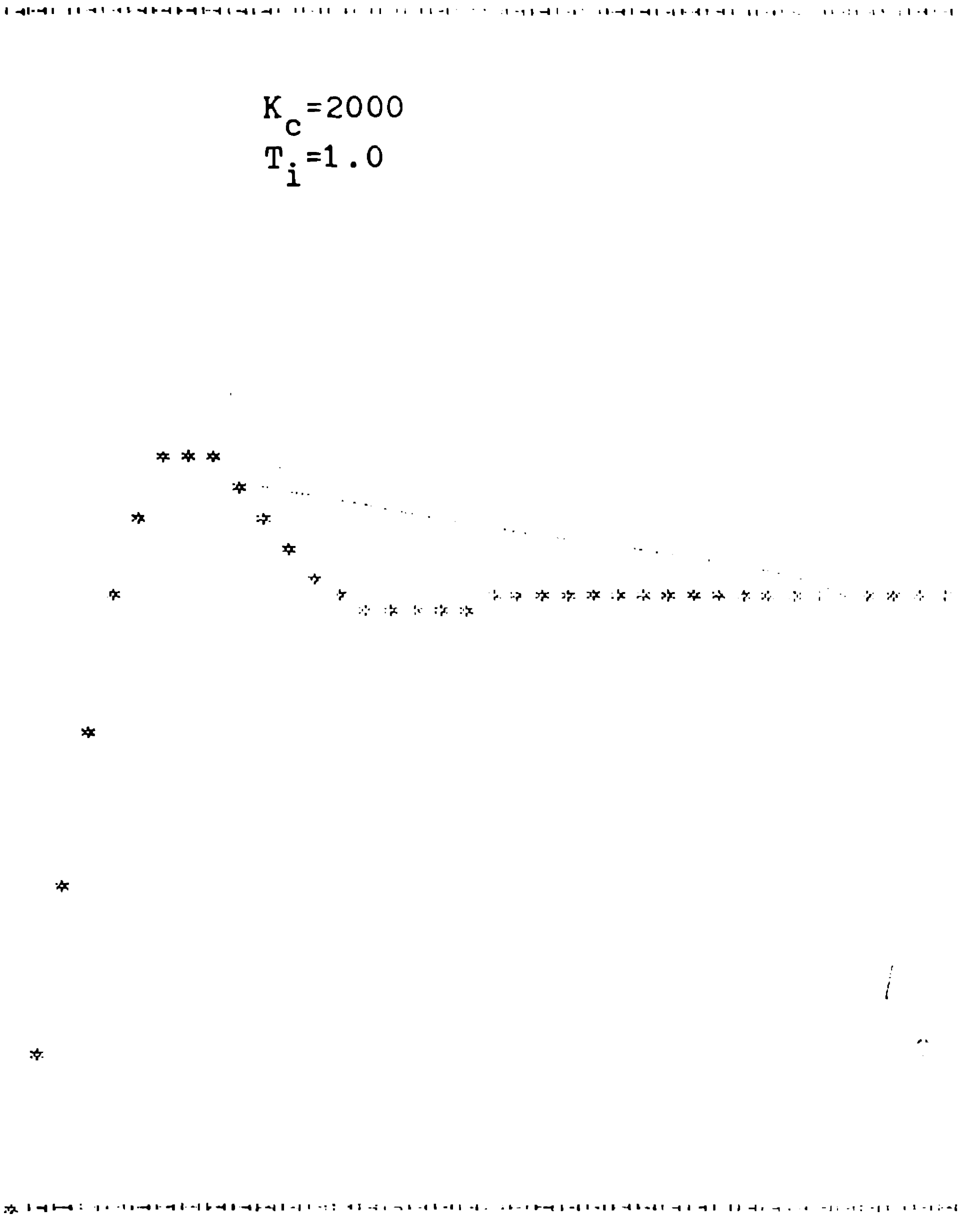


Fig. 2.4(b)

Results of Weld System Simulations

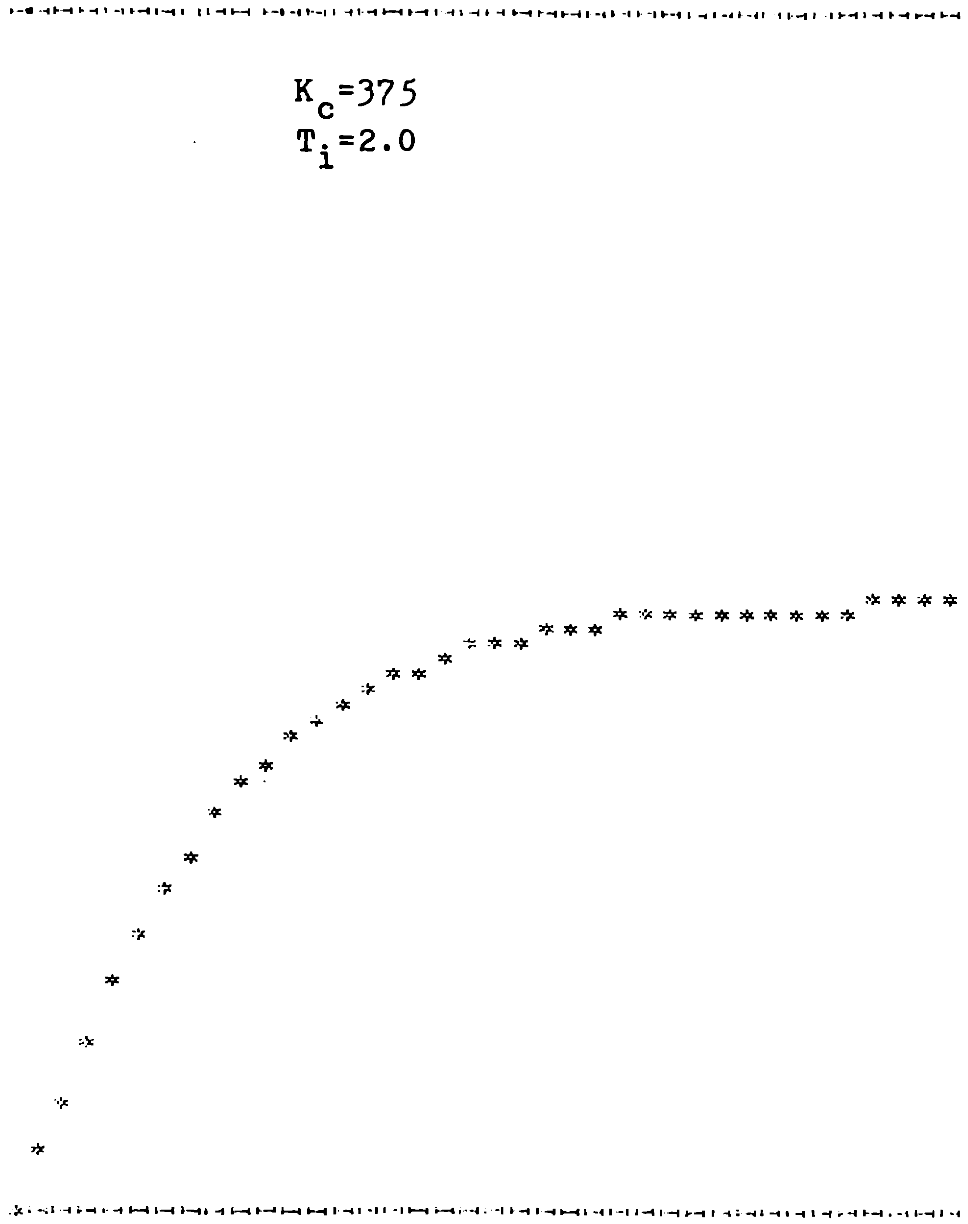


Fig. 2.4(c)

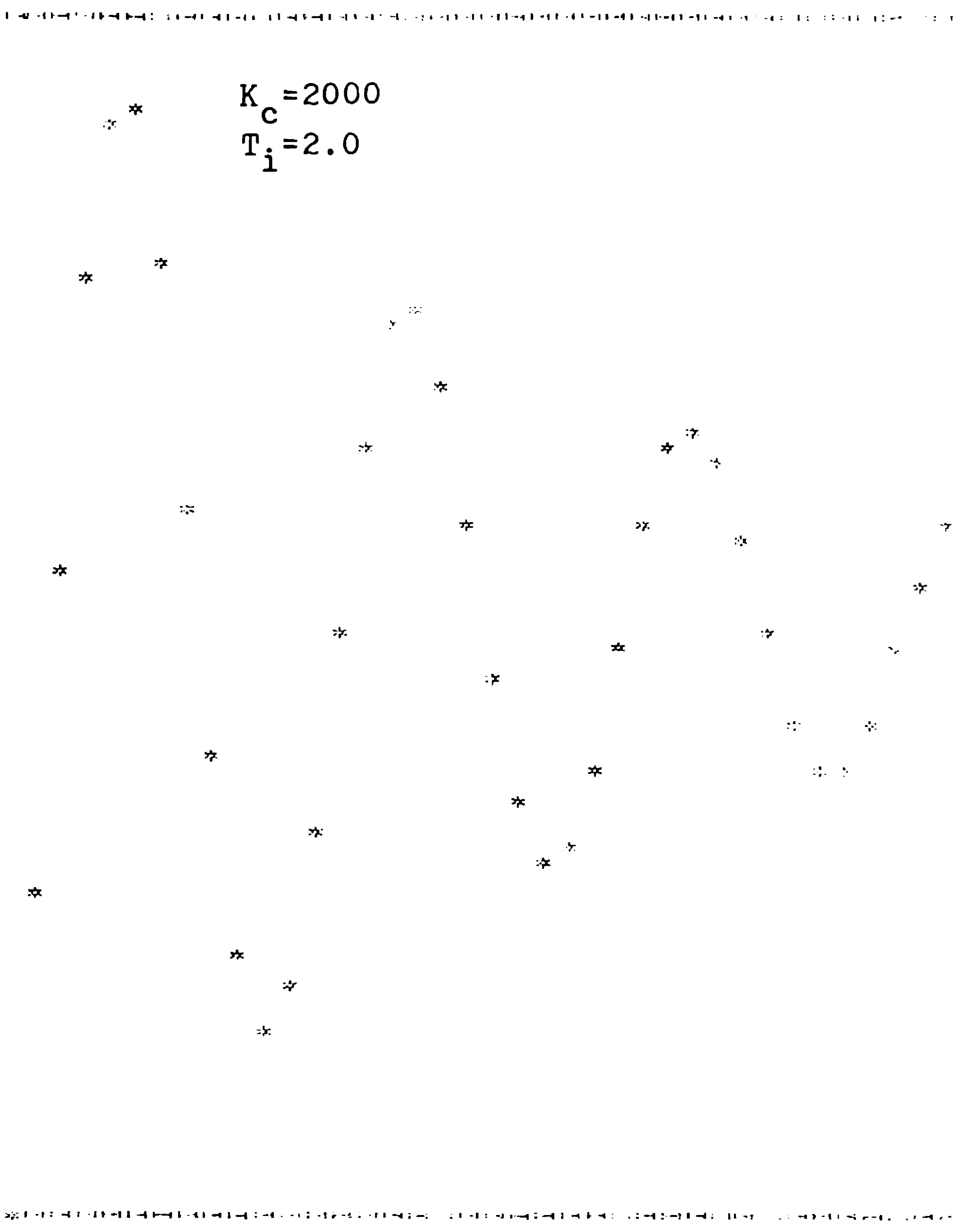


Fig. 2.4(d)

Results of Weld System Simulations

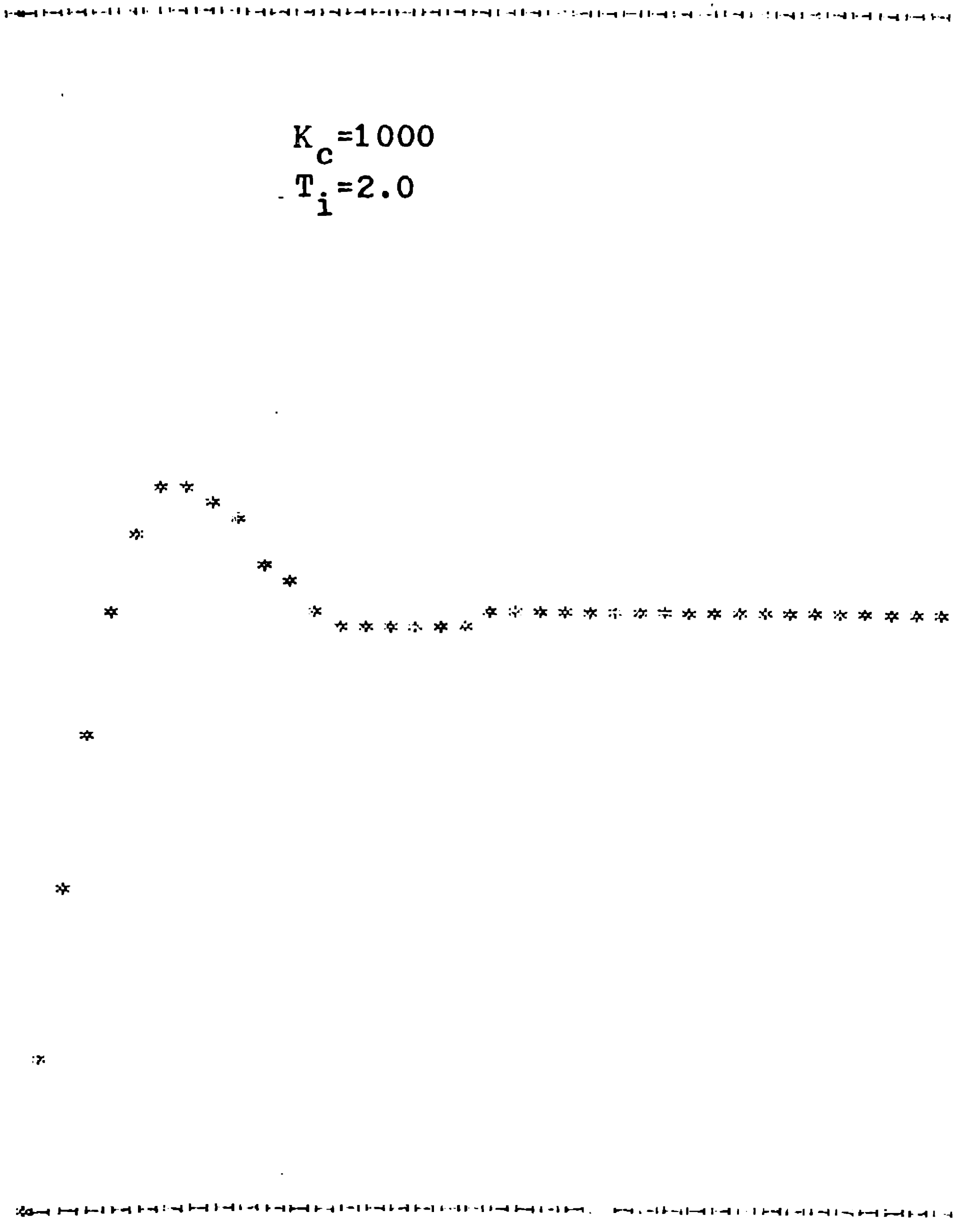


Fig. 2.4(e)

