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University of Sheffield

Department of Control Engineering

SPAID - AN INTERACTIVE DATA ANALYSIS PACKAGE AND ITS APPLICATION TO THE IDENTIFICATION OF AN ELECTRIC ARC FURNACE CONTROL SYSTEM

S. A. Billings, M. J. H. Sterling, D. J. Batey

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Introduction

The design of an efficient control strategy will usually require a suitable model representing both the steady-state and dynamic performance of the process. In most practical problems the complexity of the process usually dictates a complicated theoretical model which is not readily compatible with the need to design simple regulators. However, the majority of high order and stochastic effects that characterise the operation of a large dynamic complex system can frequently be represented in terms of simple dynamic models which can be readily used to design suitable controllers. Identification can often be used to estimate such models from input/output data records and gives further knowledge and insight of the process and its environment.

Effective data handling and estimation programs are necessary for efficient identification and the present study describes the development of an identification package SPAID - Sheffield Package for the Analysis and Identification of Data. The package which has been written for a CONPAC 4020 process computer consists of several suites of programs for logging, data handling and modification, parameter estimation, model validity tests, simulation and plotting. The programs are interactive via a graphics display terminal with user intervention to control the identification procedure. Operational data from a production electric arc furnace is analysed and properties of the arc discharge, interaction between the regulators and a difference equation model of the electrode position controller are identified.

SPAID

Structure of the Package. SPAID[1,2] is a command driven interactive identification package written in Fortran II for the identification of linear single-input, single-output time invariant systems. The package has been implemented on a CONPAC 4020 process computer which is provided with a 32K word core store (24 bit words) and 3M word exchangeable disc backing store. The operating system software enables priority multi-programming with core swapping and has been extensively modified to permit efficient multi-access via graphics terminals. The system is provided with a library of disc files known as data tables, which may be of any size, but in this case are fixed at 1024 words to correspond to the maximum number of points which can be displayed on the x-axis of a Tektronix 4010 storage tube terminal.

It was evident at an early stage of program development that the flexibility necessary for system identification could best be achieved

Dr. Billings and Dr. Sterling are, and Mr. Batey was formerly, with the Department of Control Engineering, University of Sheffield.

by ensuring that the package was structured to satisfy the following criteria:

(i) to include standard input/output and plotting facilities
(ii) to avoid the duplication of software
(iii) to enable any program to operate on data derived from any other program
(iv) to allow a large amount of data to be analysed
(v) to enable new routines to be added as required

In an attempt to satisfy the above criteria a two-level data base consisting of an area of disc which is addressable as individual words and a series of data tables was developed. The area on disc forms the main data base and contains a permanent record of the raw data. The data can be retrieved from disc and placed in data tables which can be accessed by all the programs in the package. At each stage of the analysis data is retrieved from the data table, operated on, and replaced in that data table for subsequent analysis by a different overlay segment. The modified data sequences can be stored in auxiliary data tables at any stage in the analysis and retrieved as required. Where several channels are being analysed one data table is assigned to each channel. The two-level data base thus permits sequential modification of the data by manipulation of data tables and preserves a copy of the raw data on disc.

The only constraint on the amount of data which can be analysed is the size of disc area available. The maximum in this case is 500,000 words, but in practice much smaller areas have been required, a typical size being 40,000 words or 20 screen pages of two channel data. Where large numbers of data points are available they are retained on magnetic tape, and pertinent areas are loaded onto the data base in sections of 20 screen pages as required.

A schematic diagram of the package is illustrated in Fig. 1. The program executive runs as a real time program under the system monitor. Individual programs in the suite are overlaid at the same priority as the executive, so that there is only one data analysis program (or the executive) in core at any one time. This results in economic use of the available core, whilst leaving room for other users on the system. A program which by its nature must run at a higher priority than that allocated to the executive (e.g. data logging) temporarily increases its priority for the duration of the program.

Each executive option is selected by typing its three-character mnemonic from the list shown on Table 1. Communication and control is performed by common parameters and by operator intervention via a graphics terminal. Return from each option is made to the executive with the message 'TYPE OPTION-' in anticipation of the next three character code. The menu is only displayed when the executive is first turned on, or when an illegal code is entered. All the programs have been written in Fortran II and assembler code has been used only where it is unavoidable.

The raw data can be retrieved from disc, stored in data tables and displayed on the screen by the DIS option. In this way a program can operate on any part of the data without implementing its own retrieval. Similarly, the results of each operation are displayed by a common segment. When a display of the data is required, the calling program stores its results in the appropriate data tables, and links to the displaying segment, which in turn links to the executive when the plotting is complete.

Preliminary Data Analysis and Modification. The data to be analysed can be loaded onto the data base by any of the following means

(i) by logging from an analogue source via the ADC using the LOG option
(ii) from digital magnetic tape using the MTR option
(iii) from paper tape using the INP option - the tape is in free format in specified length records
(iv) by generating artificial data using either the GMD or GEN options.

