University of Sheffield

Department of Control Engineering

Research Report No. 25

May 1974

The Automatic Vertical Steering of a Longwall Coal-Cutting Machine - An Experimental Investigation

W. A. Bogdadi and J. B. Edwards

The Automatic Vertical Steering of a Longwall Coal-Cutting Machine - An Experimental Investigation

W. A. Bogdadi and J. B. Edwards

Abstract

Although there exist mathematical descriptions of the process by which a longwall coal-cutting system is steered vertically through an undulating coal seam, numerous factors neglected in such idealised models cause significant discrepancies between predicted and actual performance and cast some doubt on the adequacy of control systems designed on a purely theoretical basis. These factors are examined in detail and the design requirements for a $\frac{1}{4}$-scale mechanical model are given together with details of its instrumentation and interfacing to the controlling computer, for the purpose of exhaustive laboratory trials.

An optimal control strategy, designed to return the process to its steady-state in as few cuts as possible, is developed theoretically and its performance in controlling the mechanical model is demonstrated. Though broadly satisfactory in performance, interesting departures from the predicted system behaviour are noted and suggestions offered for their cause and partial elimination.

From both the technical and ergonomic viewpoint this type of trial is regarded by the authors as an essential preliminary to field trials of prototype computer-control systems in mines.

1. Symbols

α = conveyor tilt (face-advance direction)

a = component of drum height due to conveyor tilt α

$\hat{a}$,a' = machine tilts at insection of state space trajectory with a domain of controlability

b = intercept with y axis of a straight line in system state space

c = slope of such a straight line

$F_o(s)$ = transfer function of near-optimal filter

$F_{o1}(s)$ = constituent transfer function of $F_o(s)$

$F_r(s)$ = rate-meter transfer function

J = extension of steering jack

J^* = optimum control

J_1^*, J_2^* = floating limits of J^* in minimum time control

J_m = maximum jack extension

k_g = tilt gain

k_h = height gain

ℓ = distance travelled along one cut

ℓ_{m1} = horizontal distance between rear skids and drum shaft

ℓ_{m2} = horizontal distance between front and rear skids

L = face length

n = number of cuts (general)

N = number of cuts (total)

T_o = time-constant in optimal filter implementation

T_r = rate-meter time-constant

W = width of drum and of conveyor, where equal

W_c, W_d = conveyor width and drum width, where unequal

X = horizontal distance between drum centre and centre of coal-sensor

y = thickness of roof coal ceiling left by cutting drum (face-side)

y_{ref} = desired roof coal thickness (constant)

z = deviation of coal seam from some flat datum

superscript ^{T} denotes transpose of a matrix

2. Introduction

With the dramatic revival of interest in the United Kingdom in coal as a continuing source of energy and with the loss of labour from the mining industry in recent years which has resulted from our earlier fuel policies favouring oil and natural gas, the automation of coal winning and handling operations requires urgent attention[1]. The problems are considerable in view of the arduous underground environment where methane, dust, water, vibration, heat and rockfall make enormous demands on the instrument and systems designer if times-between failures of many months are to be achieved. Detailed engineering of the necessary control systems presupposes that the control problems involved are fully understood and theoretically analysed: a situation by no means achieved at the present time because of the complexity of the process dynamics. Design changes to components and systems are not only particularly expensive in themselves because of the specialised non-proprietory nature of the hardware but also because of project delays ensuing from the need for the smallest circuit change to undergo lengthy and rigorous Ministry* testing for intrinsic safety. This was found to be a major problem in the mid 1960's when energetic attempts at coal-face automation were made in the R.O.L.F.† projects[2] using purpose-built electronic hardware.

Based on this experience and on the future need to extract seams of 0.6 metres and lesser thicknesses, where men will be unable to crawl with the high-speed cutting machines and where automation must therefore succeed at the first attempt, it is obvious that automation projects must involve exhaustive design studies and surface trials prior to the field trial when, of necessity, the system hardware design is virtually "frozen" for the reasons stated. To provide the essential flexibility for further changes in control strategy at this stage of the project and beyond, computer control systems must be envisaged. In many mining problems, the enormous transport delays encountered also demand the use of data-storage facilities available only to digital computer controllers.

---

* Ministry of Fuel and Power, (Safety in Mines Research Establishment).