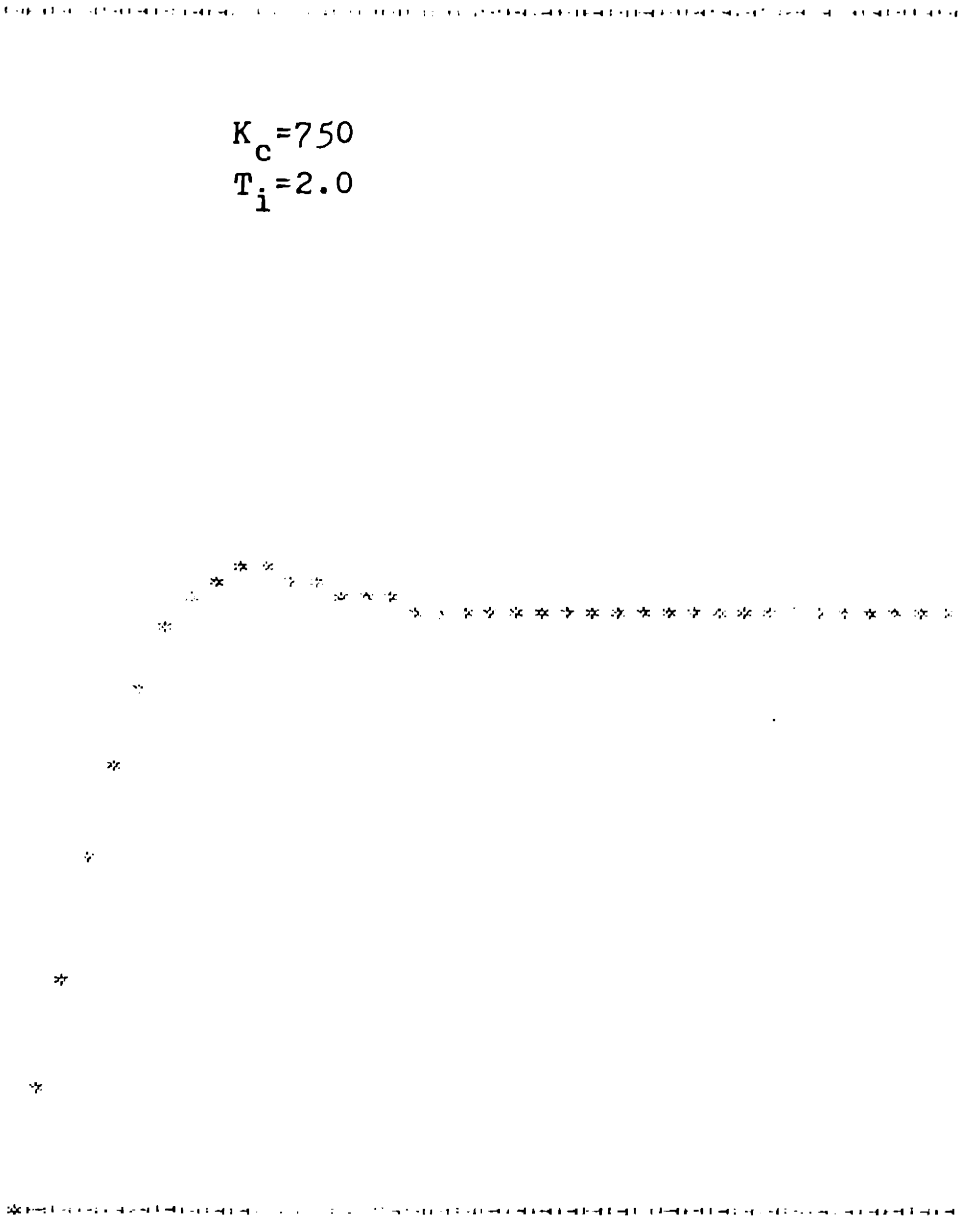


Fig. 2.4(f)

Results of Weld System Simulations

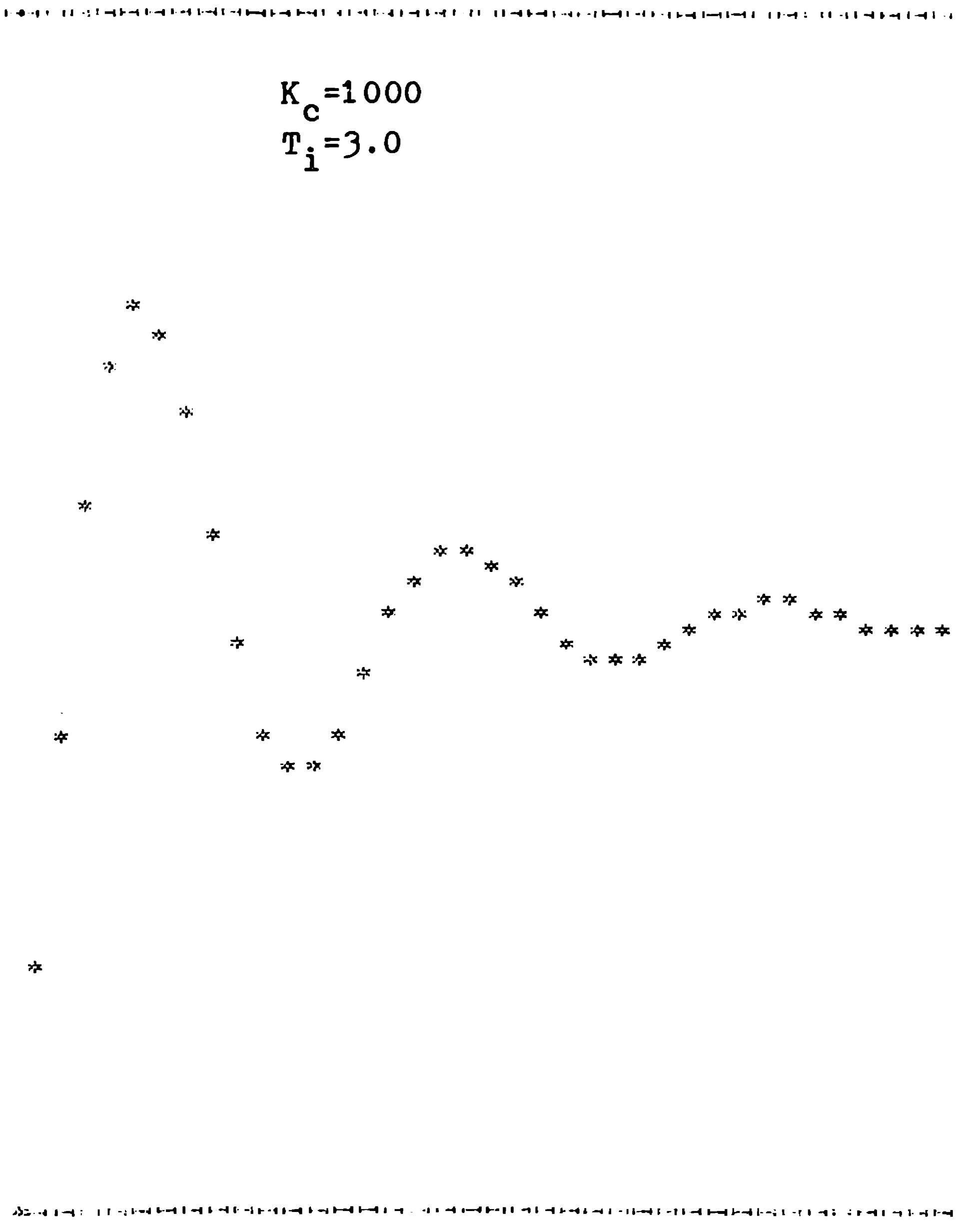


Fig. 2.4(g)

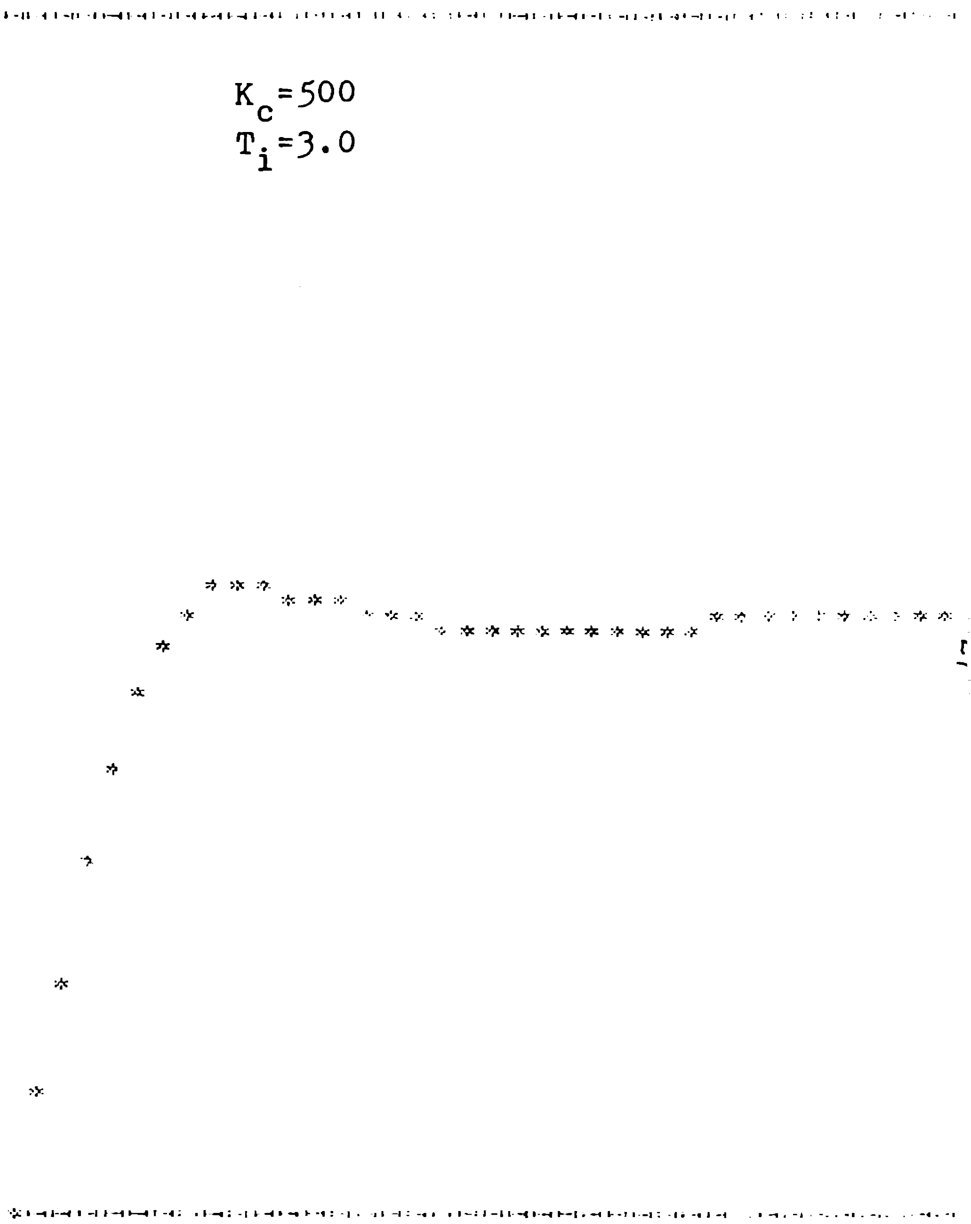


Fig. 2.4(h)

Results of Weld System Simulations

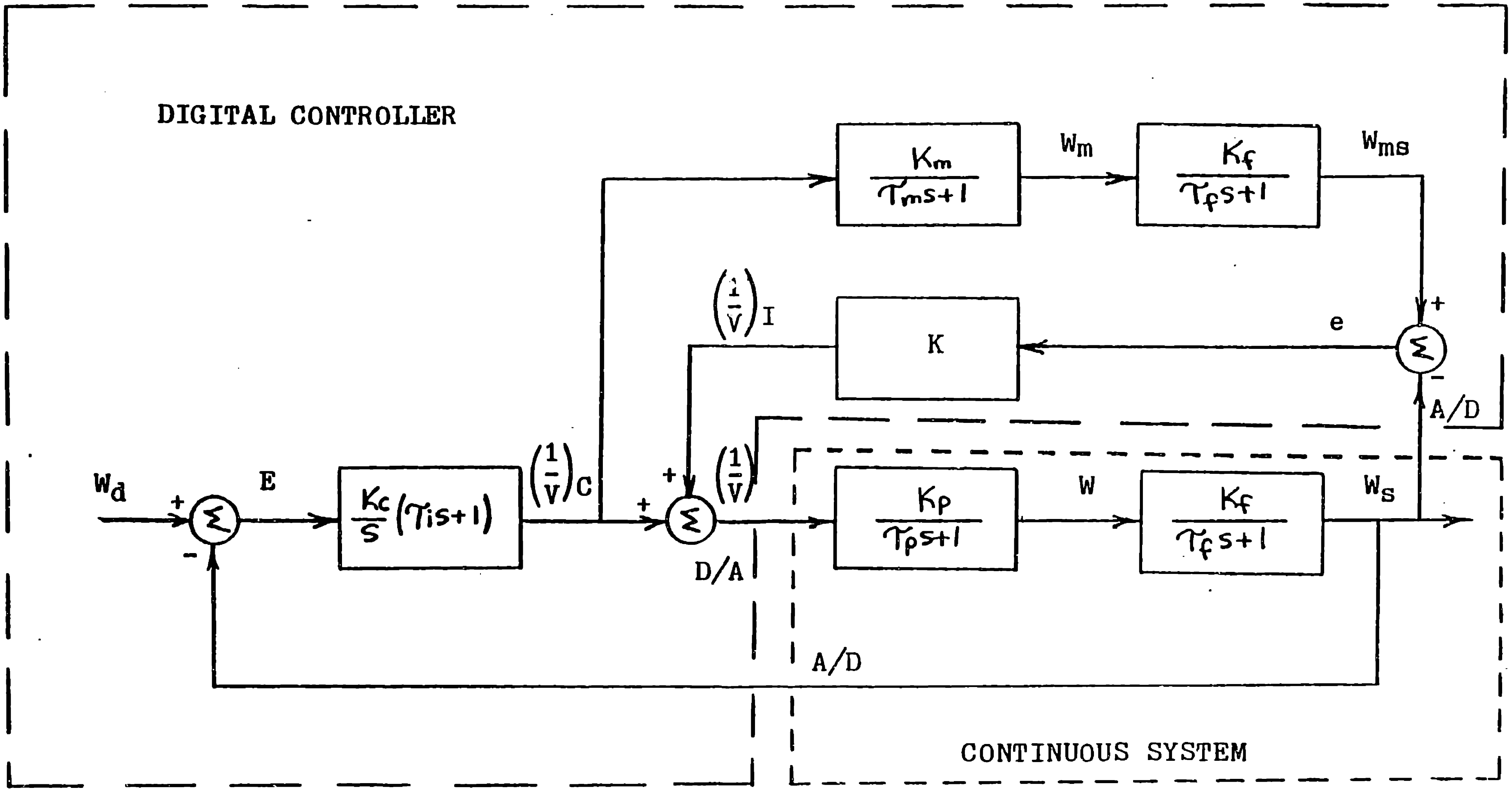


Figure 2.5(a) Block diagram of MRAC system.

