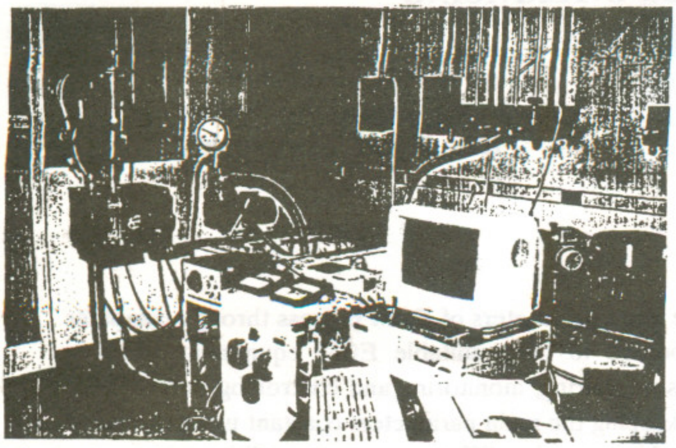


Figure 1. Photograph of the self-made EC-sinking Equipment.

1. EC-Sinking Machine

A hand fed upright drilling machine (1), Figure (2) has been used as a main frame which has been modified to be suitable EC-sinking machine. A suitable tool feed drive has been designed to feed the tool cathode (2) axially towards the workpiece anode (3) with controllable and practically small feed rates necessary for ECM process. As a drive a variable speed DC-motor is connected to a speed reduction unit of reduction 1:30 (5), Figure (2). The motion is then transmitted to the spindle driving screw (7) through the pulley drive (a,b). A section through the spindle drive is shown in Figure (3). The screw (7), Figure (3), pushes the tool carrying spindle (8) in an axial direction 0.5 mm/rev of pulley b.

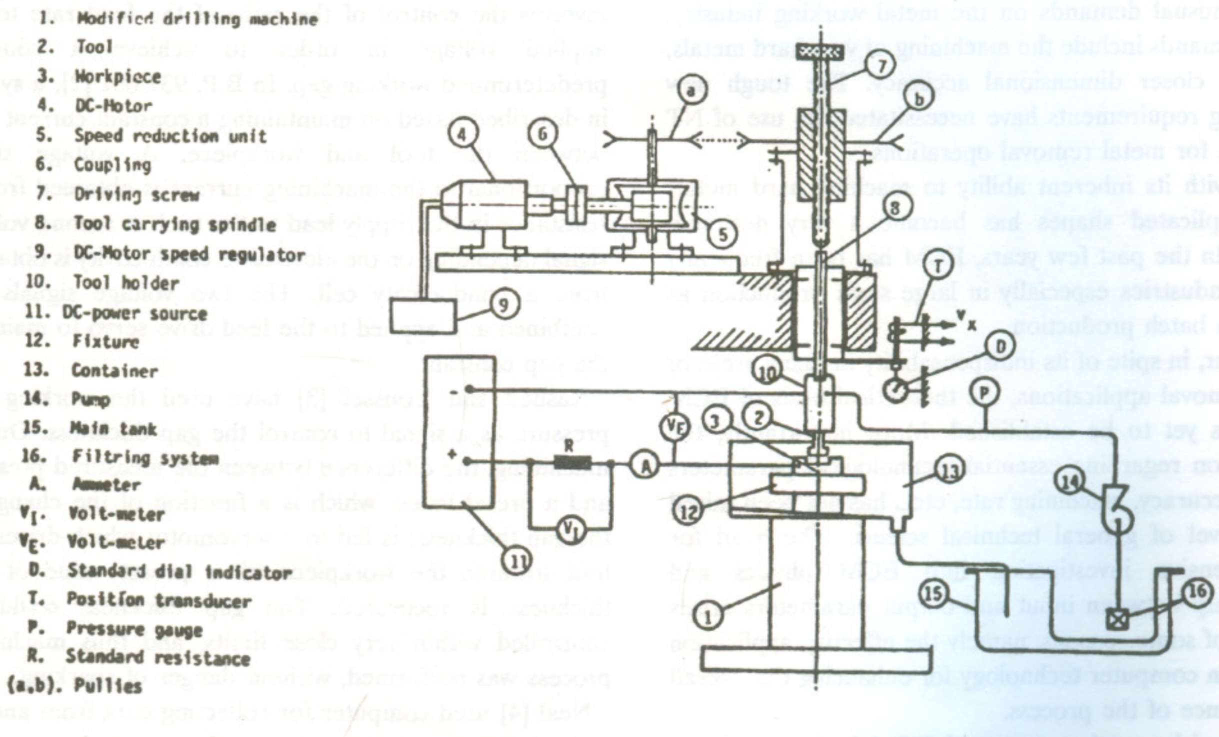


Figure 2. Diagrammatic layout of the self-made EC-sinking Equipment.