† R.O.L.F. - Remotely operated longwall face.

The vertical steering of a coal-cutter within the undulating coal-seam is a first essential to successful face automation in order to ensure that the machine produces coal uncontaminated with rock cut from roof or floor. This is one particular process requiring computer storage as an essential ingredient of its control system as has been reported earlier[3]. Bunker and conveyor controls are other examples[4]. Coal cutter steering is unfortunately a process which is far from amenable to theoretical modelling either for the purposes of control system analysis and design or for performance prediction by computer simulation. Test rigs are therefore essential and the present paper describes in detail the features a quarter-scale coal cutter model instrumented and interfaced to a CONPAC 4020 process control computer for exhaustive preliminary trials of an optimal control strategy derived on the basis of a much-idealised mathematical model of the process.

2.1 The Idealised Theoretical Model

This is based on a consideration of the geometry of the process illustrated diagramatically in figures 1, 2 and 3. Figures 1 and 2 show the coal-cutter in side-elevation and plan view respectively and illustrate the basic operation of the longwall system of working in which the coal-cutting machine is hauled along the entire length, (up to 300m.), of the face riding on the semi-flexible structure of the armoured face conveyor, (A.F.C.), which transports away the coal cut by the rotating drum shown. Machines generally cut in only one direction, (left to right in figures 1 and 2), at a speed of typically three to seven $m.min^{-1}$ and are hauled back in reverse at high speed for the start of the next pass. Between passes, the conveyor is snaked forward hydraulically such that it now rests on the floor produced during the previous pass. This operation is shown in the lower sketch of figure 2.

During the cutting operation, the machine's drum may be raised or lowered with respect to the conveyor by hydraulically tilting the machine body about a pivot line on the drum, or face-side. This facility therefore permits the vertical steering of the entire longwall face installation, (machine, conveyor and roof-support units), to maintain it within the undulating confines of the coal seam's roof and floor. A nucleonic coal-sensor situated some distance behind the drum measures the thickness of the coal ceiling left by the machine and thus provides the primary feedback signal for steering control.

The end-elevation in figure 3 shows the cut to cut behaviour of the steering system but the diagram is idealised in that perfect conveyor flexibility is assumed: a situation far from the truth. On this basis, however, making the additional assumption of small angular changes, (between cuts and in total), from an inspection of figure 3 the following state-transition equation may be written

$$\begin{bmatrix} y(n+1,\ell) \\ a(n+1,\ell) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} y(n,\ell) \\ a(n,\ell) \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} J(n,\ell) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \left[z(n,\ell) - z(n+1,\ell) \right] \qquad (1)$$

where y denotes the roof coal thickness at the face-side of the drum, a, $(= W\alpha)$, represents the component of the drum height due to A.F.C. tilt, J is the manipulable extension of the steering jack and z is the deviation of the coal-seam from some flat datum. The integer n denotes the number of the particular cut considered, and ℓ is the distance of the machine from the face-end at which cutting commenced.

2.2 Control Guidelines

Much theoretical analysis is possible on the basis of equation 1 which is valuable in providing at least guide-lines for control strategies to ensure stability and/or to yield optimal performance according to some criterion (e.g. minimisation of stone cut or of number of cuts taken to restore steady-state from a disturbed condition). As has been demonstrated by the authors[3], for instance, when controlled by an elementary analogue strategy of the form

$$J(n,\ell) = k_h\{y_{ref} - y(n+1,\ell-X)\} - k_g\, a(n,\ell) \qquad (2)$$

, where X is the distance between drum and coal sensor and where k_h and k_g are constant gains, complete instability is predicted whereas control of the form

$$J(n,\ell) = k_h(y_{ref} - y(n,\ell)) - k_g a(n,\ell) \qquad (3)$$

, obtained by increasing X to one face-length by computer storage, produces stable control for acceptable values of k_h and k_g. Optimal control is discussed in section 5.