If the data is entered via an ADC using the LOG option the sampling frequency is fixed by an external clock. An Applied Dynamics 4 analogue computer is available for signal conditioning.

The data points are stored on disc in single length floating point format, and are preceded by a data description. Included in this description are details of the data base required by the retrieval and display program DIS. The information is also available to any overlay segment requiring it. A list of the data description is illustrated in Table 2.

The data description can be readily modified using the CHA option, if required. For example the data can be decimated by altering the interval between points. Multichannel data is stored as scanned, adjacent words being derived from adjacent channels. Paging of the data on the display, is carried out using the DIS, NXT and BCK options. The MTD and MTR options allow each user to copy his data base onto magnetic tape and to free the package for the next user. Hardcopy of points stored in a data table may be determined by punching out the data and listing it off-line using the PUN option.

The data sequences can be inspected on a VDU, which can display up to 1024 data points and 4 channels of data. Paging through the data permits the user to select an appropriate sequence for subsequent analysis. The values of selected data points may be read from the screen using the CRT and CRF options. Cross-wires activated by thumb-wheels are positioned on the graph in the required position and the value of that data point is determined by look-up in the appropriate data table. Spurious data points are readily removed by selecting the offending point using cross-wires and computing a new data point by interpolation.

Actual operating data frequently contains a drifting component, and data modification is necessary to produce stationary records that can be analysed by the parameter estimation techniques. Several data modification options are available in the package including, normalisation and data scaling, data differencing, low, high and band pass filtering and least squares trend removal.

Parameter Estimation. The parameter estimation programs are designed to operate on selected input/output data sequences u_t, y_t ($t=1 \ldots N$) and produce optimal models of discrete time stochastic systems of the form

$$y_t = \frac{z^{-k}B(z^{-1})}{\nabla^p A(z^{-1})} u_t + \frac{C(z^{-1})}{\nabla^p D(z^{-1})} \xi_t \qquad (1)$$

where z denotes the shift operator $zx(t) = x(t+1)$, ∇ is the differencing operator $(1-z^{-1})$ and A,B,C,D are polynomials of the form

$$A(z^{-1}) = 1+a_1 z^{-1} + \dots + a_n z^{-n}$$
$$B(z^{-1}) = \quad b_1 z^{-1} + \dots + b_n z^{-n}$$
$$D(z^{-1}) = 1+d_1 z^{-1} + \dots + d_m z^{-m}$$
$$C(z^{-1}) = 1+c_1 z^{-1} + \dots + c_m z^{-m}$$

where all the roots of A and D are within the unit circle.

Initial identification consists of choosing appropriate values of the time delay k, process model order n, noise model order m, and the number of integrations p in the system and noise models. Cross-correlations can be performed to produce an estimate of the impulse response, which often indicates possible values of these parameters. Autoregressive models can be fitted to the input sequence and the input/output data prewhitened if the input was non-white. The determinant ratio test[3] is frequently applied to indicate possible values of the process model order and time delay.

After the raw data has been modified to conform with the estimation techniques the operator may select one of the parameter estimation options. The options currently available include maximum likelihood,[4] generalised least squares,[5,6] suboptimal least squares,[7] spectral analysis[8] and Box-Jenkins[9] time series analysis and forecasting. On completion of the parameter estimation a printout of the estimates and statistical properties of the models can be obtained. Options are available which allow the operator to graphically inspect the predicted output, deterministic prediction errors and residuals of the estimated model.

Model Diagnostics. Model order tests[3] are incorporated in the package and include determinant ratio test, F-ratio test, loss function analysis, pole-zero cancellation, tests for independence and operations on the residuals. Autocorrelations of the residuals and cross-correlations are readily applied to check the adequacy of the model by selection of the relevant data table. Comparisons of the estimated model pulse response and the system impulse response computed by cross-correlation are available. The estimated model frequency response can be compared with the response estimated using spectral analysis if required.

The operator selects the final model after application of all the tests and inspection of the predicted output and statistical properties of the model.

Identification of an Electric Arc Furnace Control System. The study relates to a 3-phase arc impedance controlled 135 tonne 35 MVA production arc furnace.[10] The furnace consists of a refractory lined shell with service doors and a tapping launder. Three electrodes (typically 6m long and 60cm dia.) pass through holes in the roof which can be swung aside in a horizontal plane to permit scrap charging from an overhead basket. Electrical power is supplied to the furnace electrodes through bus-bars and water-cooled flexible cables from the furnace transformer. Heat is transferred to the scrap steel from electric arcs drawn between the tips of the electrodes and the metallic charge. Typical operation results in currents of approximately 36kA at 560V. A schematic diagram of the arc impedance controlled furnace is illustrated in Fig. 2.

Throughout the period of a melt the arc length varies erratically due to scrap movement within the furnace and some form of control is required to maintain the desired power input level. The existing control philosophy is based upon both short and long term control policies. The long term policy consists of manually adjusting the power input to the furnace at various stages of the melt by selection of a suitable transformer voltage tap. Short term dynamic control is based upon maintaining a preselected constant arc impedance by adjusting the electrode position in response to disturbances. Each electrode is individually positioned by an electrode position controller which attempts to maintain a reference arc impedance compatible with the long term power input schedule.