The speed of the DC-motor n_m is usually controlled through either the field flux ϕ or armature voltage V_a according to the equation,

$$n_m = (V_a - I_a r_a)/k\phi$$

where k = constant, $I_a r_a$ = armature loss voltage. However, the speed control through the armature voltage V_a is preferred, because the torque will not be affected by the motor speed as in the case of speed regulation through the flux.

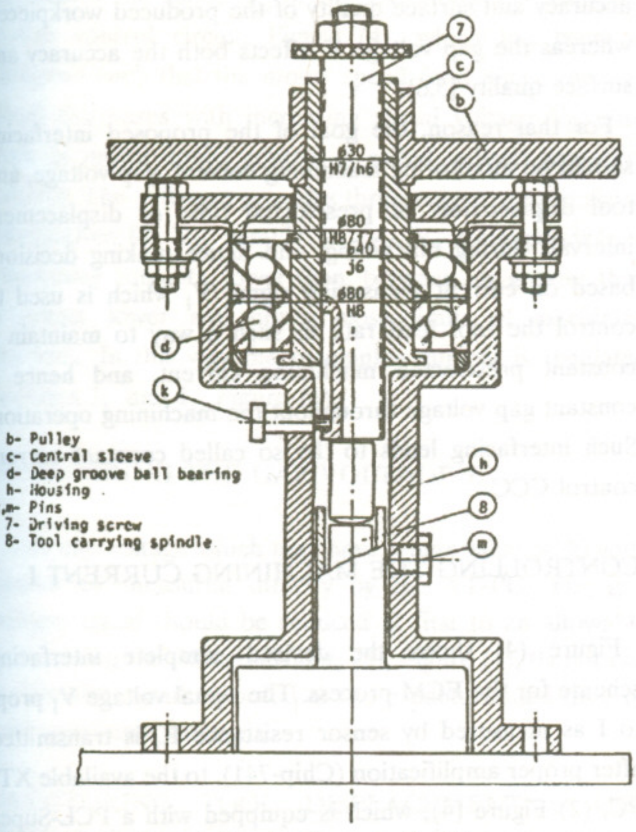


Figure 3. Sectional view in the spindle drive.

The motor control circuit consists of four main parts, Figure (4).

a) DC-rectifier (11), providing constant flux ϕ

b) Simple linear firing circuit (12), which has a signal voltage V_s (V_1, V_2, V_3) from XT-PC as input after being magnified by the chip 714 (6) with gain 2. The short pulses as a final output from the firing circuit is fed to two thyristors gates (G_1 K_1 and G_2K_2). The firing angle α is prop. to signal voltage V_s.

c) Controlled rectifiers (thyristors) Q_1 and Q_2) (14), which are used to provide the variable AC voltage as output with variable rms value from fixed input voltage of an AC-source, and the pulses for G_1K_1 and G_2K_2 which determine firing angle α as input.

d) The bridge rectifier (13) which converts the variable AC voltage with variable rms value into a variable DC voltage fed to the DC-motor armature.

An electrolyte circulation system of maximum delivery of 1.5 m^3/hr at a pressure of 4 atm with efficient electrolyte filtering, has been used, Figure (2).

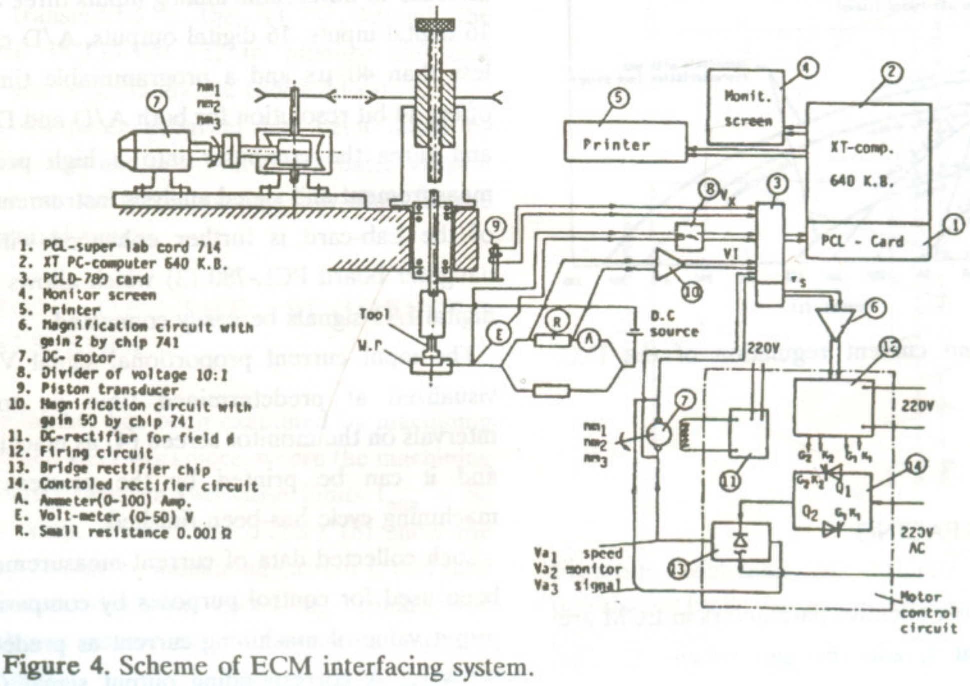


Figure 4. Scheme of ECM interfacing system.