3. The ¼-Scale Mechanical Model

As already mentioned, one of the chief limitations of the mathematical model of the vertical steering process is its neglect of the rigidity of the steel pans, which together comprise the face-conveyor structure, and the existence of only limited flexibility of the inter-pan joints. In fact N.C.B. specifications[5] lay down that these spigot joints should allow freedom for four degrees of relative tilt between consecutive pans viewed in the along-face direction, (angle of bend), and 0.5 degrees viewed in the face-advance direction, (twist angle). Furthermore, the pans are 1.6m in length and when compared with the dominant dynamic term of the process, namely the sensor displacement, X, (1.3m. typically), this pan-length may clearly not be regarded as infinitesimal element. It is obviously important therefore that pan geometry and the restricted freedom of the joints should be correctly reproduced in any scale model conveyor.

In the real process there is a tendency for the conveyor pans to rock on the undulating cut floor and to bend under the weight of the machine. In addition, on installations where one or more of the four machine skids are vertically as well as horizontally trapped to guide-rails on the sides of the conveyor, there is some tendency for the machine lift the conveyor beneath it rather than for the conveyor to dictate the machine's attitude. To properly account for these effects in a test rig it is therefore necessary that, in reducing scale, the following parameters are preserved: (a), the ratio machine weight/pan weight, (b), the weight distribution within the model machine, (c), the ratio machine weight/pan stiffness and (d), relative trapping clearances.

The theoretical model assumes the drum shaft to be situated vertically above the trailing skids of the machine. With modern machines however the drum is often outslung behind the machine to ease stable-hole cutting at the face-end. In such cases, strong coupling therefore exists between the process response at location n, ℓ and at locations $n, (\ell+\ell_{m1})$ and $n, (\ell+\ell_{m2})$, where ℓ_{m1} and ℓ_{m2} are the horizontal distances between drum-centre and rear skids and between front and rear skids respectively. No such coupling exists in the mathematical process model which assumes the behaviour of infinessimal lengths of conveyor to be independent of the behaviour of neighbouring elements. This again demonstrates the important need for simulation by test rig. Other geometrical differences between the actual process and the sketches of figures 1 to 3 include the fact that conveyor and drum width, though always comparable, are rarely equal as assumed in the mathematical modelling and the small-angle assumptions in the latter can also account for discrepancies between theoretical and actual performance.

Haulage and cutting forces are important factors totally ignored in the mathematical model. A few high-speed machines with forward-rotating drums, (hence generating upward cutting reactions), are, in fact, steered quite effectively by manual manipulation of haulage speed and, though this technique is less positive than hydraulic steering, it does demonstrate the importance of these forces in any steering process. The magnitude of cutting and haulage forces varies considerably with drum dimensions, hardness of coal, machine-speed, drum-speed, cutting-tool condition and other factors so that, in modelling, it is practical only to achieve the correct relative order of cutting and haulage force.

With a geometrical scale reduction of 4:1 it has been found that the cutting of expanded polystyrene, (to simulate the coal), at a speed of 1/6th normal, (expressed in pan lengths p.u. time), allows cutting to a depth of about 53 m.m. with a 106 m.m. drum driven at 1600 rpm by a 0.5 k.W. 3 ph. motor, this being the heaviest drive allowable consistent with limitations on total weight and weight distribution. The drum forces, approaching 10 to 12.5 kg., were thus comparable with the total model machine weight of 40 kg, as in real life*, and the depth of cut achievable allowed large-scale steering manoevres to be made with the drum well-immersed in the polystyrene. The haulage speed reduction to 1/6th normal necessitated a period of some 40 minutes for a cut of 20 scaled pan lengths which, though slow, was not unduly inconvenient since complete automation of the experiments, with exception of conveyor pushover, obviated the need for continuous supervision.

The model used in the experiments here reported is illustrated in figures 4 and 5 which clearly show the polystyrene bed, the aluminium conveyor pans, the flat, level datum ceiling used as a basis for all measurements and the model machine itself on which the cutting drum and its drive, the chain haulage arrangements, the electrical steering servomechanism and various transducers are all obvious. Not shown is the vacuum cleaner hose, normally attached to a drum shroud, and fitted for clearing of the polystyrene dust.

4. Instrumentation for Remote Computer Control

4.1 Basic Measurements

These, at instant $(n+1,\ell)$, are the variables $y(n+1,\ell-X)$ and $a(n,\ell)$ which are extracted from the model from the vertical rectilinear potentiometer and the pendulum potentiometer, (inclinometer), shown in figures 4 and 5.

The delay X is, in fact, effected within the digital computer, and any seam disturbances z added electronically to the height potentiometer output.