Mathematical Modelling. The servomechanism for positioning the electrodes consists of an amplidyne Ward-Leonard regulator operating on an error signal. The arc impedance measuring circuit compares currents proportional to transformer secondary voltage and arc current and produces an error when they are unequal. Under steady-state conditions the error signal ε can be represented by

$$\varepsilon = CI_1 - KV_m \tag{2}$$

hence the term arc impedance control. The error signal is applied to the control winding and excites the amplidyne Ward-Leonard drive which positions the electrode through suitable gearing and a winch system.

Interaction between the electrode position controllers is minimised when operating under arc impedance control and the weight of the electrodes and supporting mast structure is pneumatically counterbalanced. A circuit diagram of the single phase electrode regulator is illustrated in Fig. 3.

The single-phase electrode position controller has been modelled using transfer-function relationships[10] and can be represented as shown in Fig. 4. The defining state-space equations can then be determined as follows, using the symbols defined in Fig. 4.

Amplidyne: $$\dot{x}_1 = \{-D'G_4 - AG_5)x_9 - F_D x_3 - F_S x_2 - x_1\}/T_1 \tag{3}$$

$$\dot{x}_2 = (K_1 x_1 - x_2)/T_2 \tag{4}$$

Generator: $$\dot{x}_3 = (K_2 x_2 - K_2 K_E x_4 - x_3)/T_3 \tag{5}$$

Motor: $$\dot{x}_4 = (x_3 - F_B x_6 - x_4)/T_4 \tag{6}$$

$$\dot{x}_5 = (G_1 x_4 - x_5)/T_5 \tag{7}$$

$$\dot{x}_6 = x_5/G_2 \tag{8}$$

$$\dot{x}_7 = G_3 x_6 \tag{9}$$

Mast Dynamics: $$\dot{x}_8 = \omega_N^2(x_7 - x_9) - 2\xi\omega_N x_3 \tag{10}$$

$$\dot{x}_9 = x_8 \tag{11}$$

The amplidyne and generator saturation curves and a dead zone associated with motor stiction are included within the model to provide a realistic description of the furnace control system.

The single-phase furnace transmission system including the high power arc discharge can be represented as[11]

$$i_1 = \frac{FDh}{FR^o_{a1} - I^o_1} \quad \text{or } i_1 = - WDh \tag{12}$$

$$v_m = Dh\{(1-WR_{c1})(R^o_{a1} + R_{c1}) - WX_1^2\} \, |z_{t1}|^{-1}$$

$$\text{or } V_m = D'h \tag{13}$$

where $$F = \frac{(-I_1^o)^3\{(R_{t2}+R_{t3}) \sum_{i,\ell=1}^{3}(R_{ti}R_{t\ell}-X_iX_\ell)+(X_3+X_2)\sum_{i,\ell=1}^{3}R_{ti}X_\ell\}}{E^2\{(-R_{t3}-R_{t2}/2-\sqrt{3}X_2/2)^2+(\sqrt{3}R_{t2}/2-X_2/2-X_3)^2\}}$$

$$i \neq \ell$$

$$|z_{t1}| = \{(R_{a1}+R_{c1})^2 + X_1{}^2\}^{\frac{1}{2}} = \{(R_{t1})^2 + X_1{}^2\}^{\frac{1}{2}}$$

Rai represent arc resistances, Rci and X_i the system line resistance and reactance respectively, v_m the change in measured secondary voltage, i the change in arc current, h the change in arc length, D the arc discharge coefficient, D' the discharge coefficient and WD the arc gain.

Combining the models of the electrode position controller, arc discharge and transmission system provides a complete mathematical description of the furnace control system. Simulation of the combined model using a Runge-Kutta-Merson integration routine, with a step change in the mast position is illustrated in Fig. 11.

<u>Identification of the Furnace Control System.</u> Although the theoretically derived state-space model proved to be representative of the furnace it was felt that a more concise description of the electrode regulator and further information about the process could be obtained from an identification study. The basic aims of the identification were threefold and included:

(i) identification of properties of the arc discharge

(ii) investigation of the interaction between the regulators of an arc impedance controlled furnace, and

(iii) identification of a low order representation of the electrode position controller.

The diversity of the identification requirements entailed designing several experiments and recording a large amount of data. This was usually done in an iterative manner so that the initial experiments added to the knowledge of the process and suggested the form of future experiments. Often the time allowed for the experiments was severely restricted by production demands and the input signal, recorded variables and experiment length were chosen to ensure that the maximum information was obtained.

<u>Data Collection.</u> The environment for data collection and experiments on the furnace was particularly harsh because of the excessive dust and high temperatures associated with electric steelmaking. Although the furnace instrumentation was adequate for monitoring normal production several additional transducers had to be installed to enable the required variables to be logged. Various experiments were conducted on the furnace including the recording of normal operating records, on-line and off-line PRBS data. All the signals were passed through a signal conditioning unit, and a small analogue computer was used to remove mean levels and amplify the signals to give a high resolution prior to recording on an F.M. tape recorder.