The machine has been then instrumented by the necessary measuring devices, needed for in-process measuring, monitoring, and controlling purposes of the process parameters, Figure (2). The machining current I is measured as a function of the potential difference across the standard resistance R, whereas the gap voltage E is measured by the voltmeter V_E. The tool penetration x and hence the tool feed f can be measured using the position transducer (T), Figure (2).

2. *DC-Power Supply*

As a power supply, the available DC welding Rectifier THRIDOYNRK 320 is used. It is a motor-generator-set, whose supply voltage and current output are regulated using different regulating elements. It has E-I falling characteristic which is visualised for all possible voltage and current settings, Figure (5). Optimum setting as shown in Figure (5) -not steep characteristic- has been selected, since it provides high current densities needed for ECM, and limits the gap voltage to 35 volts, after which sparking is liable to occur, [5].

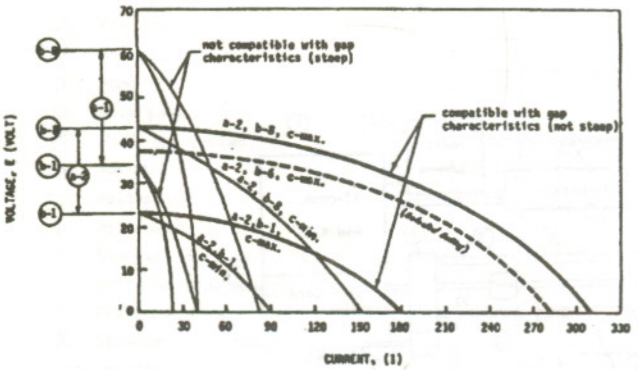


Figure 5. Voltage and current regulation of the D.C. power supply.

COMPUTER INTERFACING

The main and the most effective parameters in ECM are the machining current I, and the gap voltage E. The current I affects considerably the stock removal rate, the accuracy and surface quality of the produced workpieces, whereas the gap voltage E affects both the accuracy and surface quality [5,6].

For that reason, the goal of the proposed interfacing should be monitoring machining current, gap voltage, and tool displacement at preselected time or displacement intervals during machining, and hence making decisions based on current measuring signal V_I which is used to control the tool feed rate in such a way to maintain a constant preselected machining current, and hence a constant gap voltage throughout the machining operation. Such interfacing leads to the so called constant current control CCC.

CONTROLLING THE MACHINING CURRENT I

Figure (4) shows the devised complete interfacing scheme for the ECM process. The signal voltage V_I prop. to I as measured by sensor resistance R, is transmitted after proper amplification (Chip-741), to the available XT-PC, (2) Figure (4), which is equipped with a PCL-Super Lab Card, Model 714, (1), which offers most desirable measurement and control functions. Its versatile function includes 16 differential analog inputs three analog outputs, 16 digital inputs, 16 digital outputs, A/D conversion time less than 40 μs and a programmable timer/counter. It offers 14 bit resolution for both A/D and D/A conversion and turns the computer into a high precision voltage measurement and signal analysis instrument. The versality of the Lab-card is further enhanced with the optimal daughter board PCL-780 (3) which allows analog and/or digital I/O signals be easily connected.

The input current proportional signal V_I can then be visualized at predetermined time or tool movement intervals on the monitor screen (4) as machining proceeds, and it can be printed by the printer (5) after the machining cycle has been finished.

Such collected data of current measurements (V_I) have been used for control purposes by comparing it with the preset value of machining current as predetermined by a software. A corresponding output signal (V_s) from the computer is used after appropriate amplification (chip 741) to control the speed n_m of the DC-motor (7) using the motor control circuit, Figure (4), which has been so designed such that the motor speed (and hence the tool feed) decreases with increasing signal voltage V_S. This type of motor speed control is called indirect armature control. The software provides three output voltage signal alternatives for V_S, namely V_1, V_2, V_3 corresponding to machining currents, lower than, between, or greater than a preset lower and upper close limits of machining currents. In this way the machining current is regulated between I_1, and I_2, Figure (6).

MONITORING THE GAP VOLTAGE E

The gap voltage which may have a max value of 40 volts cannot be measured directly by the XT-PC. The gap voltage signal should be reduced at first to an allowable value, using the voltage divider, (8), Figure (4), then it can be visualized and recorded at the predetermined time or tool movement intervals.

MONITORING TOOL DISPLACEMENT x AND FEED RATE f

The signal voltage V(x) of the positioning transducer (9), Figure (4), is transmitted to the XT-PC through the functional board PCLD-780 (3) to monitor the tool displacement x and accordingly the tool feed rate f.