*A real machine of 5 tonne weight would produce cutting forces of the order of 1.8 tonne.

In practice the nucleonic coal-sensor produces a random Poisson-distributed pulse train whose <u>mean</u> frequency, c, is a function[6] of the process variable y. This randomness is an important source of control error[7] and is simulated on the model by first using the potentiometer signal to modulate the clocking of a Poisson sequence generator here programmed on an AD4 analogue computer. The accumulated pulse-counts stored on this computer are then read into the CONPAC 4020 process control computer along with the tilt signal, a, at each sampling instant. The steering jack extension signal, $J(n,k)$, measured on the model by the multiturn potentiometer of the electrical steering servo is also read in to the CONPAC computer for logging and security purposes, along with the true signal y also for logging purposes only.

The computer interrupt signals for initiating the control and logging programs and for reading data in and out of the CONPAC are distance pulses generated by a switch actuated by a rotating cam on the haulage drive, geared to give 15 pulses per pan length.

4.2 The Steering Servo Mechanism

In practice this is an electro-hydraulic system having a fairly substantial time-constant of the order of 2.75 sec. in real time, equivalent to 6x2.75 = 16.5 sec. on the slower model. On the model, a fast-acting electrical bang-bang servo is used, the reference signal for which is derived from a simulation of the 16.5 sec. lag implemented on the AD4 computer and which in turn receives a calculated jack-demand signal from the CONPAC 4020. The jack-demand and jack feedback signals are constantly compared within the process computer to check on the correct functioning of the servo. Adjustable preset limits to the jack-travel are conveniently set on the analogue computer.

4.3 General On/Off and Emergency Features

Apart from reasons of purely local convenience, it was required to automate the experiments and the model operation as far as possible, in order that the trials should be realistic and show up the ergonomic system requirements for satisfactory remote computer control from the point of view of the machine operator and the trials engineer. The now-mandatory, pre-start, audible warning on the machine is implemented by means of suitable timing segments in the initialisation portion of the control program which raise logic lines to initiate the claxon for three seconds and then, after a further two seconds delay to switch in the appropriate haulage and drum motor-start and direction relays as selected. Logic inputs to the computer test the availability of the necessary power supplies before allowing the pre-start warning to sound. The machine automatically stops upon receipt of a predetermined number of interrupts, raises the drum clear and returns for the start of the next cut.

As an aid to the laboratory experimentor, the same audible warning is employed to monitor the computer operation and to sound continuously upon expiry of a watchdog timer which is normally reset by a logic output pulse raised after each execution of the control program segment. This is believed to be an important feature for incorporation into the real system. A display of the computer calculated machine position, updateable by the machine operator by the pulsing of a manual interrupt button, is a further feature found to be required in practice.

Coal thickness data from the simulated coal sensor, (amounting to some 4000 samples on a complete coal face), would, on a dedicated underground computer, be stored probably only in core since bulk storage underground is difficult to envisage at the present state of technology. In this experimental situation, (and as will probably be the case on first field trials[8]), a remote multi-user computer is used and, though core and disc data-tables are employed for inter-cut data storage, a magnetic tape of this data is also produced for refreshing the tables at the start of the next cut in the event of a system failure resulting in loss of data between cuts.

During each cut, extensive use is made of the visual display screens not only for remote process initiation and for the display of alarm messages, but also for the display of all process variables in tabular or graphical form. Purely for off-line data-analysis at a future date, and not necessarily part of any on-line controller, a second cumulative tape record of all these variables, identified by cut number, is also produced. The records displayed in this report were in fact photographed off-line from the visual display of this taped data for a sequence of seven consecutive cuts.

5. Computer Control Algorithms

A number of possible control algorithms are worthy of appraisal by means of laboratory trial and indeed the first task of the mechanical model was to confirm the predicted instability of the elementary "analogue" control law of equation 2 and the stability of the elementary, stored-data, proportional control law of equation 3. The latter, however, is based on a total neglect of the practical limits, $\pm J_m$, of the available stroke of the steering jack and the controller therefore exhibits considerable overshoot in responding to large perturbations unless gains are reduced, in which case a heavily-slugged response is obtained. Of much more interest is the performance of the system controlled by strategies designed in full knowledge of the existence of the jack limits.