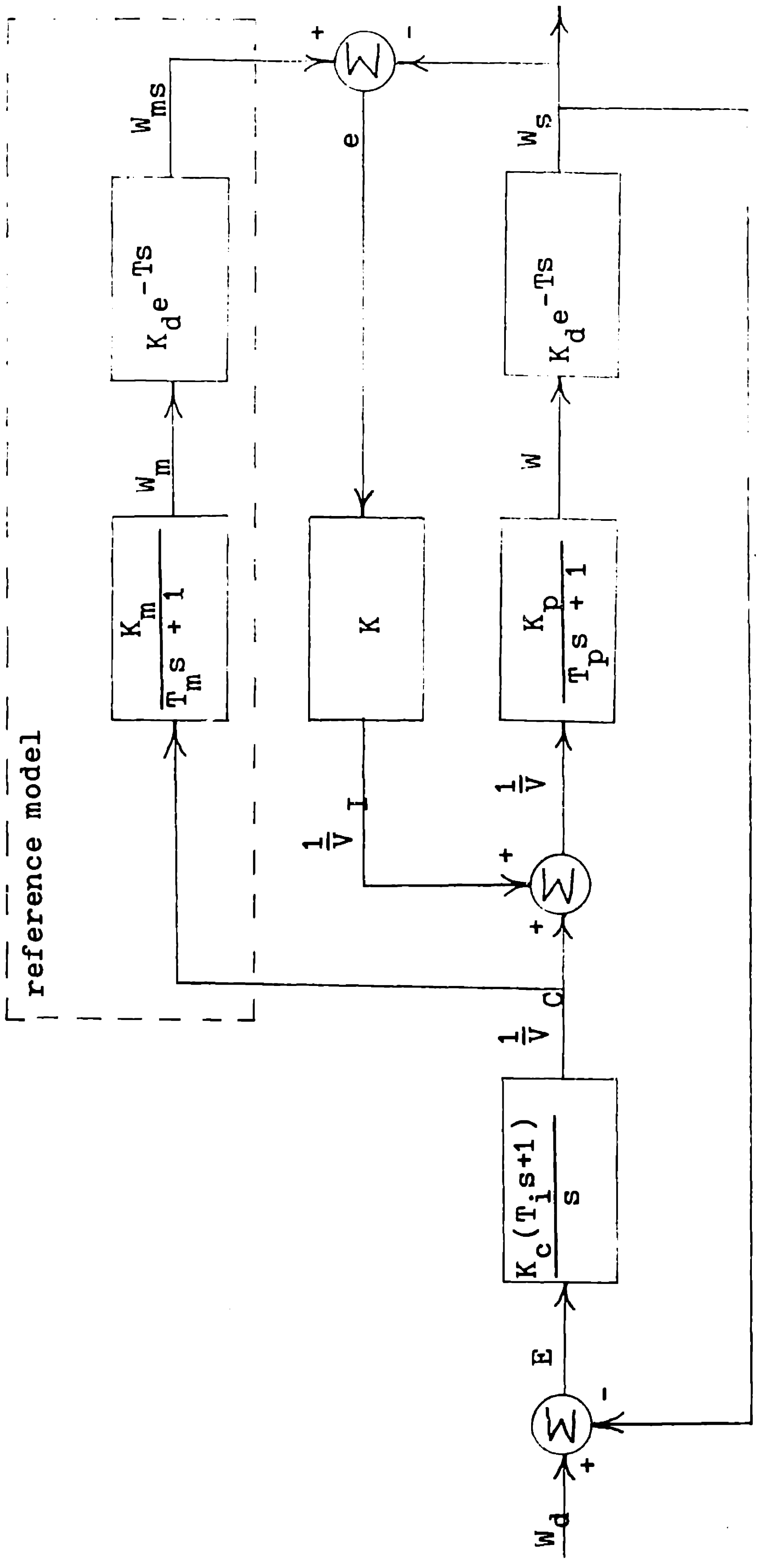

reference model
$\frac{K_m}{T_m s + 1}$
W_m
$K_d e^{-Ts}$
W_{ms}
+
-
e
K
$\frac{1}{V_I}$
+
+
$\frac{K_p}{T_p s + 1}$
W
$K_d e^{-Ts}$
W_s
$\frac{1}{V}$
C
$\frac{1}{V}$
$\frac{K_c(T_i s+1)}{s}$
E
+
-
W_d

Fig. 2.5(b)

Exp.	WD1 (in)	WD2 (in)	I1 (amp)	I2 (amp)	K_c	T_i	Preheat
1	.2	.2	125	125	750	2.0	NO
2	.2	.2	100	100	750	2.0	YES
3	.175	.225	115	115	750	2.0	YES
4	.175	.225	115	115	725	2.0	NO
5	.175	.225	115	115	725	2.0	YES
6	.2	.2	115	115	750	2.0	NO
7	.175	.225	115	115	750	2.0	NO
8	.175	.225	115	115	675	2.0	NO
9	.175	.175	100	125	700	2.0	NO
10	.2	.2	100	125	700	2.0	NO
11	.175	.175	100	75	700	2.0	YES
12	.2	.2	100	125	700	2.0	YES
13	.2	.2	100	125	700	2.0	NO
14	.2	.2	100	125	700	2.0	YES
15	.2	.2	100	100	750	2.0	NO
16	.2	.2	115	115	725	2.0	YES