The relevant computer program has been made by making use of the easy and powerful Quick Basic Version 4.0 Figure (7) shows the corresponding flow chart for the devised CCC control system.

EVALUATION OF THE SUGGESTED INTERFACING SYSTEM

The system reliability has been examined by machining a hole in a hardened steel workpiece, where the machining current is regulated between two close limits $I_{min} = 80$ and $I_{max} = 85$ Amp. Print 1, and Figure (8) show the values of the gap voltage E, machining current I, tool feed rate f and motor regulating speed n_m against the machining depth x as measured and monitored at constant intervals of 0.2 mm.

The detailed machining conditions are given in Figure (8), from which it is clear that the current attains an initial value of about 30 Amp, depending on the initial gap thickness h_o, and then it increases with a rate depending upon the selected max regulation feed f_1, zone I, Figures (8) and (9). If f_1 is decreased to f''_1, the current increases with smaller rate I", Figure (9). On the other hand, if f_1 is increased to f'_1, the current increases with higher rate, current I', Figure (9), and thus it reaches rapidly the max preset current value I_{max} (pt.A), after which current regulation takes place. If f is selected over a certain limit, sparking is liable to occur. In this respect, it has been found that the optimum value of upper regulating feed f_1 lies between 5 and 6 mm/min.

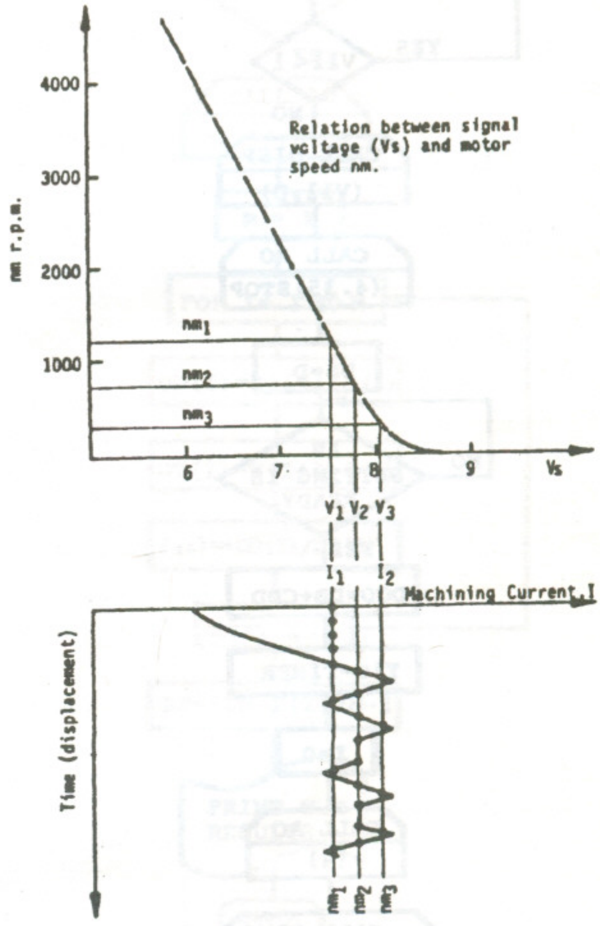
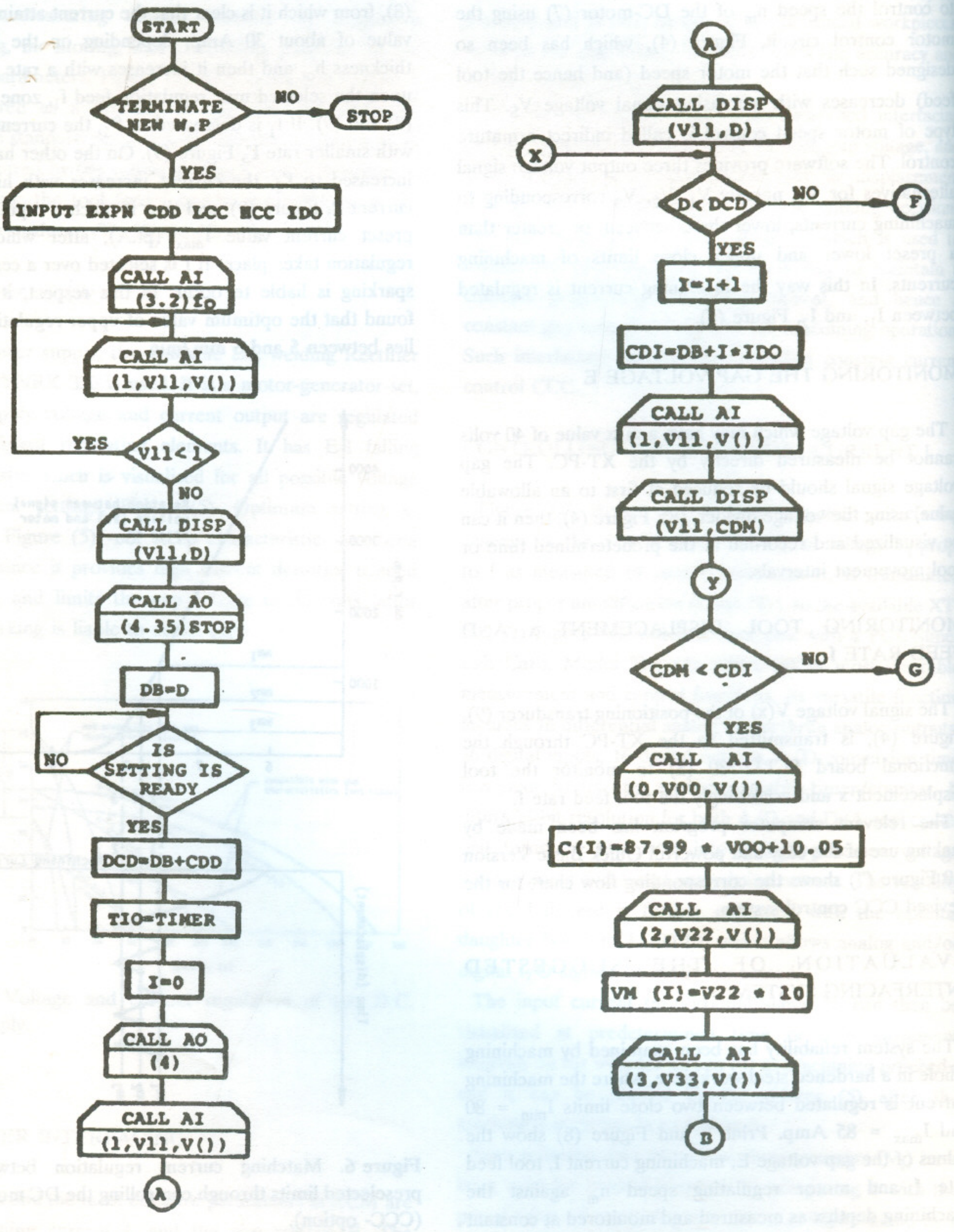