5.1 The Minimum Time Controller

The process being distance rather than time-based, this is more precisely described as a Minimum Distance controller, but the latter term is an unfamiliar one and therefore discarded. The object of the controller is, never-the-less to return the process to its steady-state from any disturbed initial state in the minimum number of passes, or cuts. Very briefly, its derivation is as follows:

Firstly, for simplicity, the constant y_{ref} (= the steady state value of y) is taken as zero and, since all along-face coupling in the process model is neglected, the argument ℓ is dropped from the state equation, (1), which may now be written, without the random coal-seam disturbances, in the form

$$\begin{bmatrix} y(n+1) \\ a(n+1) \end{bmatrix} = \begin{bmatrix} 1, & 1 \\ 0, & 1 \end{bmatrix} \begin{bmatrix} y(n) \\ a(n) \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} J(n) \tag{4}$$

where $|J(n)| < J_m$ (5)

The controller is derived by working backwards from the terminal state of a process (of total duration, say, N passes), which is desired to be

$$[y(N), \; a(N)]^T = [0 \; , \; 0]^T \tag{6}$$

From equations 4 and 5, this desired end state is attainable in a single pass from a range of states at the N-1th pass, given by

$$\begin{aligned} & y(N-1) = y(N) - a(N) = 0 \\ \text{and} \quad & a(N-1) \; \varepsilon \; [a(N) - J_m, \; a(N) + J_m] = [-J_m, \; +J_m] \end{aligned} \tag{7}$$

i.e., the penultimate states can occupy a straight-line segment of the state-space lying on the axis of a(N-1).

In general, the N-ith state, $[y(N-i), a(N-i)]^T$, of the process is related to the N-(i+1)th states from which it can be attained in a single pass, by the mapping

$$\begin{aligned} & y(N-\overline{i+1}) = y(N-i) - a(N-i) \\ \text{and} \quad & a(N-\overline{i+1}) \; \varepsilon \; [a(N-i) - J_m, \; a(N-i) + J_m] \end{aligned} \tag{8}$$

i.e., any point in the state-space at stage N-i maps back to a straight-line segment in the state-space at stage N-(i+1).

It is readily shown, using equation 8, that a continuous straight-line

$$y(N-i) = b_{N-i} - c_{N-i} a(N-i) \tag{9}$$

in the state space at stage N-i is attainable from states at the N-(i+1)th stage of the process which lie within a domain bounded by the two continuous straight lines

$$y(N-\overline{i+1}) = \left[b_{N-i} \pm (c_{N-i} + 1)J_m\right] - (c_{N-i} + 1)a(N-\overline{i+1}) \qquad (10)$$

From the general relations 8 and 10 for the single-step, backward mapping of points and straight-lines, a simple backward recursive procedure yields the straight-line boundaries of domains of the state-space from which the desired end-state is attainable in 1,2,3...N steps respectively.

Putting i = 1,2,3,4,5 successively in equations 8 and 10, and substituting at each stage the newly calculated line intersections and parameters, b_{N-i} and c_{N-i}, yields boundary equations as follows:

<u>i = 1</u>, (2-step domain)

$$y(N-2) = \pm J_m$$
$$y(N-2) = \pm J_m - a(N-2) \qquad (11)$$

<u>i = 2</u>, (3-step domain)

$$y(N-3) = \pm 3J_m$$
$$y(N-3) = \pm 2J_m - a(N-3) \qquad (12)$$
$$y(N-3) = \pm 3J_m - 2a(N-3)$$

<u>i = 3</u>, (4-step domain)

$$y(N-4) = \pm 6J_m$$
$$y(N-4) = \pm 4J_m - a(N-4)$$
$$y(N-4) = \pm 4J_m - 2a(N-4) \qquad (13)$$
$$y(N-4) = \pm 6J_m - 3a(N-4)$$

<u>i = 4</u>, (5-step domain)

$$y(N-5) = \pm 10\ J_m$$
$$y(N-5) = \pm 7J_m - a(N-5)$$
$$y(N-5) = \pm 6J_m - 2a(N-5) \qquad (14)$$
$$y(N-5) = \pm 7J_m - 3a(N-5)$$
$$y(N-5) = \pm 10J_m - 4a(N-5)$$

<u>i = 5</u>, (6-step domain)

$$y(N-6) = \pm 15J_m$$
$$y(N-6) = \pm 11J_m - a(N-6)$$
$$y(N-6) = \pm 9J_m - 2a(N-6) \qquad (15)$$
$$y(N-6) = \pm 9J_m - 3a(N-6)$$
$$y(N-6) = \pm 11J_m - 4a(N-6)$$
$$y(N-6) = \pm 15J_m - 5a(N-6)$$

Equations 6, 7 and 11 to 15, thus specify the boundaries of domains from which a minimum of 0, 1, 2...6 steps are required to attain the desired end-state, $[0,0]^T$, and these are graphed in figure 6.