Fig. 3.1 Experimental Parameters

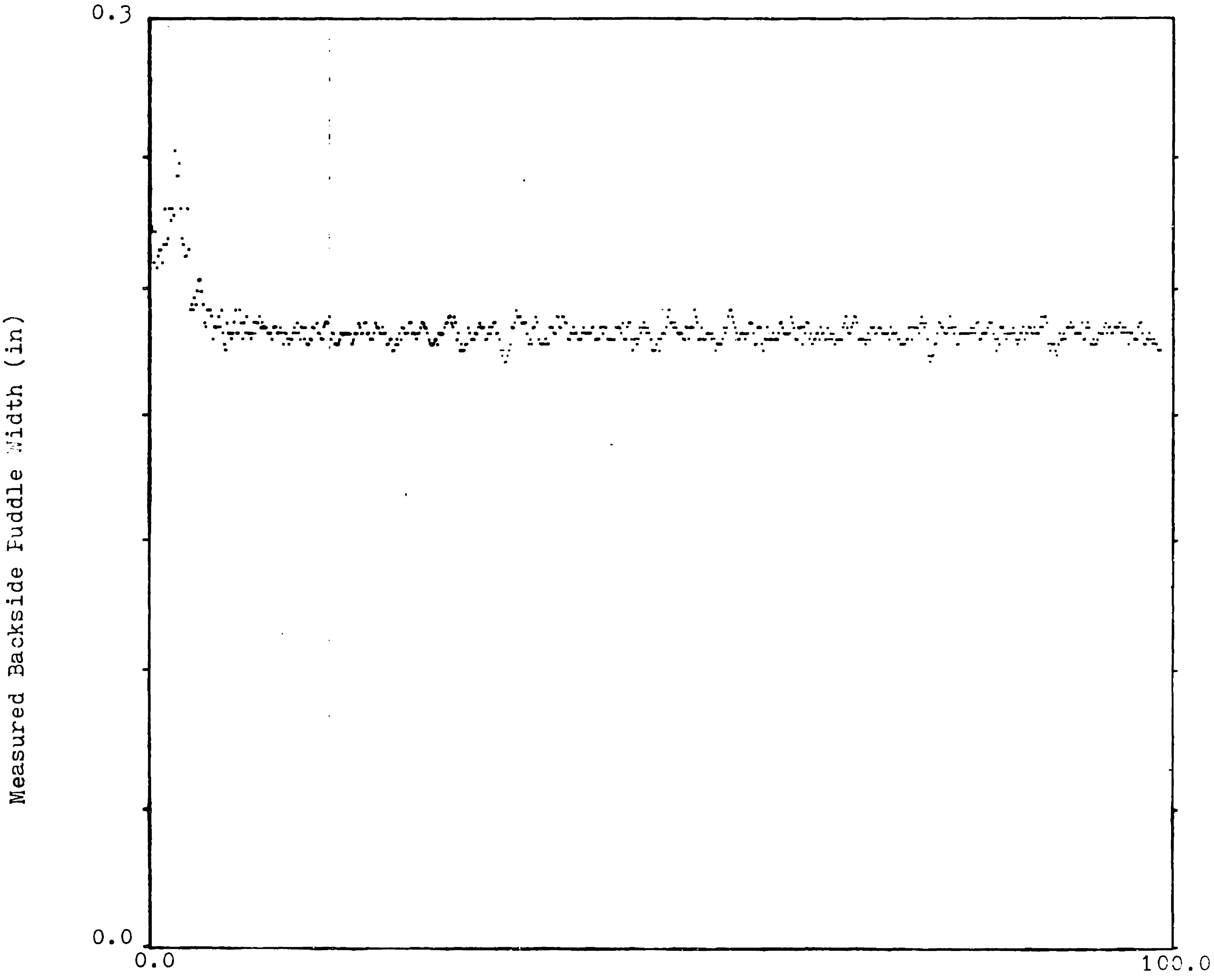


Fig. 3.2 Results of Experiment 1

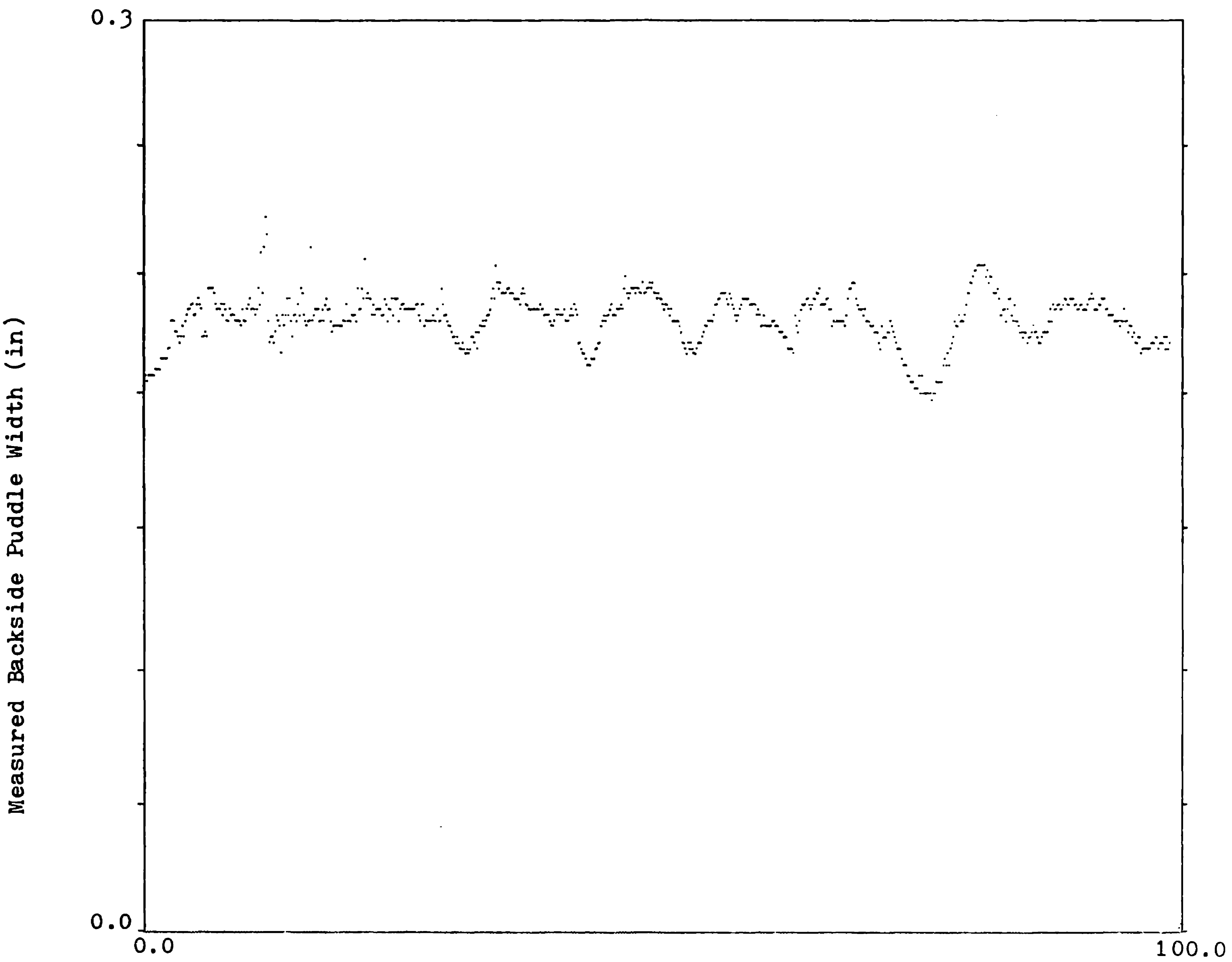


Fig. 3.3 Results of Experiment 2

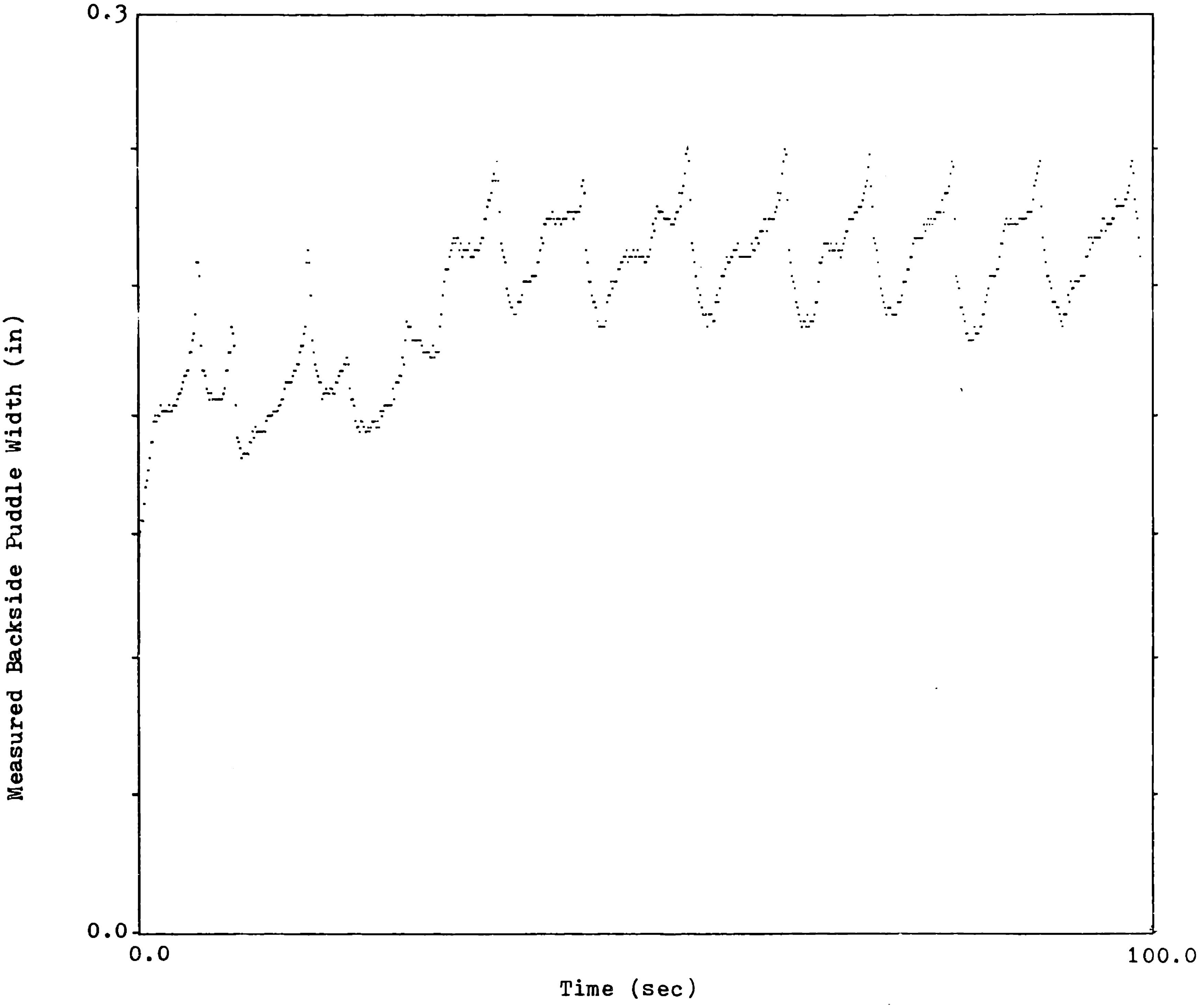


Fig. 3.4 Results of Experiment 3

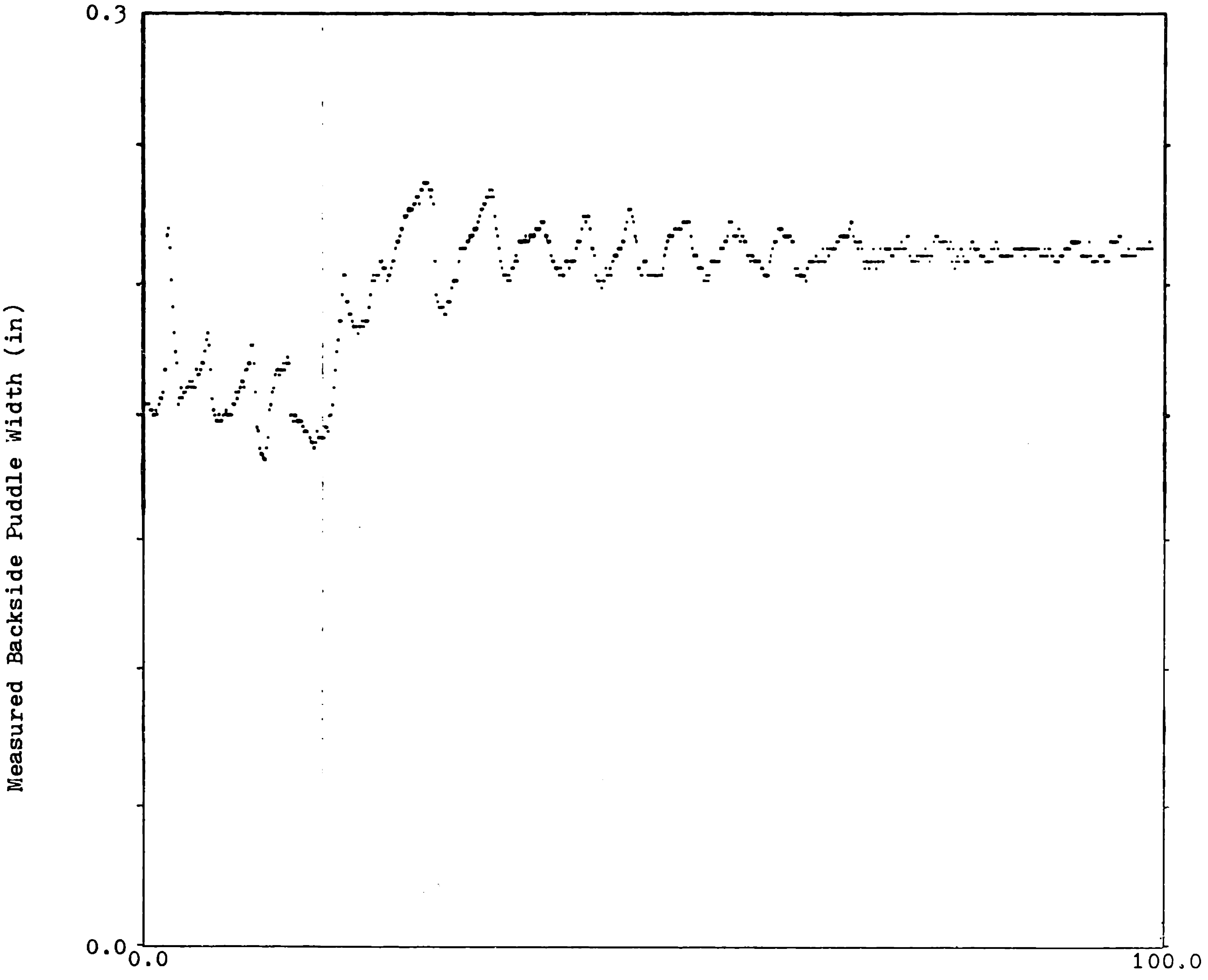


Fig. 3.5 Results of Experiment 4