<u>Identification of Properties of the Arc Discharge.</u> Normal operating data for a typical melt was recorded to enable the relationship between mast position, transformer secondary voltage and arc current, and a non-linear representation of the arc impedance to be investigated.

The normal operating data was analysed to determine the discharge coefficient and arc gain. During the first basket, the discharge coefficient D' was found, typically, to be 3764V/m with an arc gain of 859 kA/m. The values of the discharge coefficient (1653 V/m) and arc gain (367 kA/m) estimated during refining were notably lower than those experienced during the first basket because of the ionization of the furnace atmosphere.

Dynamic volt-ampere characteristics of the arc discharge in a production furnace during refining and at the beginning of a melt are illustrated in Fig. 5 The two distinct slopes of the characteristics over each a.c. cycle correspond to the two resistance model of the arc[10]. Inspection of the dynamic characteristics clearly shows the instability of the arc at the beginning of the melt and indicates the dependence of the arc characteristics on the furnace environment (i.e. temperature).

Interaction between the Regulators. A 127 bit 33.3mS PRBS sequence was injected into the amplidyne control winding of phase 2 electrode position controller, with the furnace in normal operation during refining, to enable the interaction between the regulators to be investigated. An on-line correlator was then used to identify the impulse responses between the various inputs and outputs of the three phase system. Thus if there is any interaction between the regulators the cross-correlations will be representative of the impulse response of the interacting system. Inspection of the cross-correlation, Fig. 6, confirms that there is minimal interaction when operating under arc impedance control.

However, the PRBS input excitation may have been of insufficient power to excite the interacting modes of the system or overcome any deadzone or stiction associated with the regulators. Thus as a further check on the interaction manual step disturbances were applied to the electrode position controller with the furnace in normal steady state production during refining. The disturbances were applied by manually raising each electrode in turn and allowing the controller to re-establish the preset arc impedance with the other electrodes under normal automatic control. Numerous on-line step disturbance tests were analysed and indicated that the interaction between the regulators was approximately 7%. confirming the correlation analysis.

Identification of the Electrode Position Controller. During the on-line PRBS tests it was noticed that the error feedback from the arc impedance measuring circuit had an extremely low S/N ratio and as such was not recorded. This necessitated open loop tests on the furnace to satisfy the identifiability conditions[12] for the estimation of the electrode position controller forward loop transfer function.

To satisfy the identifiability conditions the feedback loop in the electrode position controller was broken by turning the power off such that there was no arc discharge and no feedback of current and voltage signals. Initially step inputs were applied to the open loop system to check the linearity of the system over the operating range, estimate the system gain and assess the characteristics of the noise. Three PRBS sequences, 511 bit 10ms, 127 bit 33.3ms and 64 bit 100ms of amplitude 64mA were then injected in the amplidyne control field and motor speed and mast movement recorded. All the signals were recorded on an F.M. tape recorder and digitized off-line prior to analysis using SPAID.

Of the three PRBS sequences injected into the open loop system, data obtained using the 64 bit 100ms sequence was selected for the identification of the electrode regulator. The lower bandwidth excitation of this sequence has the advantage that a higher proportion of the total power can be concentrated in the lower frequencies which raises the S/N ratio and lowers the estimation error and dc gain variance.

The step input tests indicated the presence of an integrator at the system output, and consequently the output sequence was differenced to give a model structure of the form

$$y_t(1-z^{-1}) = \frac{z^{-k}B(z^{-1})}{A(z^{-1})} u_t + \frac{C(z^{-1})}{D(z^{-1})} \xi_t \tag{14}$$

The estimated system impulse response illustrated in Fig. 7 indicated the presence of a time delay and suggested that the system may be described by a 2nd or 3rd order model. The determinant ratio test, Fig. 8, failed to indicate either the approximate model order or time delay, possibly because of the low S/N ratio of the differenced output sequence.

Generalised least squares parameter estimation was applied to the modified data sequences for increasing model orders and time delays in the range suggested by the deconvoluted impulse response. The optimum time delay for each model order was selected to be that which minimised the sum of squared residuals, The selection of the time delay was critical for low order models since failure to select the appropriate value often resulted in divergence of the identification algorithm.

A 10th order noise model was used throughout the identification and convergence was achieved in typically 10-20 iterations. The predicted output of all the models indicated a good fit, except in the first order case. The F-ratio test results (compared at a 5% risk level), Table 3, suggest a 5th order model; however, this should be viewed with caution since the F-test has been shown to suggest too high a model order in practice.

Inspection of the poles and zeros of the estimated models, Table 4, clearly shows the presence of characteristic roots, which are especially evident in the 3rd and 5th order, and 2nd and 4th order models. The system gain estimated as 1.18m/A from the step input tests is only accurate for models of order $n = 3$ and above, suggesting that a 3rd order model may be optimum. A comparison of the weighting sequence and estimated model pulse response for $n = 3$ is illustrated in Fig. 7 and clearly shows the adequacy of the 3rd order model. Autocorrelations of the residuals and cross-correlations between the input and residuals are shown in Fig. 9 for a 3rd order model.