Now it is merely necessary to establish a value of control at each stage of the process to take it to the next domain. This control is non-unique generally and its range is bounded by floating limits J_1^*, J_2^* which are determined as follows:

Eliminating the control J between the two component equations of state-equation 4, it follows that, for a given initial state, $[y(N-\overline{i+1}),\ a(N-\overline{i+1})]^T$, the resulting state must lie on the locus given by

$$y(N-i) = y(N-\overline{i+1}) + a(N-i) \qquad (16)$$

Now the intersection of this locus with the closed boundary of the i-step domain yields two limiting values of a(N-i) denoted here by $\hat{a}(N-i)$ and $\hat{a}'(N-i)$. Thus, from the state equation, it follows that the bounding values of the optimum control for the transition are given by

$$J_1^* = \hat{a}(N-i) - a(N-\overline{i+1}), \quad |\hat{a}(N-i) - a(N-\overline{i+1})| \leq J_m \qquad (17)$$

$$J_1^* = J_m \quad , \quad \hat{a}(N-i) - a(N-\overline{i+1}) > J_m \qquad (18)$$

$$J_1^* = -J_m \quad , \quad \hat{a}(N-i) - a(N-\overline{i+1}) < -J_m \qquad (19)$$

$$J_2^* = \hat{a}'(N-i) - a(N-\overline{i+1}) \quad , \quad |\hat{a}'(N-i) - a(N-\overline{i+1})| \leq J_m \qquad (20)$$

$$J_2^* = J_m \quad , \quad \hat{a}'(N-i) - a(N-\overline{i+1}) > J_m \qquad (21)$$

$$J_2^* = -J_m \quad , \quad \hat{a}'(N-i) - a(N-i+1) < -J_m \qquad (22)$$

and the optimum control $J^*(N-\overline{i+1})$ is merely governed by

$$J^*(N-\overline{i+1}) \in [J_1^*, J_2^*] \qquad (23)$$

The computer control algorithm therefore builds at each sampling instant up the domain boundary equations 6, 7 and 11 to 15 in that sequence, testing each time to determine whether or not the present process state $[y,\ a]^T$ is enclosed. Once the domain order has been thus established, equation 16 is used to determine the intercepts $\hat{a}$ and $\hat{a}'$ with the next domain and thus the bounds J_1^* and J_2^* are determined according to equations 17 to 22. A free choice for the optimum control exists within these bounds and in the trials here reported, the limit giving the new state closest to the origin was used.

5.2 The Smoothing of the Coal-Sensor Signal

As described in section 4.1 the nucleonic coal-sensor, (and its simulation), produces an output signal contaminated with a considerable level of noise. In conventional analogue control, (equation 2), simple ratemeter filtering is all that is possible, using effectively a filter transfer-function of the form

$$F_r(s) = \frac{K_r}{1 + T_r s} \qquad (24)$$

The use of stored-data control (for example equation 3 or control of the form just described) allows much more sophisticated filtering to be used, however, due to the filter having access to data received before and after the point in space for which the y-estimate is to be made. A near-optimal filter[7] for this application has the transfer-function

$$F_o(s) = \frac{K_o}{1 - T_o^2 s^2} \qquad (25)$$

For its implementation in the time-domain, this filter requires the entire input data-stream to be recorded, and subsequently passed, in reverse-time sequence through a transfer-function

$$F_{o1}(s) = \frac{0.5K_o}{1 + T_o s} \qquad (26)$$

, the output function of which is again recorded and then reversed in time-sequence. The filter output is now formed from the summation of this last time function and the original input function, itself pre-processed by $F_{o1}(s)$.