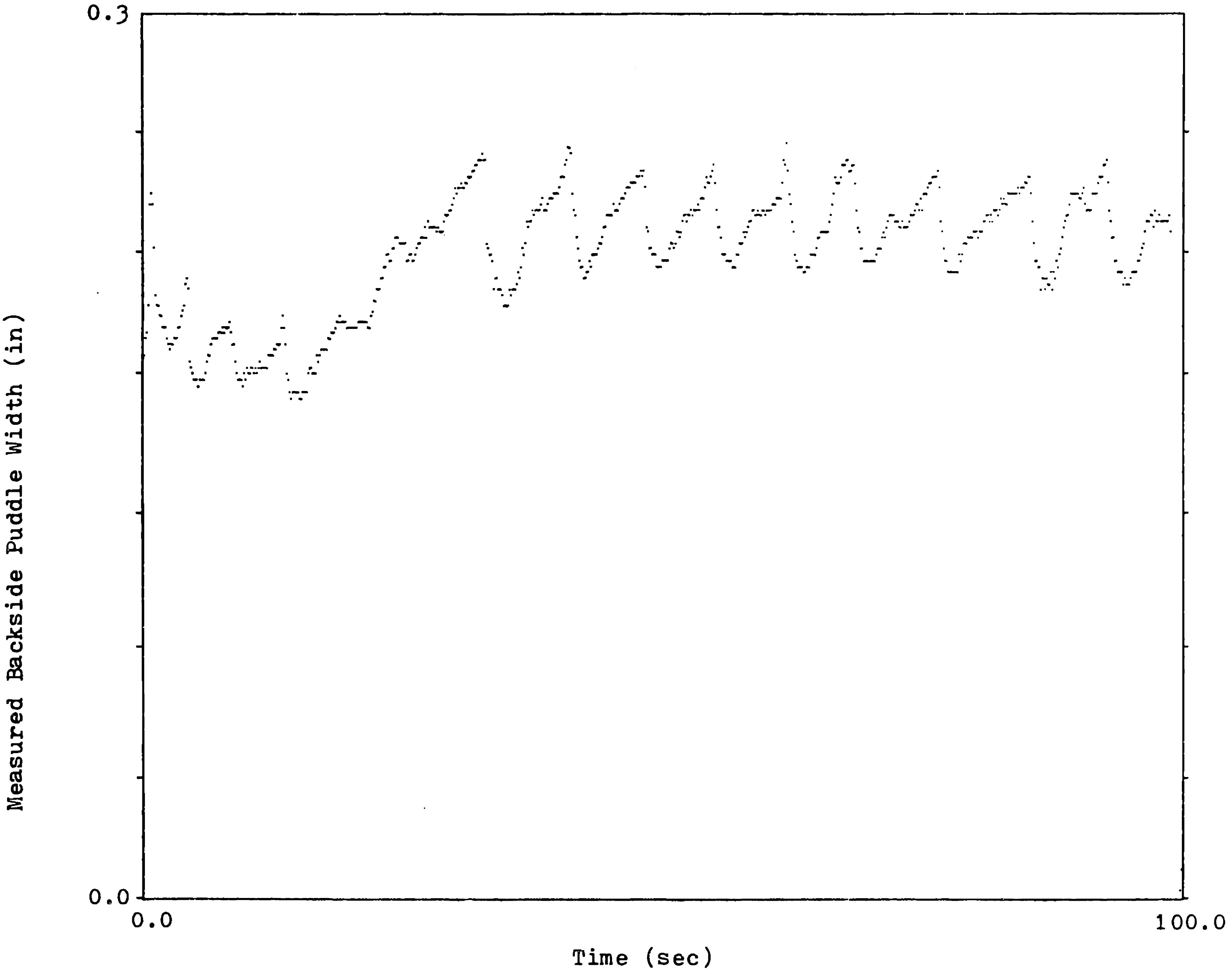


Fig. 3.6 Results of Experiment 5

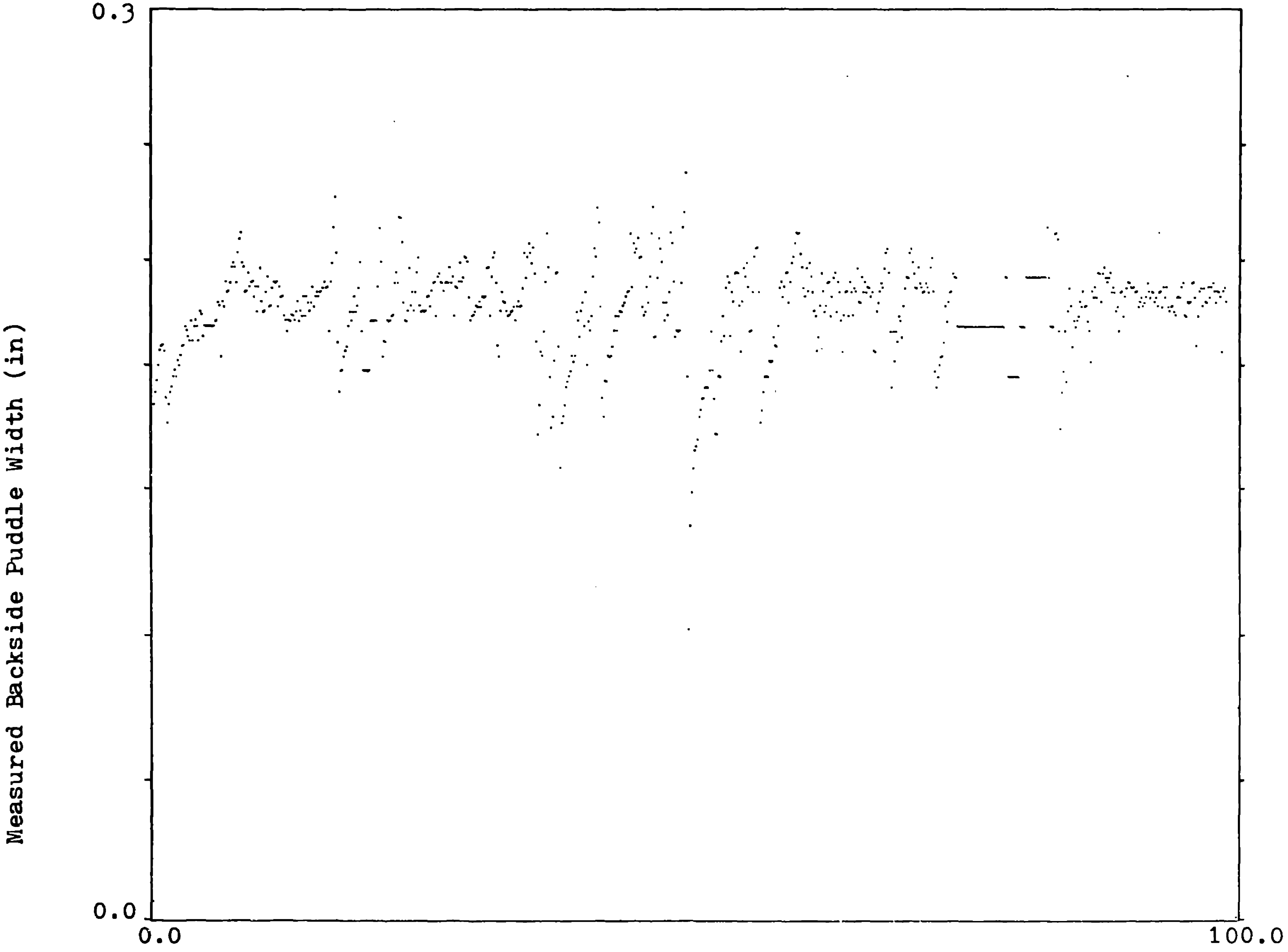


Fig. 3.7 Results of Experiment 6

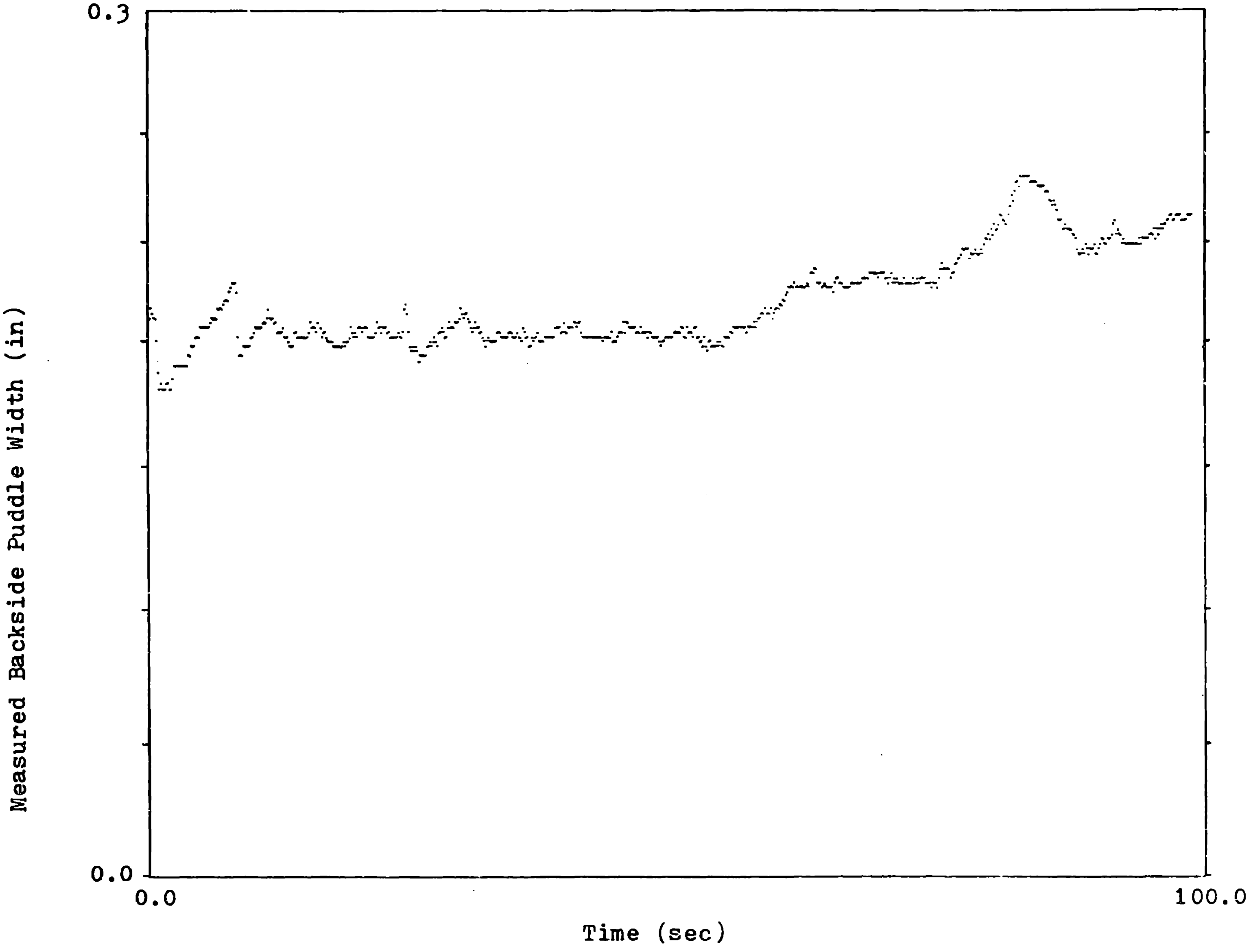


Fig. 3.8 Results of Experiment 7

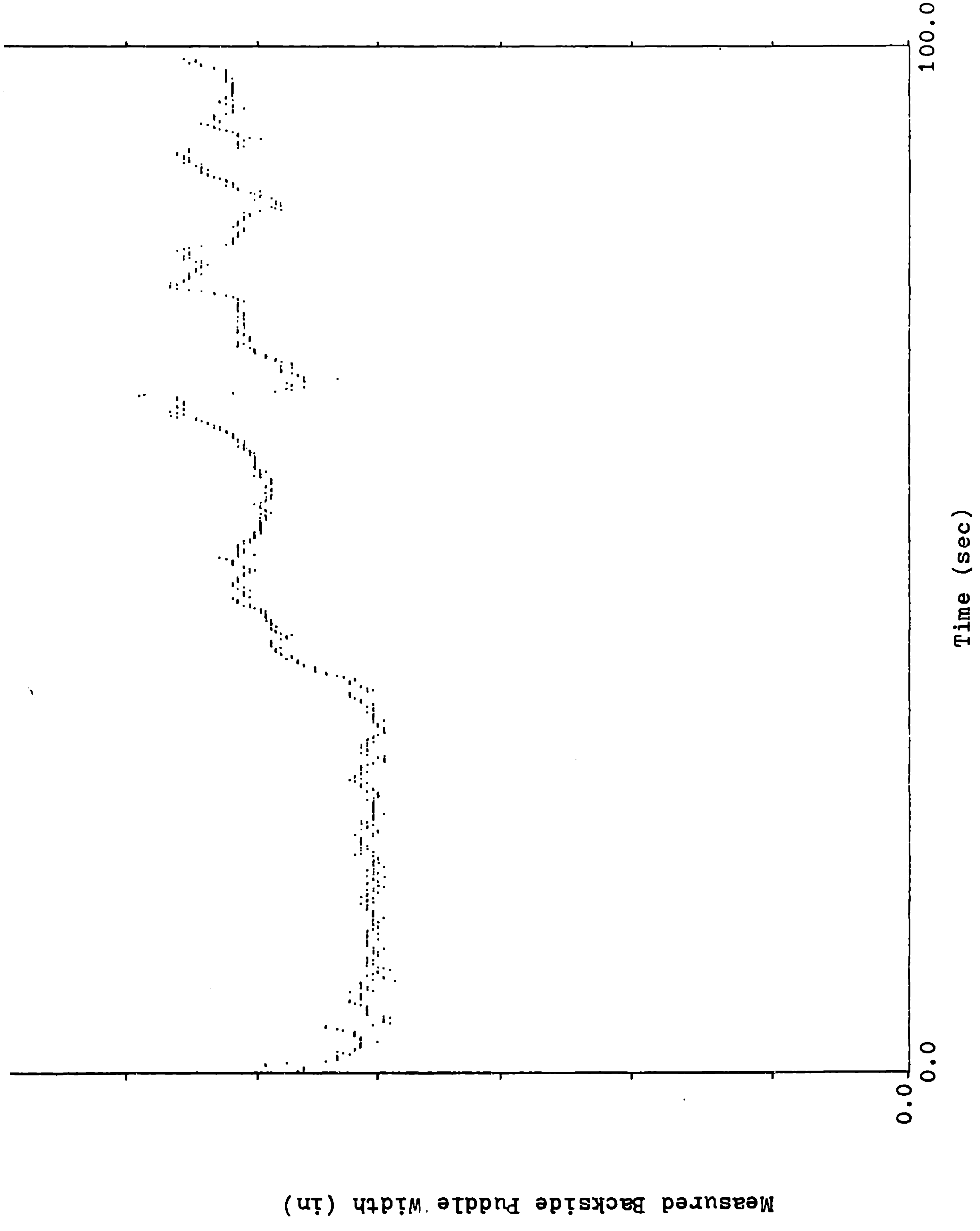


Fig. 3.9 Results of Experiment 8

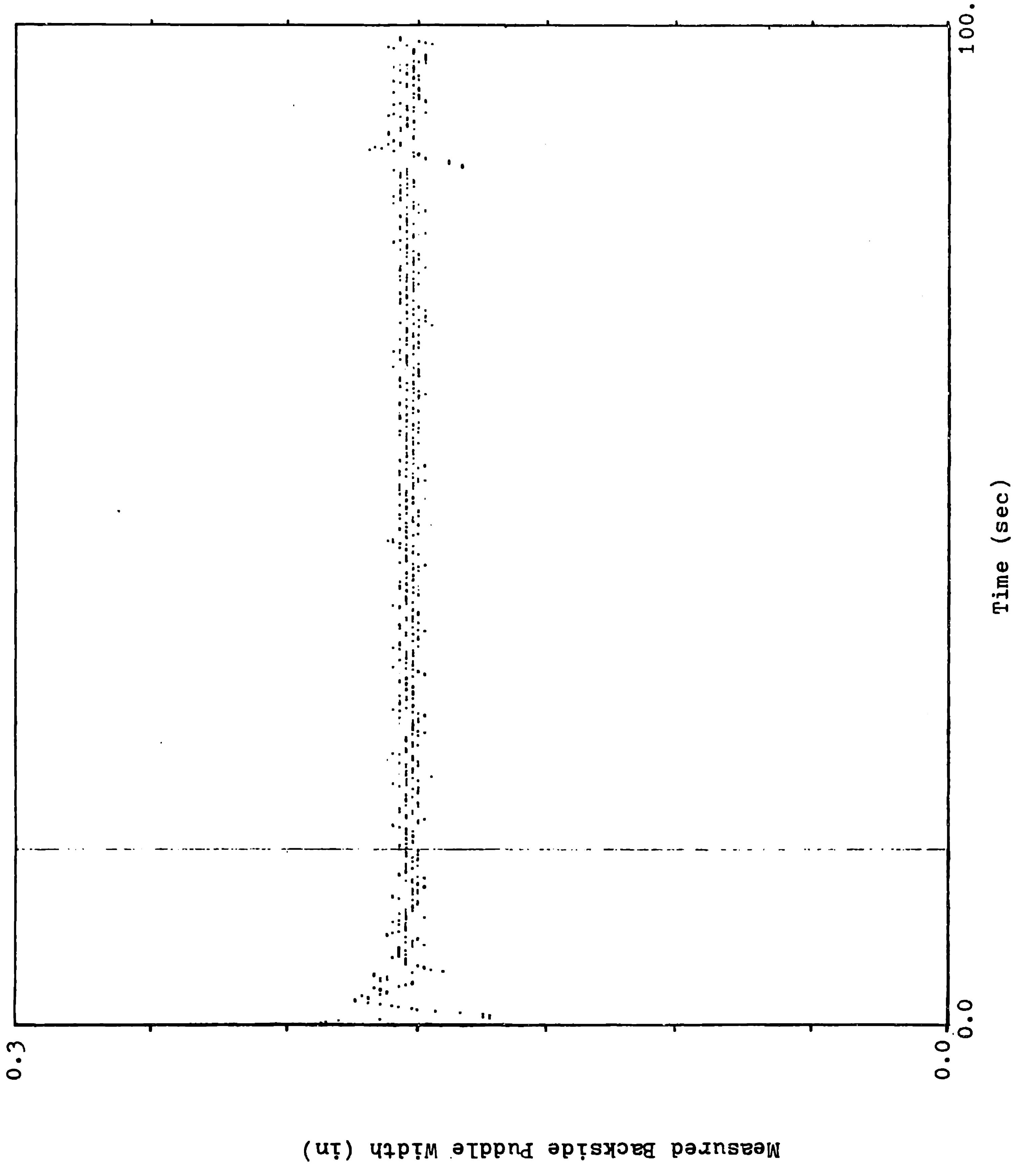