The final process model relating the differenced mast position and the control field current was found to be

$$y_{t_{diff}} = \frac{z^{-2}(0.5996\ z^{-1} + 0.739\ z^{-2} + 0.2288\ z^{-3}).10^{-2}}{1- 2.547\ z^{-1} + 2.279\ z^{-2} - 0.7177\ z^{-3}} u_t \tag{15}$$

The results of the identification are illustrated in Fig. 10.

The time invariance of the estimated model and stationarity of the process were checked by identification over a different data sequence. The estimated model

$$y_{t_{diff}} = \frac{z^{-2}(0.523\ z^{-1} + 0.8425\ z^{-2} + 0.379\ z^{-3}).10^{-2}}{1-2.528\ z^{-1} + 2.2462\ z^{-2} - 0.7007\ z^{-3}} u_t \tag{16}$$

was notably consistent with the model obtained using the original data (equation (15)) with all the parameters well within their standard deviations and the pole locations of the two models almost coincident.

Thus combining the identification results of the arc discharge, interaction between the regulators, and the electrode position controller provides a complete description of the furnace control system. A comparison of the step responses of the analytical and identified models, Fig. 11, shows the similarity of the responses of the two models derived by independent means.

The identified models have been successfully used to design new control schemes for the arc furnace, including a dual impedance/current control strategy,[13] a temperature weighting adaptive controller[14] and PID and minimum variance regulators.[10] Although the work is as yet imcomplete it is believed that the final controller design will result in improved melting efficiency and hence lower production costs in electric steelmaking.

Conclusions. The design of an interactive identification package SPAID and its application to the identification of an electric arc furnace control system has been described. The package has been designed to include dedicated input/output routines, avoid software duplication, allow the chaining of options and to enable new routines to be added as required. Chaining of segments has proved to be one of the most useful facets of the package. Paths which previously required one-off programming can now be explored almost as quickly as the desire to follow them is realised. This gives a truly interactive design technique and provides the flexibility necessary for efficient identification.

The package has found wide application in a variety of research fields including the identification of an electric arc furnace, analysis of the behaviour of a human duodenum, estimation of wear in a milling machine tool and prediction of gas and water consumptions. Experiments and demonstrations using the package have also been incorporated into the teaching of both undergraduate and postgraduate courses.

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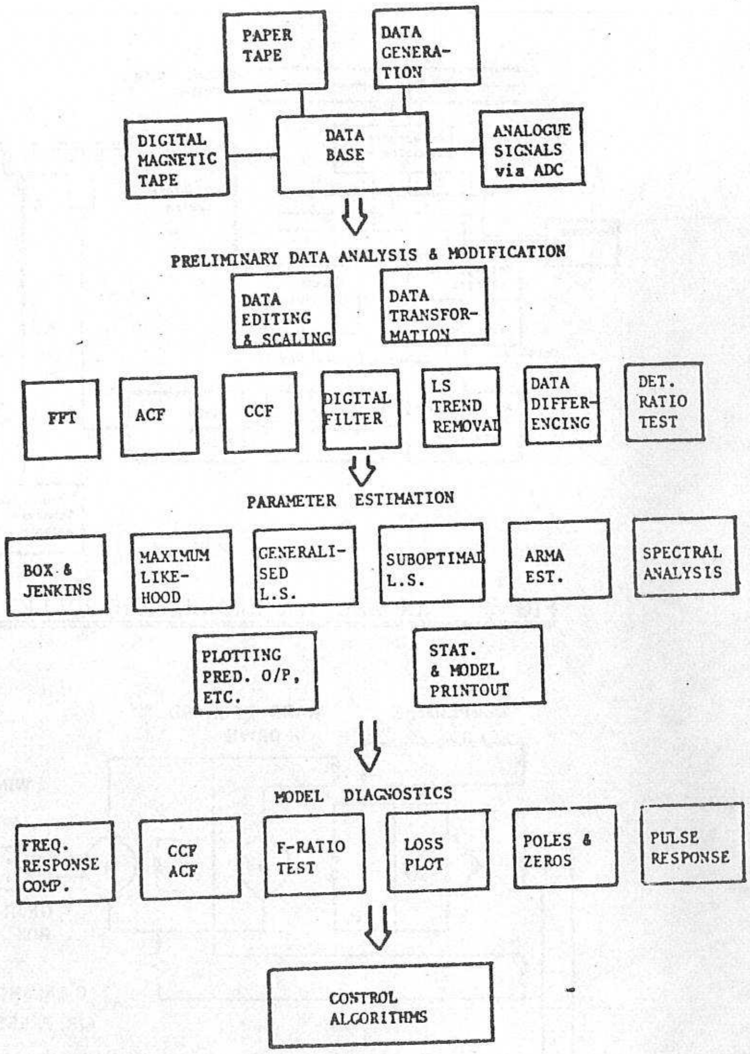