Figure 6. Matching current regulation between two preselected limits through controlling the DC motor speed (CCC- option).


START
TERMINATE NEW W.P
NO
STOP
YES
INPUT EXPN CDD LCC HCC IDO
CALL AI (3.2) f$_0$
CALL AI (1,V11,V())
YES
V11<1
NO
CALL DISP (V11,D)
CALL AO (4.35) STOP
DB=D
NO
IS SETTING IS READY
YES
DCD=DB+CDD
TIO=TIMER
I=0
CALL AO (4)
CALL AI (1,V11,V())
A
A
CALL DISP (V11,D)
X
D<DCD
NO
F
YES
I=I+1
CDI=DB+I*IDO
CALL AI (1,V11,V())
CALL DISP (V11,CDM)
Y
CDM < CDI
NO
G
YES
CALL AI (0,V00,V())
C(I)=87.99 * VOO+10.05
CALL AI (2,V22,V())
VM (I)=V22 * 10
CALL AI (3,V33,V())
B

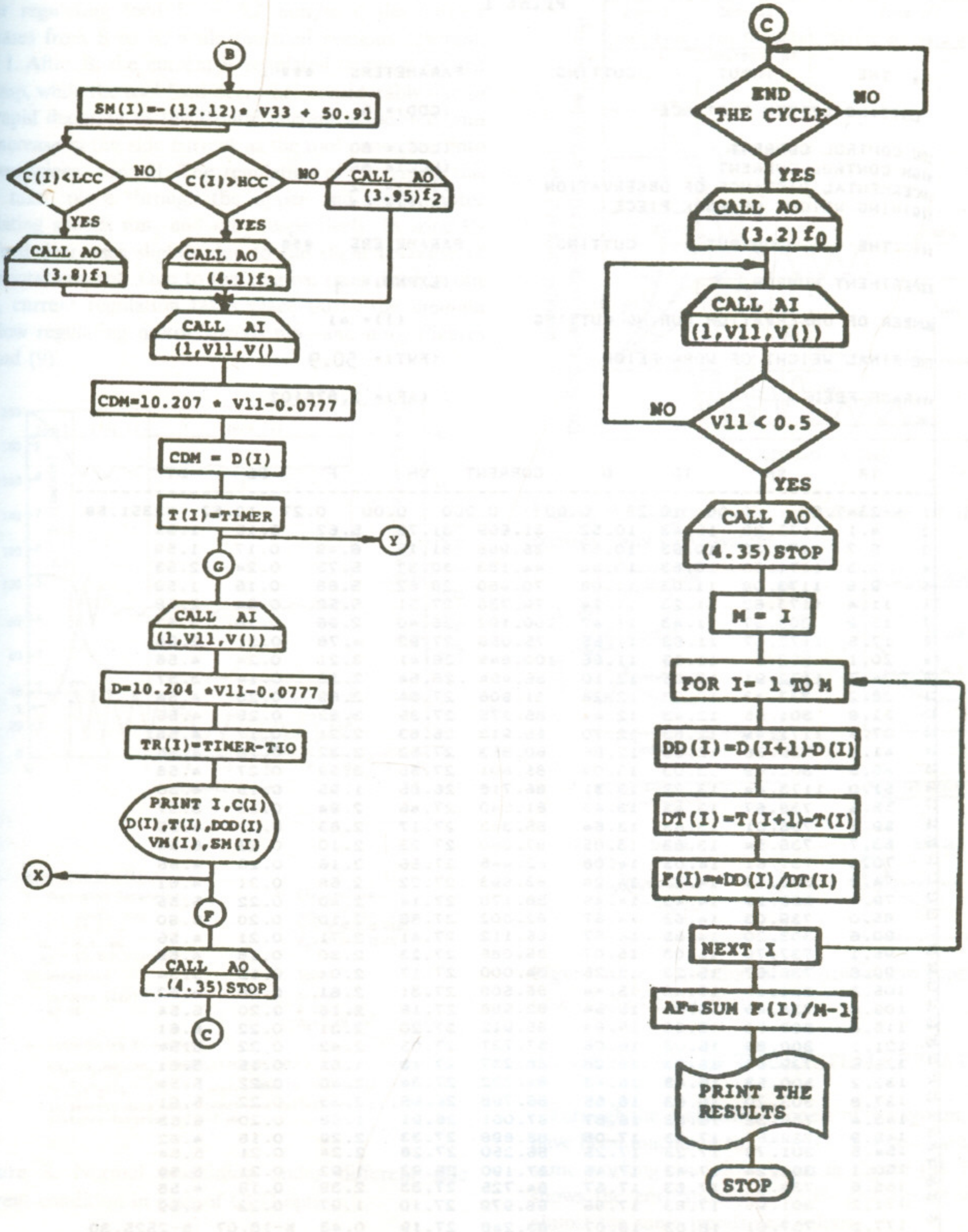
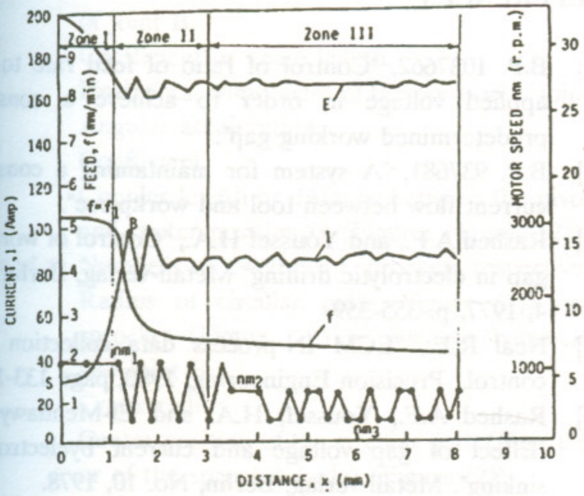


Figure 7. Flow-chart of program shows the steps of software and calculation for CCC control system.