The operations are therefore executed by the computer between cuts and the smoothed y-data thus obtained used during the subsequent cut for control purposes.

6. Results and Conclusions

The results here presented are those from a trial designed to test the control system as rigorously as possible. The conveyor was initialised on a suitably-profiled launching platform at varying heights and tilts along its length which were chosen to generate state-trajectories sweeping through as large a volume of the state-space as allowed by the limitations on depth of cut. The desired steady-state was a flat horizontal surface.

The model's response, $y(n,\ell)$, over a sequence of seven cuts, photographed direct from the screen of the visual display unit, is shown in figure 7 and, for purposes of comparison, the computed response based on equation 1 is given in figure 8 for virtually identical initial conditions. The model and system parameters were as shown in table 1 below.

Table 1. Model and System Parameters (adjusted to full scale)

Conveyor Width	= 813 mm	J_m	= 38 mm
		Initial conditions:-	
Drum Width	= 712 mm	$y(0,0)-y_{ref}$	= 152mm
Pan Length	= 1524 mm	$a(0,0)$	= 50.6mm
Length of test cut, L	= 30.5 m	$y(0,L)-y_{ref}$	= 254mm
Sensor Displacement	= 1220 mm	$a(0,L)$	= -50.6mm
Machine Speed	= 3.3 $m.min^{-1}$		
Distance between machine feet	= 4.37 m	Sampling distance	= 102mm
Horizontal distance between drum shaft and trailing feet	= 0.0 m	Vertical trapping	= none
Opt. Filter Time-Constant	= 5.0 sec	Drum rotation - forward	
Actuator Time-Constant	= 2.75 sec		

The mechanical model is quite clearly controlled in a stable manner but is rather slower in achieving steady-state than is the idealised process. In the along-face direction this is presumably the result of conveyor inflexibility and, in the face-advance direction, because of the unpredicted undershoot which resulted from excessive downward tilts experienced on the downward portion of the state trajectories. These occurred despite the upward cutting force and are attributable to the model's centre of gravity being higher by 20% than in a real machine and to the absence of vertical trapping which is, with hindsight, clearly necessary for such drastic manoevres. Trapping merely of the trailing skid opposite the drum would probably suffice and thus avoid the risk of machine and conveyor becoming iron-bound.

Finally, as a demonstration of the idealised nature of the mathematical model, figure 9 is here included to compare the predicted and actual conveyor behaviour from cut to cut. The actual change of conveyor tilt is plotted against the appropriate applied jack extension, for a number of widely-separated stations along the face. The scatter is typical of field experience[9]. The data presented was extracted from the cumulative taped record of the experiment, again via the visual display unit.

7. References

1. Policy statement by N.C.B. Chairman to Mining Research and Development Establishment, April 1974, Mining Technology, May 1974, Vol.56, No.643, pp.188-189.
2. Pidgeon, B.G. and Thomas, V.M., "Remote control of face machinery", Proc. of Symposium on Remote Control of Electrical & Mechanical Equipment at the Coal Face, Harrogate, No.v 1964, A.M.E.M.E. Journal, Vol.45, pp.277-304.
3. Edwards, J.B. and Bogdadi, W.A., "Progress in the design and development of automatic vertical steering systems for underground coal cutters", Proc. I.E.E., Vol.121, No.6, June 1974, pp.533-536.
4. Edwards, J.B. and Marshall, S.A., "The integrated plant and control system design for the operation of a mine at minimum cost", Proc. of I.F.A.C. International Symposium on Automatic Control in Mining Mineral and Metal Processing, Sydney, Aug. 1973, IFAC Conf. Pub. No. 73/4, pp.237-244.
5. N.C.B. Specification No. 371/1963, "Line pans for 7" heavy armoured conveyors (Mark III)".

6. Cooper, L.R., "Gamma-ray backscatter gauges for measuring coal thickness on mechanised coal faces", Proc. of I.E.E. International Conference on Industrial Measurement and Control by Radiation Techniques, Guildford, 1972, I.E.E. Conf. Pub. No. 84, pp.89-93.

7. Edwards, J.B., "Coal sensing optimisation with the aid of an on-line process control computer", Report submitted to N.C.B., M.R.D.E., May 1974.