Fig. 3.10 Results of Experiment 9

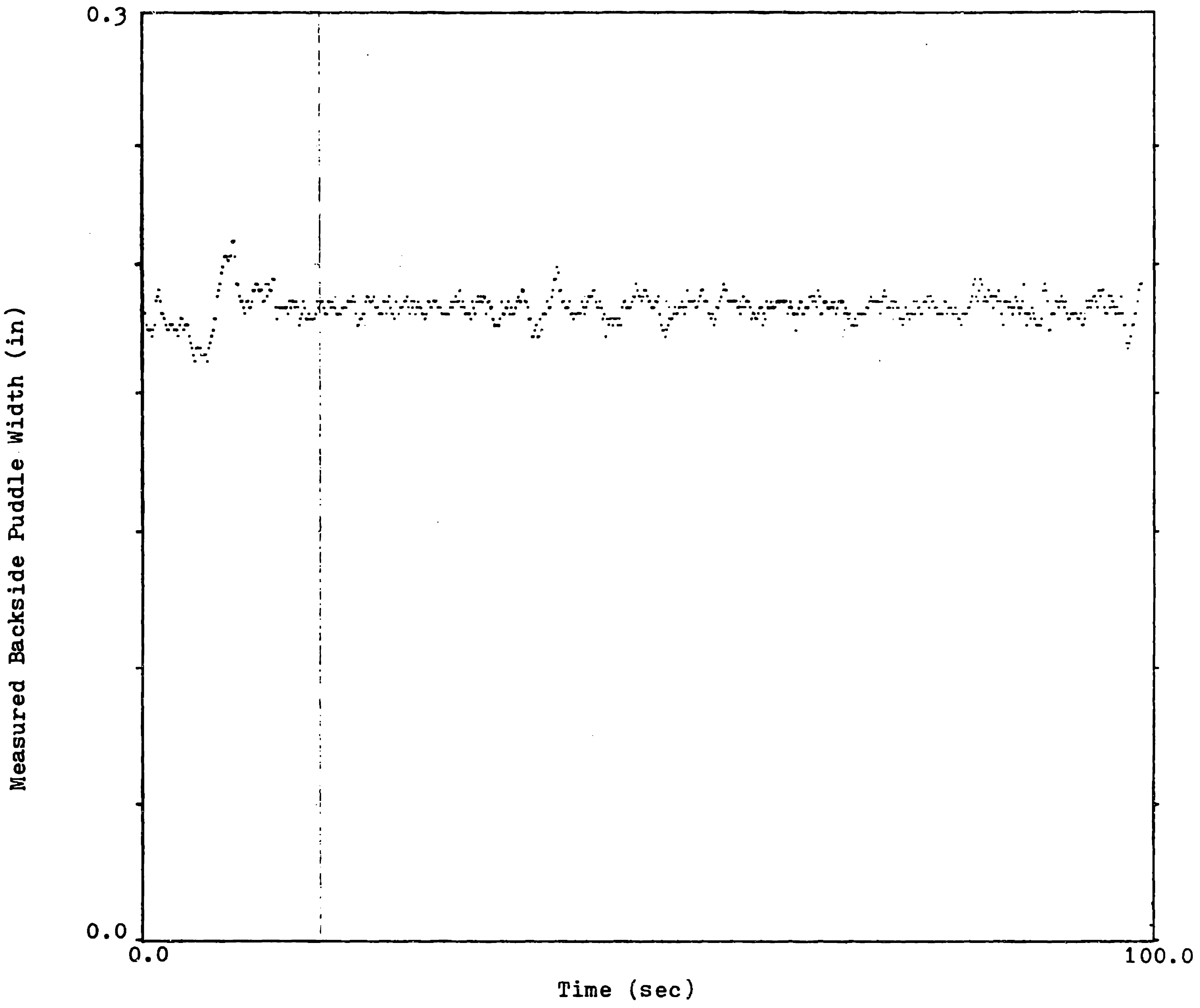


Fig. 3.11 Results of Experiment 10

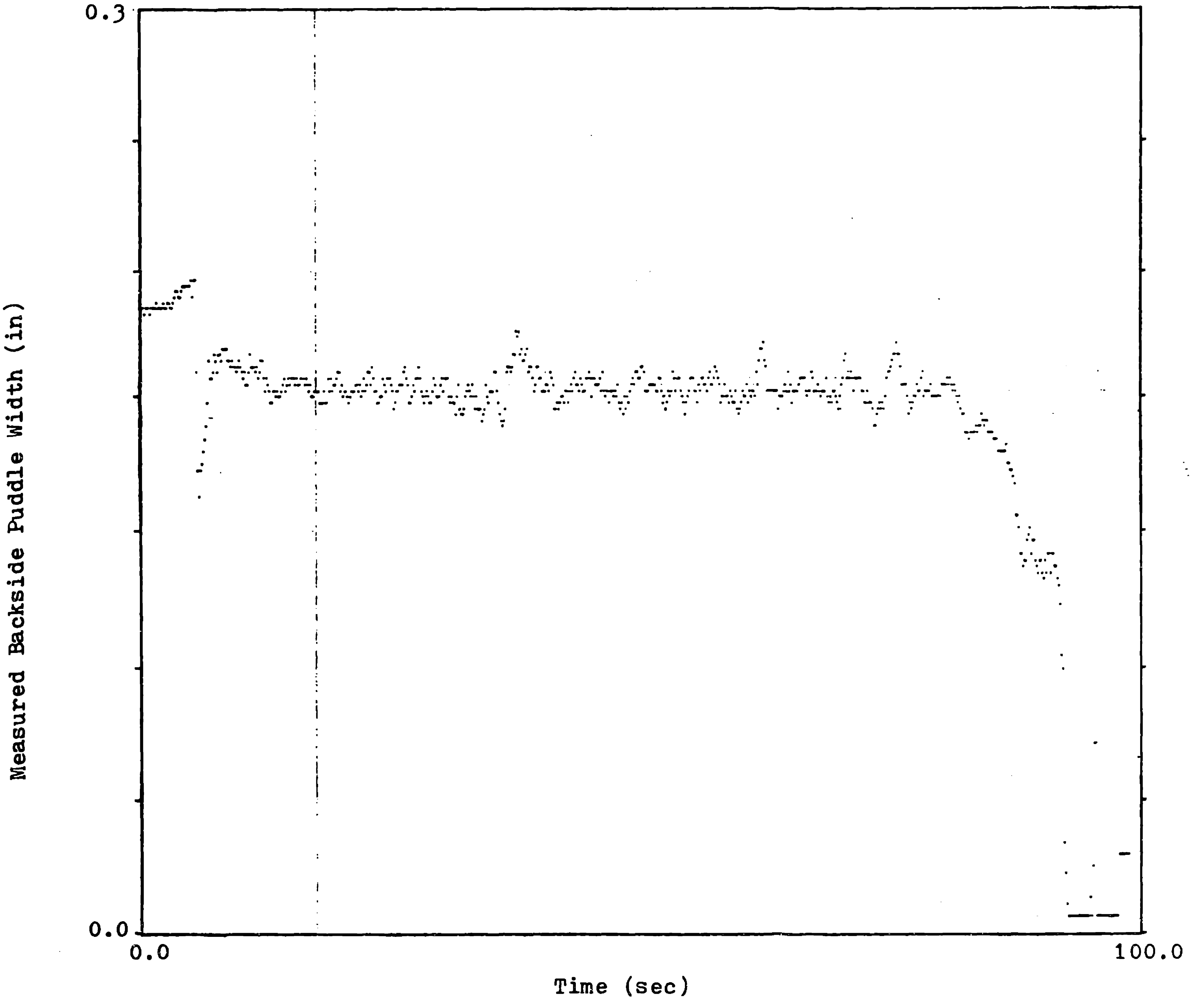


Fig. 12 Results of Experiment 11

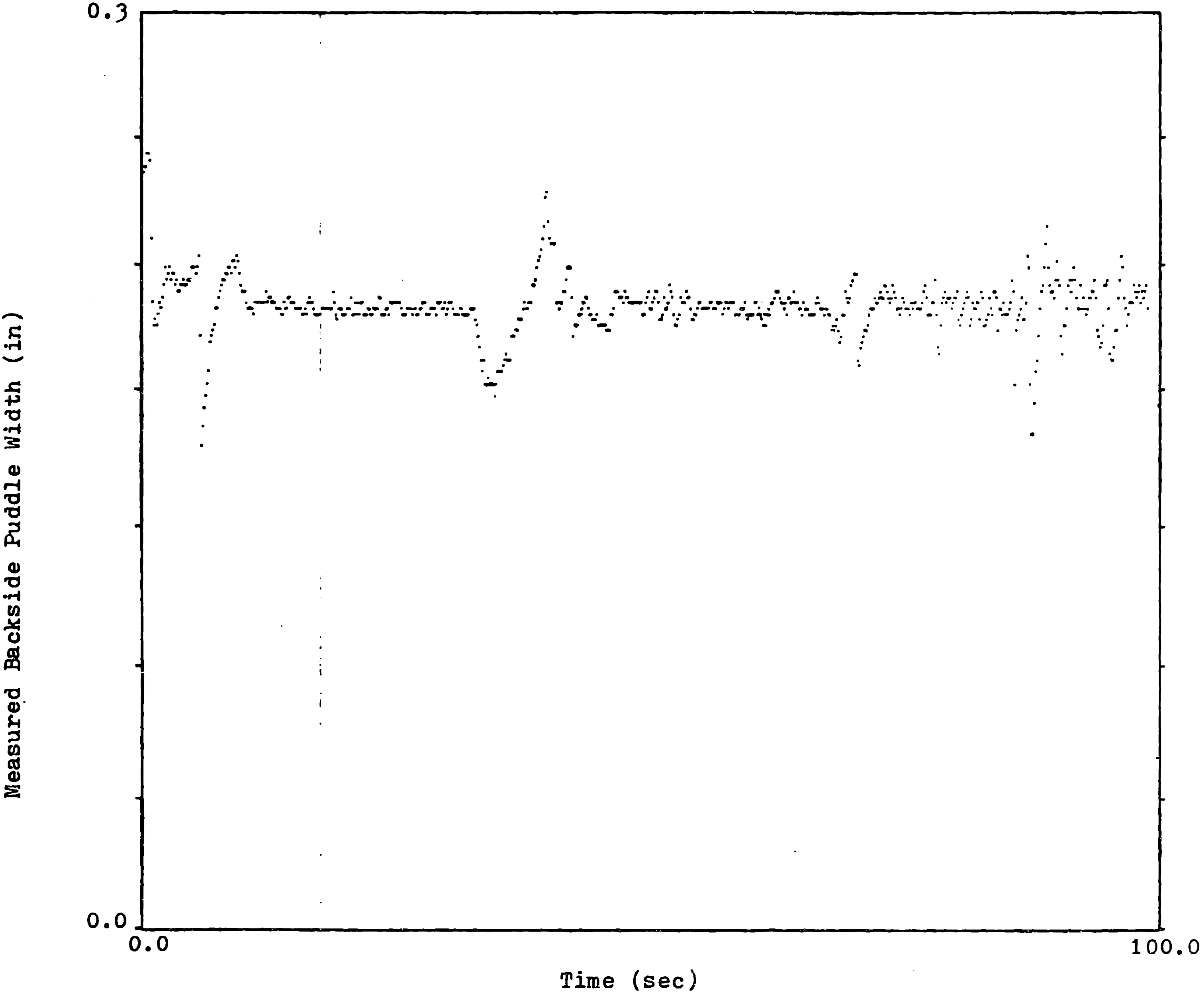
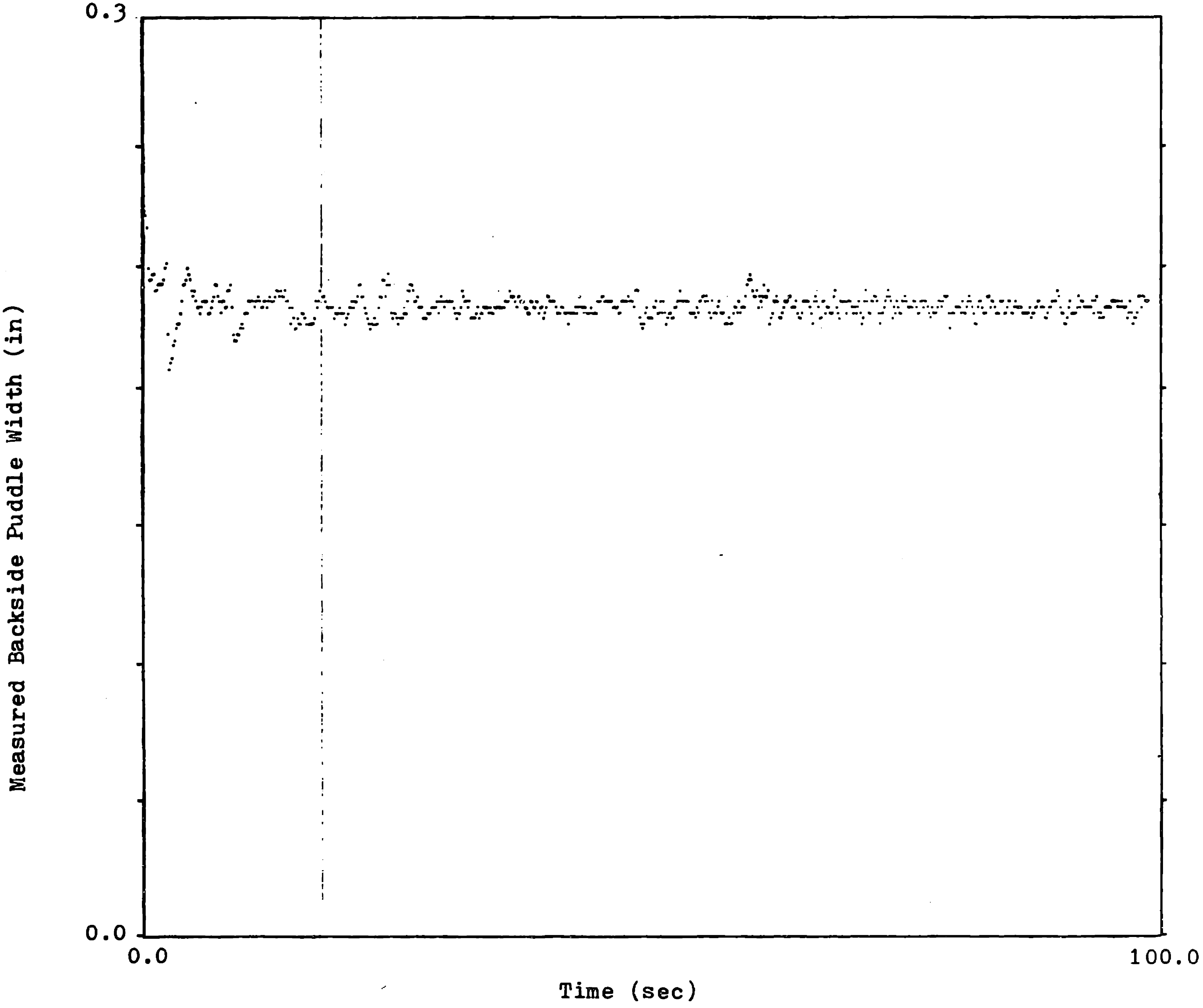


Fig. 3.13 Results of Experim


0.3
0.0
0.0
100.0
Measured Backside Puddle Width (in)
Time (sec)