Print 1

```
** THE         INPUT        CUTTING          PARAMETERS   ***

 CUTTING DEPTTH DISTANCE                      (CDD)= 8

OW CONTROL CURRENT                            (LCC)= 80
IGH CONTROL CURRENT                           (HCC)= 85
INCERMENTAL DISTANCE OF OBSERVATION           (IDO)= .2
IGINING WEIGHT OF WORK PIECE                  (BWT)= 53.9

** THE         OUTPUT       CUTTING          PARAMETERS   ***

XPERIMENT NUMBER                              (EXPNO)= 1

UMBER OF OBSERVATION DUR,NG CUTTING              (I)= 41

HE FINAL WEIGHT OF WORK PEICE                  (FWT)= 50.9

VERAGE FEED                                     (AF)= 2.876102


      TR       SM       ID       D       CURRENT    VM        F       DD       DT
----------------------------------------------------------------------------------
1  %-2547.5     0.00  10.23    0.00     0.000    0.00    0.27   10.52  %2351.58
2      4.1   1172.20  10.43   10.52    31.669   31.78    5.62    0.15    1.59
3      5.7   1174.33  10.63   10.67    35.966   31.15    6.49    0.17    1.59
4      7.3   1174.50  10.83   10.84    44.183   30.32    5.75    0.24    2.53
5      9.6   1173.08  11.03   11.08    70.960   28.62    5.88    0.16    1.59
6     11.4   1173.62  11.23   11.24    79.736   27.51    5.52    0.24    2.58
7     13.9    303.37  11.43   11.47   100.192   26.40    2.96    0.18    3.57
8     17.5   1172.37  11.63   11.65    75.056   27.92    4.78    0.21    2.58
9     20.1    302.84  11.83   11.86   100.846   26.41    3.21    0.24    4.56
10    24.7   1172.91  12.03   12.10    66.454  .26.64    2.38    0.14    3.57
11    28.2    737.43  12.23   12.24    81.906   27.64    2.69    0.20    4.56
12    32.8    301.95  12.43   12.44    85.375   27.35    3.32    0.25    4.56
13    37.4   1171.49  12.63   12.70    85.912   26.83    2.21    0.17    4.56
14    41.9    739.38  12.83   12.86    80.853   27.52    2.32    0.18    4.56
15    46.5    302.49  13.03   13.04    85.601   27.55    3.59    0.27    4.56
16    51.0   1173.44  13.23   13.31    86.718   26.85    1.95    0.15    4.56
17    55.6    738.67  13.43   13.46    81.540   27.46    2.94    0.16    3.57
18    59.2    736.01  13.63   13.64    85.343   27.17    2.83    0.21    4.55
19    63.7    736.54  13.83   13.85    87.260   27.23    2.10    0.23    6.54
20    70.3    737.61  14.03   14.08    82.446   27.66    2.16    0.16    4.56
21    74.8    303.55  14.23   14.24    83.893   27.22    2.68    0.21    4.61
22    79.4    299.29  14.43   14.45    86.178   27.14    2.40    0.22    5.55
23    85.0    739.03  14.63   14.67    82.002  .27.56    2.10    0.20    5.60
24    90.6    303.20  14.83   14.87    85.112   27.41    2.71    0.21    4.56
25    95.1    737.79  15.03   15.07    85.085   27.23    2.30    0.18    4.62
26    99.8    738.67  15.23   15.25    84.000   27.17    2.04    0.19    5.54
27   105.3    301.60  15.43   15.44    86.508   27.31    2.61    0.20    4.62
28   109.9    738.49  15.63   15.64    82.588   27.16    2.16    0.20    5.54
29   115.4    300.53  15.83   15.84    85.912   27.20    2.31    0.22    5.61
30   121.1    300.89  16.03   16.06    87.727   27.05    2.42    0.22    5.54
31   126.6    739.03  16.23   16.28    88.237   27.13    1.65    0.15    5.61
32   132.2    300.53  16.43   16.43    84.322   27.34    2.40    0.22    5.54
33   137.8    303.20  16.63   16.65    86.798   26.96    2.33    0.22    5.61
34   143.4    738.32  16.83   16.87    87.061   26.91    1.88    0.20    6.53
35   149.9    739.56  17.03   17.08    83.898   27.33    2.29    0.18    4.62
36   154.5    301.78  17.23   17.25    86.250   27.28    2.24    0.21    5.54
37   160.1    301.24  17.43   17.46    87.190   26.92    1.92    0.21    6.59
38   166.6    738.67  17.63   17.67    84.725   27.33    2.39    0.18    4.56
39   171.2    301.95  17.83   17.85    88.979   27.10    1.97    0.22    6.59
40   177.8    737.61  18.03   18.07    83.248   27.19    0.43  %-18.07  %-2525.30
```

Considering again Figures (8) and (9). At optimum upper regulating feed f_1 = 5,2 mm/min, the current increases from S to B, while the feed remains constant, zone I. After B, the current is regulated between 80 and 85 Amp, while the tool feed decreases considerably due to the rapid decrease of the frontal current associated with the increase in the side current as the tool penetrates into the workpiece, zone II. The regulation of current in this zone takes place through the upper and lower motor regulating speeds nm_1 and nm_2 respectively. In zone III the feed decreases slightly due to the slight decrease of the frontal current. Due to the relative small feed in this zone, current regulation takes place throw the medium and low regulating motor speeds nm_2 and nm_3, Figures (8) and (9).



Machining Conditions:

a- Machining Parameters
I = 80-85 Amp
E = 27.5 V
h_o = 0.5 mm
h_e = (0.3-0.43) mm

b- Electrolyte
NaCl of max. conc.
p = 3.5-4.0 atm.
ρ_s = 4.5-5 Ω cm

c- Workpiece
Hardend Steel
60 RC

d- Tool
brass
ϕ 10/8 mm
A_f=0.28 cm^2

e- Interfacing Parameters
nm_0, nm_1, nm_2, nm_3 = 3600,1170,735,300 r.p.m, respectively
f_0, f_1, f_2, f_3 = 16,5.2,2.3,1.3 mm/min respectively
In-process data measurement and collection took place at distance interval of 0.2 mm.

Figure 8. Normal machining under different side current condition in case of CCC-option.

The gap voltage plot E shows a very interesting behaviour. It is approximately the exact reciprocal of the current plot I, Figure (8).