FIG 1 A SCHEMATIC DIAGRAM OF SPAID

FIN - TURN OFF	TRA - DATA TRANSFORMATIONS
INP - INPUT NEW DATA	ARC - AUTO CORRELATION
LOG - LOG FROM ADC	CCF - CROSS CORRELATION
MTR - MAG TAPE RESTORE	FFT - FAST FOURIER TRANSFORM
MTD - MAG TAPE DUMP	IFT - INVERSE FOURIER TRANSFORM
GEN - GENERATE SPECTRAL DATA	FWT - FAST WALSH TRANSFORM
GMD - GENERATE MODELLING DATA	IWT - INVERSE WALSH TRANSFORM
DIS - DISPLAY CURRENT PAGE	DFR - DIGITAL FILTERING ROUTINE
NXT - DISPLAY NEXT PAGE	DIF - DIFFERENCE DATA
BCK - DISPLAY LAST PAGE	APM - A PRIORI MODEL ORDER
CHA - CHANGE DISPLAY VALUES	LSQ - LEAST SQUARES EXEC
STR - STORE CURRENT PLOT	MLE - MAX. LIKELIHOOD EST
RES - RESTORE STORED PLOT	SLS - SUBOPTIMAL LEAST SQUARES
RED - REDISPLAY OPTIONS	TSM - TIME SERIES MODELLING
SEL - SELECT PARTICULAR CHANNELS	TFE - TRANSFER FN. ESTIMATOR
PUN - PUNCH OUT WORK TABLE	TCF - XFER AND COHERENCY FNS
CRF - CROSS-WIRES IN FREQ. DOMAIN	WIN - WINDOW DATA IN FREQ. DOMAIN
CRT - CROSS-WIRES IN TIME DOMAIN	FRO - FREQUENCY RESPONSE
DED - DATA EDITING	PUL - PULSE RESPONSE
TRE - REMOVE TREND	FMO - MODEL ORDER TESTS
NOR - NORMALISE DATA	PAZ - POLES AND ZEROS

TABLE 1. EXECUTIVE OPTIONS

WORD	
1	TOTAL NUMBER OF POINTS
2	NUMBER OF CHANNELS
3	INTERVAL BETWEEN POINTS
4	CURRENT START ADDRESS
5	POINTS PER PLOT ON SCREEN
6	TREND COEFF. A
7	TREND COEFF. B
8	NUMBER OF POINTS FOR TSM
9	SAMPLING RATE
10	REDUCED NUMBER OF CHANNELS