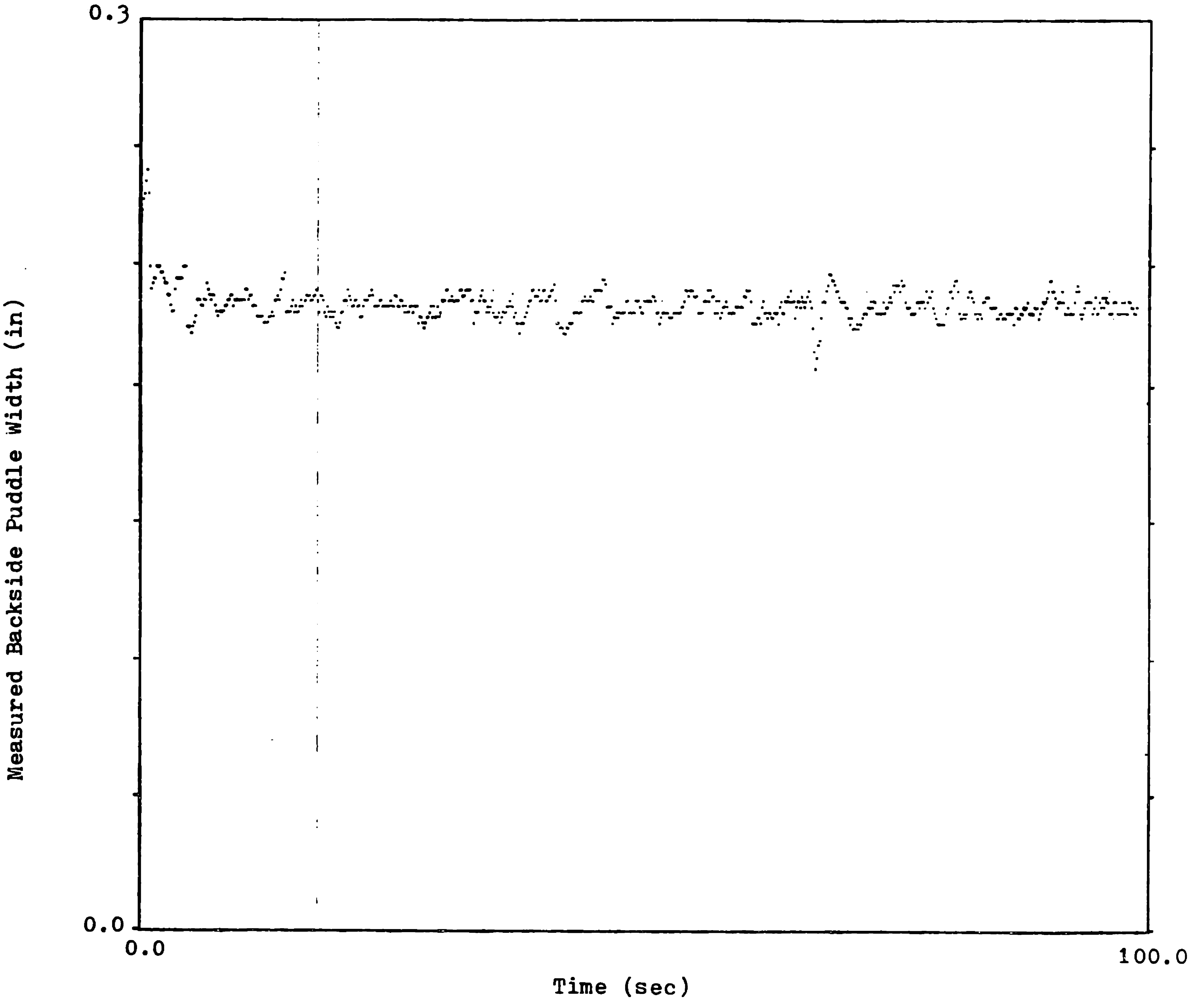


Fig. 3.15 Results of Experiment 14

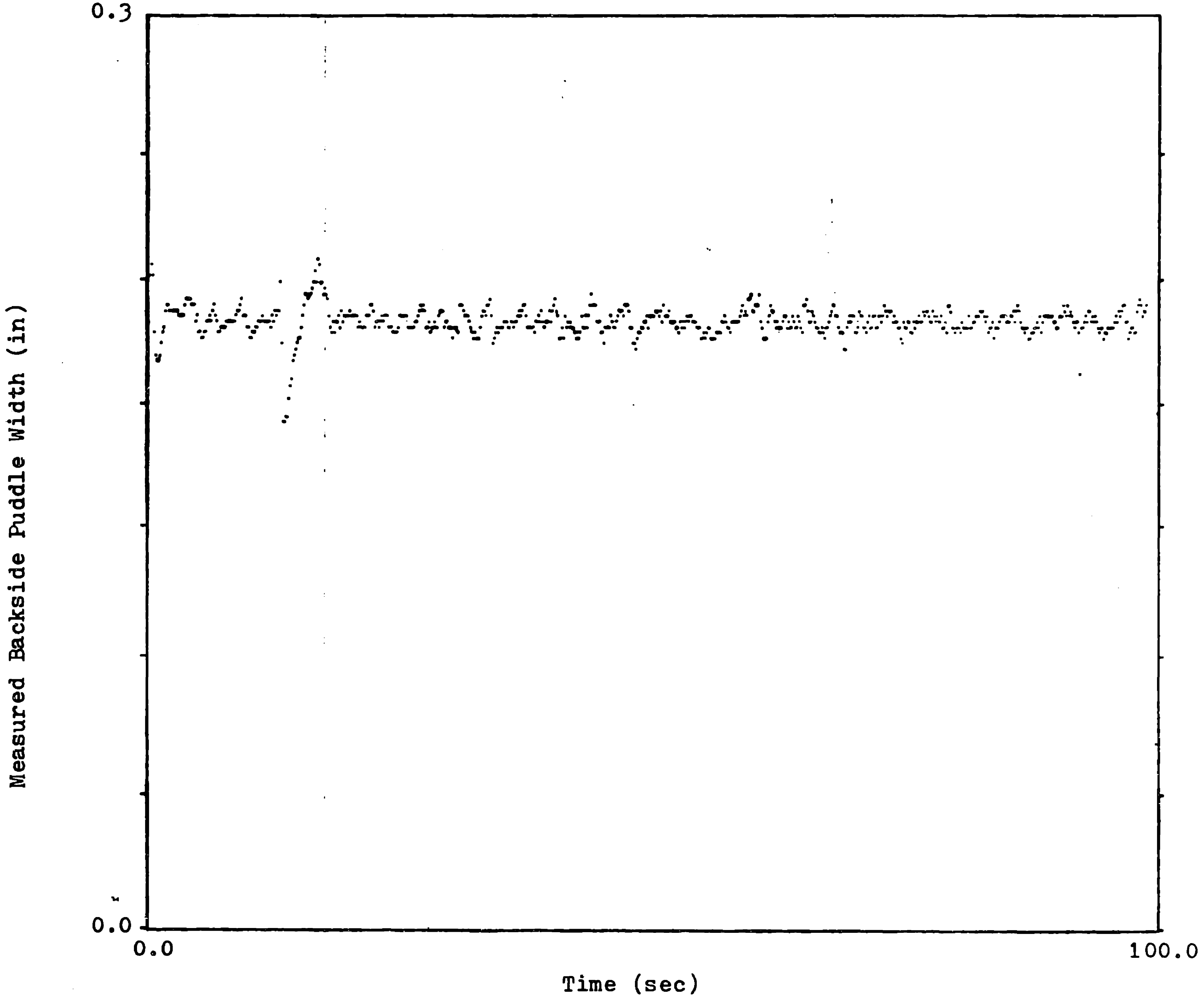


Fig. 3.16 Results of Experiment 15

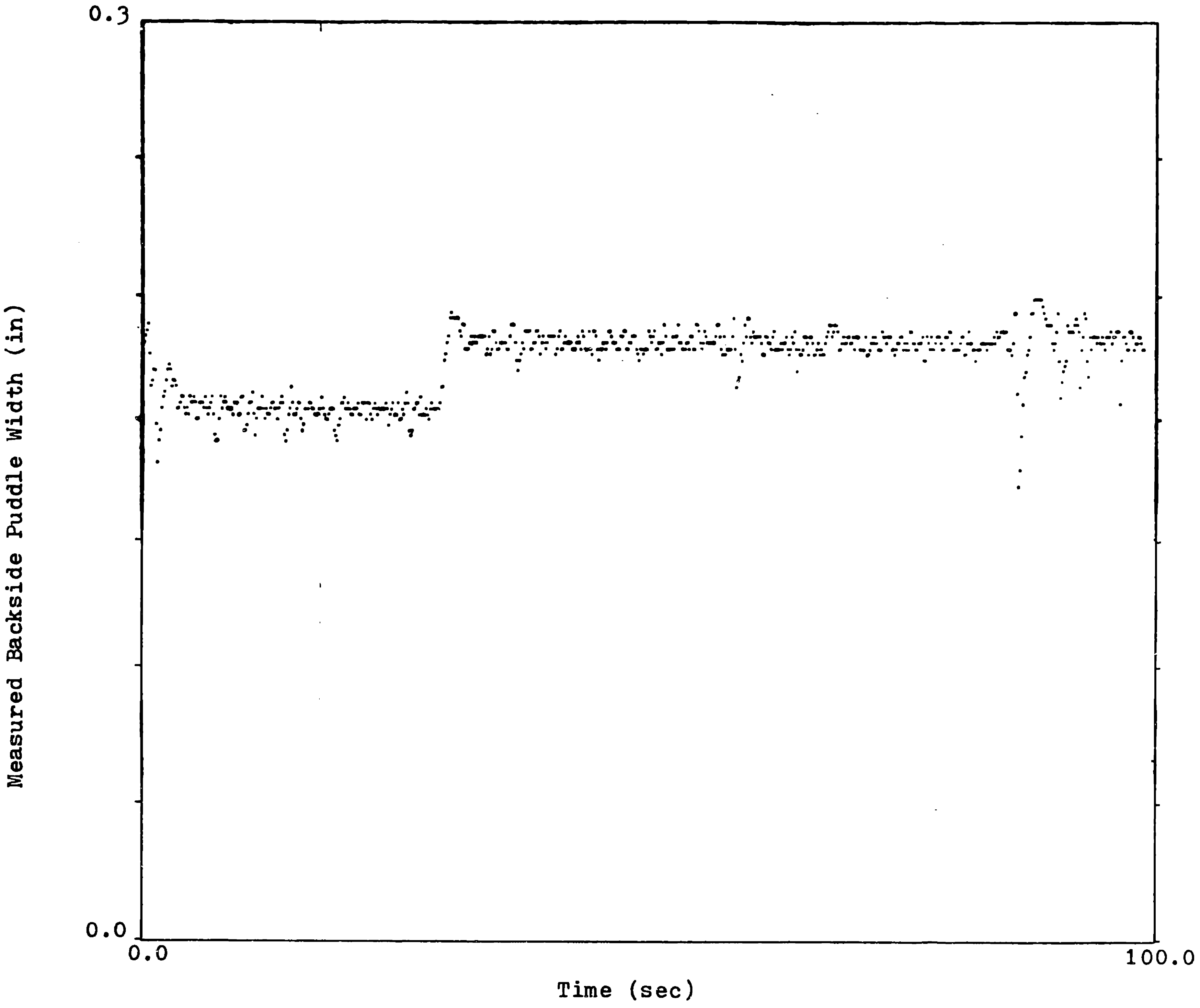


Fig. 3.17 Results of Experiment 16

APPENDIX A

```
        PROGRAM WOUT
        WRITE(5,100)
100     FORMAT( 'RESOLUTION?')
        READ(5,110) IRES
        WRITE(5,105)
105     FORMAT( 'ROW TO BE SCANNED?')
        READ(5,110) IROW
        WRITE(5,106)
106     FORMAT( 'CUTOFF GRAY LEVEL (0-14)?')
        READ(5,110) ICUTR
110     FORMAT(2I5)
        WRITE(5,111)
111     FORMAT( 'OUTPUT PORT NUMBER?')
        READ(5,110) IPORT
        WRITE(5,112)
112     FORMAT( 'TIMING FOR DMA?')
        READ(5,110) ITIME
        I1=2**15+(IROW*IRES)/2
        I2=I1+IRES/2
        ICUTL=16*ICUTR
1000    CALL OUT(IDMA,ION)
        DO 1100 J=1,ITIME
1100    CONTINUE
        CALL OUT(IDMA,IOFF)
        IW1=0
        IW2=0
        DO 200 I=I1,I2
        IBYTE=PEEK(I)
        IF (IBYTE.LT.0) IBYTE=IBYTE+256
        IF (IBYTE.GT.ICUTL) GO TO 300
        IF((IBYTE.AND.15).GT.ICUTR) GO TO 310
200     CONTINUE
300     IW1=1
310     I3=I2
        DO 400 K=1,I3
        IBYTE=PEEK(I+K)
        IF (IBYTE.LT.0) IBYTE=IBYTE+256
        IF (IBYTE.LT.ICUTL) GO TO 505
        IF((IBYTE.AND.15).LT.ICUTR) GO TO 500
500     IW2=1
505     IWIDTH=2*(K-1)+IW1+IW2
        IWIDTH=IWIDTH*256/IRES
        CALL OUT(IPORT,IWIDTH)
        GO TO 1000
        END
```

APPENDIX B

```
      WRITE(5,900)
900   FORMAT(' DATA DISK MUST BE IN DRIVE A BEFORE',/,
     *        ' RUNNING THIS PROGRAM IF IT IS DESIRED',/,
     *        ' TO SAVE DATA',//)
      DSTINT=4.0
      DFREQ=34.0
      DWD1=0.0
      DWD2=0.0
      NUM=0
      DKM=.015
      DTM=3.0
      DKC=0.0
      DTI=0.0
      DKPROP=0.0
      DK=0.0
      DKF=1.0
      DTF=.016
      DEMAX=.02
      DWERR=.02
      DKD=1.0
50    DO 100 I=1,3
      WMS(I)=0.0
      E(I)=0.0
      WS(I)=0.0
100   CONTINUE
      DO 110 I=1,1000
      IPOS(I)=0
      INV(I)=0
      IWIDTH(I)=0
110   CONTINUE
      CALL MOTION(IOFSET)
      WRITE(5,1000)
1000  FORMAT(///,' SET POSITION TO 0',/,
     *        ' PRESS <CR> TO CHECK POSITION',/,
     *        '          OR',/,
     *        ' PRESS <1><CR> TO CONTINUE',//)
150   READ(5,1100) ICONT
1100  FORMAT(I6)
      IF(ICONT.EQ.1) GO TO 200
      CALL INPUT(I)
      WRITE(5,1200) I
1200  FORMAT(' POSITION = ',I6,//)
      GO TO 150
200   WRITE(5,1300)
1300  FORMAT(' ENTER SYSTEM PARAMATERS',/,
     *        ' ALL NUMBERS ENTERED MUST BE REAL NUMBERS',/,
     *        ' IF THE DEFAULT VALUE IS DESIRED ENTER <0.>',/)
1400  FORMAT(F10.4)
1450  FORMAT(' ENTER DATA STORE INTERVAL (DEFAULT=',F10.4,')')
1500  FORMAT(' ENTER SAMPLING FREQUENCY  (DEFAULT=',F10.4,')')
1600  FORMAT(' ENTER WD1 (DEFAULT=',F10.4,')')
```

```
1700  FORMAT(' ENTER WD2 (DEFAULT=',F10.4,')')
1800  FORMAT(' ENTER KM  (DEFAULT=',F10.4,')')
1900  FORMAT(' ENTER TM  (DEFAULT=',F10.4,')')
2000  FORMAT(' ENTER KC  (DEFAULT=',F10.4,')')
2100  FORMAT(' ENTER TI  (DEFAULT=',F10.4,')')
2200  FORMAT(' ENTER KPROP (DEFAULT=',F10.4,')')
2300  FORMAT(' ENTER K   (DEFAULT=',F10.4,')')
2400  FORMAT(' ENTER KF  (DEFAULT=',F10.4,')')
2500  FORMAT(' ENTER TF  (DEFAULT=',F10.4,')')
2550  FORMAT(' ENTER EMAX(DEFAULT=',F10.4,')')
2570  FORMAT(' ENTER WERR(DEFAULT=',F10.4,')')
2575  FORMAT(' ENTER KD(DEFAULT=',F10.4,')')
2600  FORMAT(//,' INT =',F10.4,/,' FREQ=',F10.4,/,' WD1 =',F10.4,/,
     *        ' WD2 =',F10.4,/,' KM  =',F10.4,/,' TM  =',F10.4,/,
     *        ' KC  =',F10.4,/,' TI  =',F10.4,/,' KPROP=',F10.4,/,
     *        ' K   =',F10.3,/,' KF  =',F10.4,/,' TF  =',F10.4,/,
     *        ' EMAX=',F10.4,/,' WERR=',F10.4,/,' KD=',F10.4,//)
2650  FORMAT(' IF PARAMATERS ARE CORRECT - TYPE <1><CR>',/,
     *        ' IF YOU WANT TO CHANGE PARAMATERS - TYPE <CR>',//)
250   WRITE(5,1450) DSTINT
      READ(5,1400) STINT
      IF(STINT.EQ.0.0) STINT=DSTINT
      DSTINT=STINT
      WRITE(5,1500) DFREQ
      READ(5,1400) FREQ
      IF(FREQ.EQ.0.0) FREQ=DFREQ
      DFREQ=FREQ
      WRITE(5,1600) DWD1
      READ(5,1400) WD1
      IF(WD1.EQ.0.0) WD1=DWD1
      DWD1=WD1
      WRITE(5,1700) DWD2
      READ(5,1400) WD2
      IF(WD2.EQ.0.0) WD2=DWD2
      DWD2=WD2
      WRITE(5,1800) DKM
      READ(5,1400) KM
      IF(KM.EQ.0.0) KM=DKM
      DKM=KM
      WRITE(5,1900) DTM
      READ(5,1400) TM
      IF(TM.EQ.0.0) TM=DTM
      DTM=TM
      WRITE(5,2000) DKC
      READ(5,1400) KC
      IF(KC.EQ.0.0) KC=DKC
      DKC=KC
      WRITE(5,2100) DTI
      READ(5,1400) TI
      IF(TI.EQ.0.0) TI=DTI
      DTI=TI
      WRITE(5,2200) DKPROP
      READ(5,1400) KPROP
      IF(KPROP.EQ.0.0) KPROP=DKPROP
      DKPROP=KPROP
```

```
      READ(5,1400) K
      IF(K.EQ.0.0) K=DK
      DK=K
      WRITE(5,2400) DKF
      READ(5,1400) KF
      IF(KF.EQ.0.0) KF=DKF
      DKF=KF
      WRITE(5,2500) DTF
      READ(5,1400) TF
      IF(TF.EQ.0.0) TF=DTF
      DTF=TF
      WRITE(5,2550) DEMAX
      READ(5,1400) EMAX
      IF(EMAX.EQ.0.0) EMAX=DEMAX
      DEMAX=EMAX
      WRITE(5,2570) DWERR
      READ(5,1400) WERR
      IF(WERR.EQ.0.0) WERR=DWERR
      DWERR=WERR
      WRITE(5,2575)DKD
      READ(5,1400)AKD
      IF(AKD.EQ.0.0) AKD=DKD
      DKD=AKD
      WRITE(5,2600) STINT,FREQ,WD1,WD2,KM,TM,KC,TI,KPROP,K,
     *KF,TF,EMAX,WERR,AKD
      WRITE(5,2650)
      READ(5,1100) ICONT
      IF(ICONT.EQ.0) GO TO 250
      T=1.0/FREQ
      INT=IFIX(STINT)
      C1=KM*AKD*KF*(1.0-EXP(-T/TF))*(1.0-EXP(-T/TM))
      C2=EXP(-T/TM)+EXP(-T/TF)
      C4=KC*(TI+1.0/FREQ)
      C5=-(KC)*TI
      WRITE(5,2605)
      C3=-EXP(-T/TM-T/TF)
      C7=(KM*AKD)/TM
      C8=EXP(-T/TM)
2605  FORMAT(' INPUT VINVC(INITIAL): ')
      READ(5,1400) VINVC(2)
      DO 255 I=1,3
      WS(I)=WD1
      WMS(I)=WD1
255   CONTINUE
      POS=0.0
      VINV=10000.0
      WD=WD1
      WRITE(5,2610)
2610  FORMAT(//,' 1)  START ARC',/,
     *       ' 2)  WAIT FOR PUDDLE TO REACH DESIRED WIDTH',/,
     *       ' 3)  TYPE <CR> TO START CONTROL',//)
      READ(5,1100) ICONT
      DO 500 I=0,4000
      POS=POS+1.0/VINV/FREQ
      IF(POS.GT.4.0) WD=WD2
256   CALL OUT(214,0)
```

```
         ICHK=INP(214)
         IF (ICHK.AND.8) GO TO 256
NP(211)            IF (IWIRTH.LT.0) IWIRTH=IWIRTH+256
         WS(1)=(FLOAT(IWIRTH))*AKD
         IF(I.LT.100) GO TO 280
         WERRM=-(WERR)
         WERR1=WS(1)-WS(2)
         WERR2=WS(2)-WS(3)
         IF(WERR2.LT.WERR) GO TO 260
         IF(WERR1.LT..01)  GO TO 270
         WS(2)=WS(3)+WERR
         GO TO 280
    260  IF(WERR2.GT.WERRM) GO TO 280
         IF(WERR1.GT..01) GO TO 270
         WS(2)=WS(3)+WERRM
         GO TO 280
    270  WS(2)=WS(3)
    280  E(1)=WD-WS(2)
         IF(KPROP.NE.0.0) GO TO 290
         VINVC(1)=VINVC(2)+C4*E(1)+C5*E(2)
         GO TO 295
    290  VINVC(1)=KPROP*E(1)
    295  IF(VINVC(1).LT..781) VINVC(1)=.781
         IF(VINVC(1).GT.100.) VINVC(1)=100.
         WMS(1)=C7*VINVC(2)+C8*WMS(2)
         ERROR=WMS(1)-WS(2)
         IF(ERROR.GT.EMAX) WMS(1)=WS(2)+EMAX
         IF(ERROR.LT.EMAX) WMS(1)=WS(2)-EMAX
         VINV=K*(WMS(1)-WS(2))+VINVC(1)
         IF(VINV.LT..781) VINV=.781
         IF(VINV.GT.100.) VINV=100.
         IVEL=IFIX(523.344/VINV+FLOAT(IOFSET))
         CALL OUTPUT(IVEL)
         DO 300 L=1,2
         M=4-L
         N=3-L
         VINVC(M)=VINVC(N)
         WMS(M)=WMS(N)
         E(M)=E(N)
         WS(M)=WS(N)
    300  CONTINUE
         ISAVE=I/INT+1
         IF(ISAVE.GT.1000) ISAVE=1000
         IPOS(ISAVE)=IFIX(POS*1000.0)
         INV(ISAVE)=IFIX(VINV*100.0)
         IWIDTH(ISAVE)=IFIX(WS(3)*1000.0)
    500  CONTINUE
    600  WRITE(5,2700)
   2700  FORMAT(' CONTROL HAS STOPPED',//)
         WRITE(5,2800)
   2800  FORMAT(' DO YOU WISH TO SAVE DATA?',/,
```

```
      CALL NAMEIN(NAME)
      CALL OPEN(9,NAME,1)
      WRITE(9) ISAVE,KC,TI,KPROP,K,KM,TM,WD1,WD2,FREQ,INT
      WRITE(9) (IPOS(N),INV(N),IWIDTH(N),N=1,ISAVE),WERR,EMAX
      ENDFILE 9
700   GO TO 50
      END
```