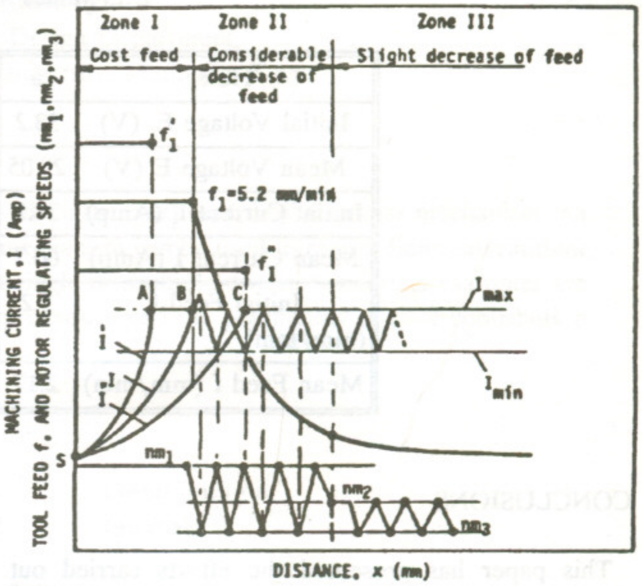


Figure 9. Diagrammatic representation of the current control using CCC-system.

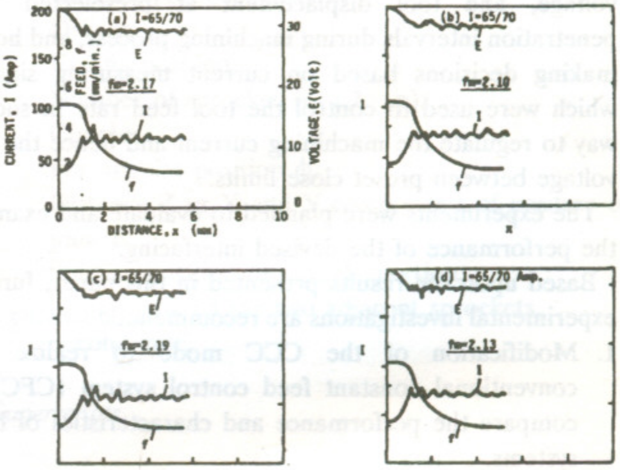


Figure 10. Examination of control system repeatability in case of the CCC-option.

EXAMINATION OF THE SYSTEM REPEATABILITY

Through the evaluation process of the system, four holes have been machined to a depth of 5.4 mm each under the same working conditions given in Figure (8). Figure (10) shows the corresponding, I-, E- and f-plots which have almost the same trends and values.

The high repeatability of the system is clearly expressed through the low standard deviations of the voltage, current, and feed values shown in table.

E,I,f values and standard deviations.

Hole	a	b,	c	d	X_{mean}	sta.dev.
Initial Voltage E_i (V)	33.2	32.0	32.9	32.3	32.75	0.387
Mean Voltage E (V)	29.05	29.5	29.3	29.35	29.3	0.162
Initial Current I_i (Amp)	38.5	41.5	40.0	42.0	40.5	1.58
Mean Current I (Amp)	66.7	66.3	66.5	55.35	66.475	0.185
Initial Feed f_i (mm/min)	5.2	5.2	5.2	5.0	5.0	0
Mean Feed f (mm/min)	2.17	2.1	2.19	2.13	2.1475	0.041

CONCLUSIONS

This paper has presented the efforts carried out to control the main parameters governing the ECM process through computer interfacing. The goal of the proposed interfacing was the monitoring of machining current, gap voltage, and tool displacement at preselected tool penetration intervals during machining process, and hence making decisions based on current measuring signals, which were used to control the tool feed rate in such a way to regulate the machining current and hence the gap voltage between preset close limits.

The experiments were planned to evaluate and examine the performance of the devised interfacing.

Based upon the results presented in this paper, further experimental investigations are recommended striving for:

1. Modification of the CCC mode to realize the conventional constant feed control system (CFC) to compare the performance and characteristics of both systems.
2. Investigation of the performance and capabilities of this interfacing in controlling and monitoring other process parameters, such as gap thickness, electrolyte pressure and temperature, etc...
3. Performing detailed investigations to determine the improvement in the dimensional and geometrical accuracy of forms machined electrochemically under interfacing conditions.

REFERENCES

[1] B.P. 1037662, "Control of ratio of feed rate to the applied voltage in order to achieve a constant predetermined working gap".

[2] B.P. 937681, "A system for maintaining a constant current flow between tool and workpiece".

[3] Rashed A.F., and Youssef H.A., "Control of working gap in electrolytic drilling" Metall-verlag, Berlin No. 4, 1977, p. 355-359.

[4] Neal R.E., "ECM IN-process data collection and control,: Precision Engineering, 1980, page 133-138.

[5] Rashed A.F., Youssef, H.A. and El-Mehdawy Y., "Effect of gap voltage and current byelectrolytic sinking". Metall-verlag, Berlin, No. 10, 1978.

[6] Rashed A.F., Youssef H.A. and El-Mehdawy Y., "Parameters affecting hole oversize by electrolytic sinking". The Bulletin of Faculty of Engg. Univ. of Alex. Vol. XV: 1-1976.