TABLE 2. DATA DESCRIPTION

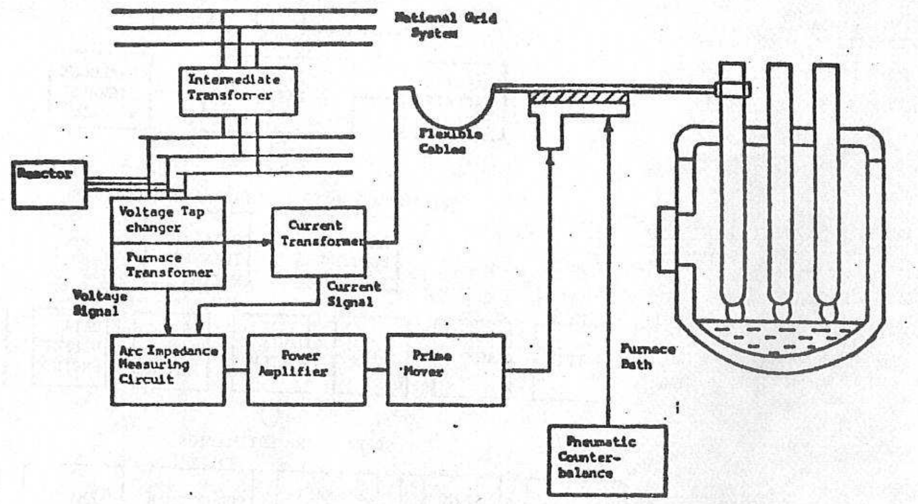


FIG 2 AN ARC IMPEDANCE CONTROLLED FURNACE

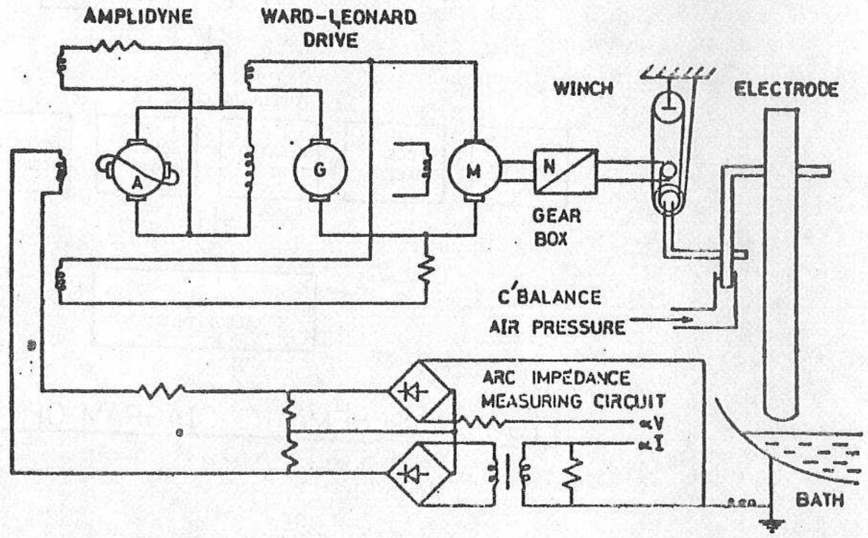


FIG. 3 WARD-LEONARD DRIVE ELECTRODE POSITION CONTROLLER.

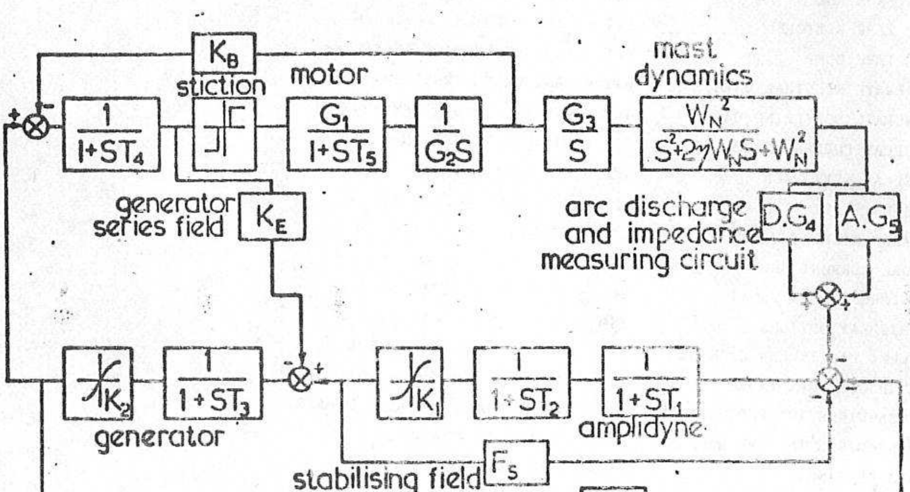


FIG 4 ELECTRODE POSITION CONTROLLER

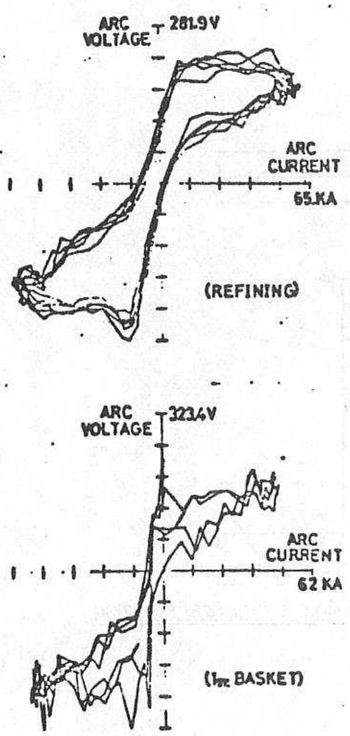
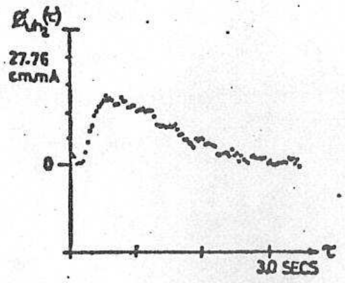
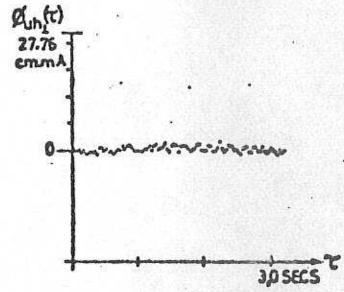