REFERENCES

1. Reiff, John, "Closed-Loop Control of Backside Puddle Width in the Gas Tungsten Arc Welding Process", S.M. Thesis, Department of Mechanical Engineering, M.I.T., December 1982.

2. Garlow, David, "Closed-Loop Control of Full Penetration Welds Using Optical Sensing of Backbead Width", S.M. Thesis, Department of Mechanical Engineering, M.I.T., June 1982.

3. Weinert, John, "A Model of Back Bead Width Dynamics for Full Penetration Weld Control", S.M. Thesis, Department of Mechanical Engineering, M.I.T., March 1983.

4. Ogata, K., Modern Control Engineering, Prentice-Hall, 1970.

5. Tsai, Nun Sian, "Heat Distribution and Weld Bead Geometry in Arc Welds", Ph.D. Thesis, M.I.T., Department of Materials Science and Engineering, May 1983.

APPENDIX B

```
      PROGRAM RDAPT
      DIMENSION IPOS(1000),INV(1000),IWIDTH(1000),VINVC(3),
     *WMS(3),E(3),WS(3)
      REAL KM,KF,K,KC,KPROP
      BYTE NAME(11)
      WRITE(5,900)
900   FORMAT(' DATA DISK MUST BE IN DRIVE A BEFORE',/,
     *         ' RUNNING THIS PROGRAM IF IT IS DESIRED',/,
     *         ' TO SAVE DATA',//)
      DSTINT=4.0
      DFREQ=34.0
      DWD1=0.0
      DWD2=0.0
      NUM=0
      DKM=.015
      DTM=3.0
      DKC=0.0
      DTI=0.0
      DKPROP=0.0
      DK=0.0
      DKF=1.0
      DTF=.016
      DEMAX=.02
      DWERR=.02
      DKD=1.0
50    DO 100 I=1,3
      WMS(I)=0.0
      E(I)=0.0
      WS(I)=0.0
100   CONTINUE
      DO 110 I=1,1000
      IPOS(I)=0
      INV(I)=0
      IWIDTH(I)=0
110   CONTINUE
      CALL MOTION(IOFSET)
      WRITE(5,1000)
1000  FORMAT(///,' SET POSITION TO 0',/,
     *         ' PRESS <CR> TO CHECK POSITION',/,
     *         '           OR',/,
     *         ' PRESS <1><CR> TO CONTINUE',//)
150   READ(5,1100) ICONT
1100  FORMAT(I6)
      IF(ICONT.EQ.1) GO TO 200
      CALL INPUT(I)
      WRITE(5,1200) I
1200  FORMAT(' POSITION = ',I6,//)
      GO TO 150
200   WRITE(5,1300)
1300  FORMAT(' ENTER SYSTEM PARAMATERS',/,
     *         ' ALL NUMBERS ENTERED MUST BE REAL NUMBERS',/,
     *         ' IF THE DEFAULT VALUE IS DESIRED ENTER <0.>',/)
1400  FORMAT(F10.4)
1450  FORMAT(' ENTER DATA STORE INTERVAL (DEFAULT=',F10.4,')')
1500  FORMAT(' ENTER SAMPLING FREQUENCY  (DEFAULT=',F10.4,')')
1600  FORMAT(' ENTER WD1 (DEFAULT=',F10.4,')')
```

```
1700  FORMAT(' ENTER WD2 (DEFAULT=',F10.4,')')
1800  FORMAT(' ENTER KM  (DEFAULT=',F10.4,')')
1900  FORMAT(' ENTER TM  (DEFAULT=',F10.4,')')
2000  FORMAT(' ENTER KC  (DEFAULT=',F10.4,')')
2100  FORMAT(' ENTER TI  (DEFAULT=',F10.4,')')
2200  FORMAT(' ENTER KPROP (DEFAULT=',F10.4,')')
2300  FORMAT(' ENTER K   (DEFAULT=',F10.4,')')
2400  FORMAT(' ENTER KF  (DEFAULT=',F10.4,')')
2500  FORMAT(' ENTER TF  (DEFAULT=',F10.4,')')
2550  FORMAT(' ENTER EMAX(DEFAULT=',F10.4,')')
2570  FORMAT(' ENTER WERR(DEFAULT=',F10.4,')')
2575  FORMAT(' ENTER KD(DEFAULT=',F10.4,')')
2600  FORMAT(//,' INT =',F10.4,/,' FREQ=',F10.4,/,' WD1 =',F10.4,/,
     *       ' WD2 =',F10.4,/,' KM  =',F10.4,/,' TM  =',F10.4,/,
     *       ' KC  =',F10.4,/,' TI  =',F10.4,/,' KPROP=',F10.4,/,
     *       ' K   =',F10.3,/,' KF  =',F10.4,/,' TF  =',F10.4,/,
     *       ' EMAX=',F10.4,/,' WERR=',F10.4,/,' KD=',F10.4,//)
2650  FORMAT(' IF PARAMATERS ARE CORRECT - TYPE <1><CR>',/,
     *       ' IF YOU WANT TO CHANGE PARAMATERS - TYPE <CR>',//)
250   WRITE(5,1450) DSTINT
      READ(5,1400) STINT
      IF(STINT.EQ.0.0) STINT=DSTINT
      DSTINT=STINT
      WRITE(5,1500) DFREQ
      READ(5,1400) FREQ
      IF(FREQ.EQ.0.0) FREQ=DFREQ
      DFREQ=FREQ
      WRITE(5,1600) DWD1
      READ(5,1400) WD1
      IF(WD1.EQ.0.0) WD1=DWD1
      DWD1=WD1
      WRITE(5,1700) DWD2
      READ(5,1400) WD2
      IF(WD2.EQ.0.0) WD2=DWD2
      DWD2=WD2
      WRITE(5,1800) DKM
      READ(5,1400) KM
      IF(KM.EQ.0.0) KM=DKM
      DKM=KM
      WRITE(5,1900) DTM
      READ(5,1400) TM
      IF(TM.EQ.0.0) TM=DTM
      DTM=TM
      WRITE(5,2000) DKC
      READ(5,1400) KC
      IF(KC.EQ.0.0) KC=DKC
      DKC=KC
      WRITE(5,2100) DTI
      READ(5,1400) TI
      IF(TI.EQ.0.0) TI=DTI
      DTI=TI
      WRITE(5,2200) DKPROP
      READ(5,1400) KPROP
      IF(KPROP.EQ.0.0) KPROP=DKPROP
      DKPROP=KPROP
      WRITE(5,2300) DK
```

```
      READ(5,1400) K
      IF(K.EQ.0.0) K=DK
      DK=K
      WRITE(5,2400) DKF
      READ(5,1400) KF
      IF(KF.EQ.0.0) KF=DKF
      DKF=KF
      WRITE(5,2500) DTF
      READ(5,1400) TF
      IF(TF.EQ.0.0) TF=DTF
      DTF=TF
      WRITE(5,2550) DEMAX
      READ(5,1400) EMAX
      IF(EMAX.EQ.0.0) EMAX=DEMAX
      DEMAX=EMAX
      WRITE(5,2570) DWERR
      READ(5,1400) WERR
      IF(WERR.EQ.0.0) WERR=DWERR
      DWERR=WERR
      WRITE(5,2575)DKD
      READ(5,1400)AKD
      IF(AKD.EQ.0.0) AKD=DKD
      DKD=AKD
      WRITE(5,2600) STINT,FREQ,WD1,WD2,KM,TM,KC,TI,KPROP,K,
     *KF,TF,EMAX,WERR,AKD
      WRITE(5,2650)
      READ(5,1100) ICONT
      IF(ICONT.EQ.0) GO TO 250
      T=1.0/FREQ
      INT=IFIX(STINT)
      C1=KM*AKD*KF*(1.0-EXP(-T/TF))*(1.0-EXP(-T/TM))
      C2=EXP(-T/TM)+EXP(-T/TF)
      C4=KC*(TI+1.0/FREQ)
      C5=-(KC)*TI
      WRITE(5,2605)
      C3=-EXP(-T/TM-T/TF)
      C7=(KM*AKD)/TM
      C8=EXP(-T/TM)
2605  FORMAT(' INPUT VINVC(INITIAL): ')
      READ(5,1400) VINVC(2)
      DO 255 I=1,3
      WS(I)=WD1
      WMS(I)=WD1
255   CONTINUE
      POS=0.0
      VINV=10000.0
      WD=WD1
      WRITE(5,2610)
2610  FORMAT(//,' 1)  START ARC',/,
     *        ' 2)  WAIT FOR PUDDLE TO REACH DESIRED WIDTH',/,
     *        ' 3)  TYPE <CR> TO START CONTROL',//)
      READ(5,1100) ICONT
      DO 500 I=0,4000
      POS=POS+1.0/VINV/FREQ
      IF(POS.GT.4.0) WD=WD2
256   CALL OUT(214,0)
```

```
          ICHK=INP(214)
          IF (ICHK.AND.8) GO TO 256
P(211)              IF (IWIRTH.LT.0) IWIRTH=IWIRTH+256
          WS(1)=(FLOAT(IWIRTH))*AKD
          IF(I.LT.100) GO TO 280
          WERRM=-(WERR)
          WERR1=WS(1)-WS(2)
          WERR2=WS(2)-WS(3)
          IF(WERR2.LT.WERR) GO TO 260
          IF(WERR1.LT..01)  GO TO 270
          WS(2)=WS(3)+WERR
          GO TO 280
    260   IF(WERR2.GT.WERRM) GO TO 280
          IF(WERR1.GT..01) GO TO 270
          WS(2)=WS(3)+WERRM
          GO TO 280
    270   WS(2)=WS(3)
    280   E(1)=WD-WS(2)
          IF(KPROP.NE.0.0) GO TO 290
          VINVC(1)=VINVC(2)+C4*E(1)+C5*E(2)
          GO TO 295
    290   VINVC(1)=KPROP*E(1)
    295   IF(VINVC(1).LT..781) VINVC(1)=.781
          IF(VINVC(1).GT.100.) VINVC(1)=100.
          WMS(1)=C7*VINVC(2)+C8*WMS(2)
          ERROR=WMS(1)-WS(2)
          IF(ERROR.GT.EMAX) WMS(1)=WS(2)+EMAX
          IF(ERROR.LT.EMAX) WMS(1)=WS(2)-EMAX
          VINV=KK(WMS(1)-WS(2))+VINVC(1)
          IF(VINV.LT..781) VINV=.781
          IF(VINV.GT.100.) VINV=100.
          IVEL=IFIX(523.344/VINV+FLOAT(IOFSET))
          CALL OUTPUT(IVEL)
          DO 300 L=1,2
          M=4-L
          N=3-L
          VINVC(M)=VINVC(N)
          WMS(M)=WMS(N)
          E(M)=E(N)
          WS(M)=WS(N)
    300   CONTINUE
          ISAVE=I/INT+1
          IF(ISAVE.GT.1000) ISAVE=1000
          IPOS(ISAVE)=IFIX(POS*1000.0)
          INV(ISAVE)=IFIX(VINV*100.0)
          IWIDTH(ISAVE)=IFIX(WS(3)*1000.0)
    500   CONTINUE
    600   WRITE(5,2700)
    2700  FORMAT(' CONTROL HAS STOPPED',//)
          WRITE(5,2800)
    2800  FORMAT(' DO YOU WISH TO SAVE DATA?',/,
         *       ' TYPE <CR> IF YES',/,
         *       ' TYPE <1><CR> IF NO',//)
          READ(5,1100) ICONT
          IF(ICONT.EQ.1) GO TO 70
```

```
      CALL NAMEIN(NAME)
      CALL OPEN(9,NAME,1)
      WRITE(9) ISAVE,KC,TI,KPROP,K,KM,TM,WD1,WD2,FREQ,INT
      WRITE(9) (IPOS(N),INV(N),IWIDTH(N),N=1,ISAVE),WERR,EMAX
      ENDFILE 9
700   GO TO 50
      END
```

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