FIG. 5 DYNAMIC ARC CHARACTERISTICS



CCF. OF PHASE 2 CONTROL FIELD CURRENT AND PHASE 2 MAST POSITION



CCF. OF PHASE 2 CONTROL FIELD CURRENT AND PHASE 1 MAST POSITION

FIG 6 CROSSCORRELATION COMPARISON

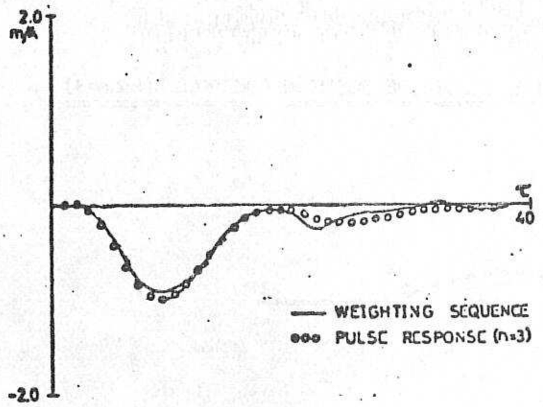


FIG. 7 PULSE TRANSFER FUNCTION COMPARISON

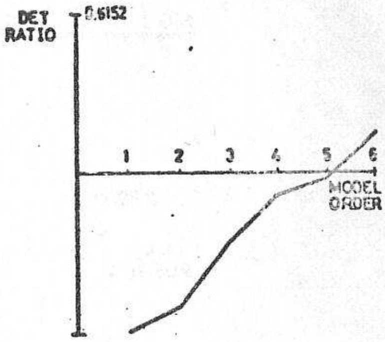


FIG. 8 DETERMINANT RATIO TEST ($K=2$, $N=400$)

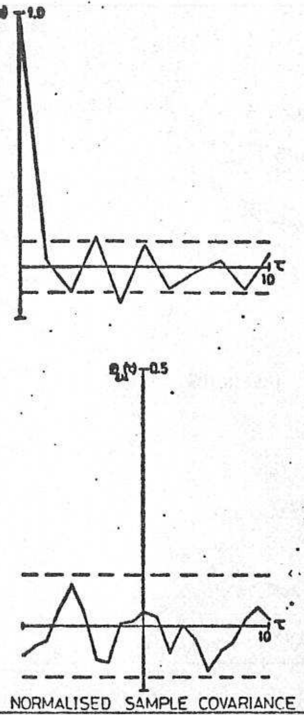


FIG 9 NORMALISED SAMPLE COVARIANCE FUNCTION

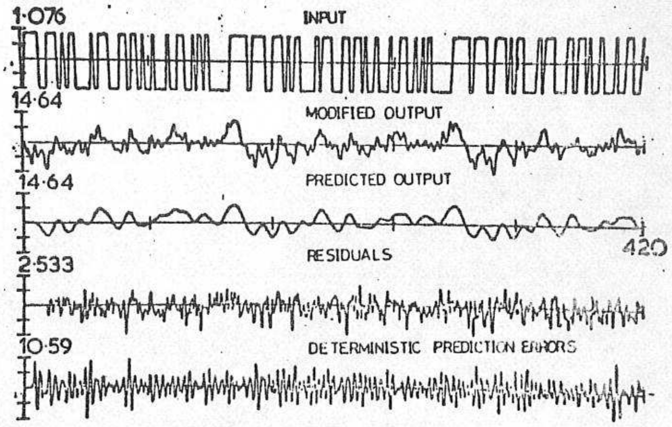


FIG 10 IDENTIFICATION OF THE ELECTRODE POSITION CONTROLLER(k=2,n=3)

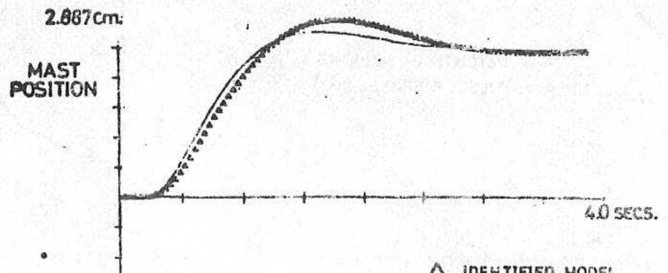


FIG 11 A COMPARISON OF CLOSED LOOP STEP RESPONSES

MODEL ORDER n	LOSS FUNCTION J_n	F RATIO TEST $t_{n,n+1}$
1	2428.0	——
2	277.5	1611.0
3	243.1	29.2
4	223.7	17.96
5	211.3	11.93
6	208.4	2.93

TABLE 3 Results of the F Ratio test using minimal values of the loss function J_n for generalised least squares identification of models of different order (n)

MODEL ORDER n	OPTIMUM TIME DELAY k	POLES	ZEROS	SYSTEM GAIN m/A
1	5	0.8011	-	0.3924
2	4	0.7830 ± j0.1257*	-1.02	0.8387
3	2	0.9054† 0.8207 ± j0.345†	-0.6162 ± j0.04289	1.09741
4	3	0.8293 ± j0.1158* -0.1188 ± j0.9257	-0.2930 -1.089 -1.807	0.9239
5	3	0.8875† 0.7871 ± j0.3544† -0.1414 ± j0.9278	-1.183 -1.442 0.3935 ± j0.5721	1.02878
6	3	0.8524 ± j0.1229* 0.1355 ± j0.7486 -0.1819 ± j0.9084	0.1588 -1.259 ± j0.09565 -0.02571 ± j0.9569	0.9063
7	3	0.8988† 0.7921 ± j0.2401† 0.2034 ± j0.9441 -0.2538 ± j0.8865	-0.3281 -1.408 0.7199 -1.188 0.1186 ± j1.064	1.05493

*Characteristic roots for even model orders

†Characteristic roots for odd model orders

TABLE 4 Poles and zeros of the estimated models