8. Bennett, S. and Edwards, J.B., "The computer control of a longwall coal cutting machine via G.P.O. line", Proc. of I.E.E. Conference on Trends in On-line Computer Control Systems, Sheffield, April 1972, I.E.E. Conf. Pub. No. 85, pp.107-116.

9. Webb, R.E., "Automatic vertical steering of coal face machines", Proc. of 3rd U.K.A.C. Control Convention, Leicester, April 1968.

Fig. 1. Side View of Coal Cutting Machine

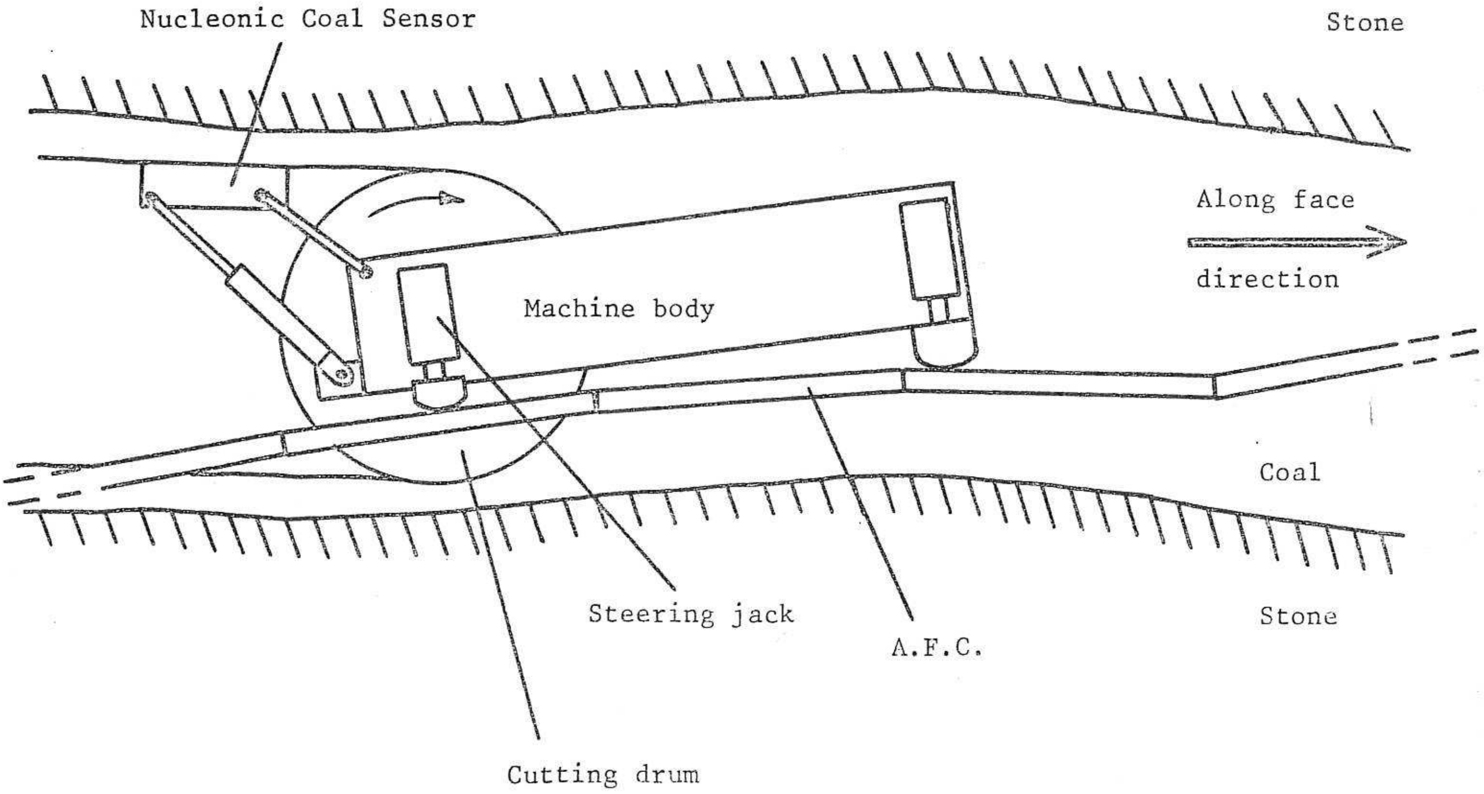
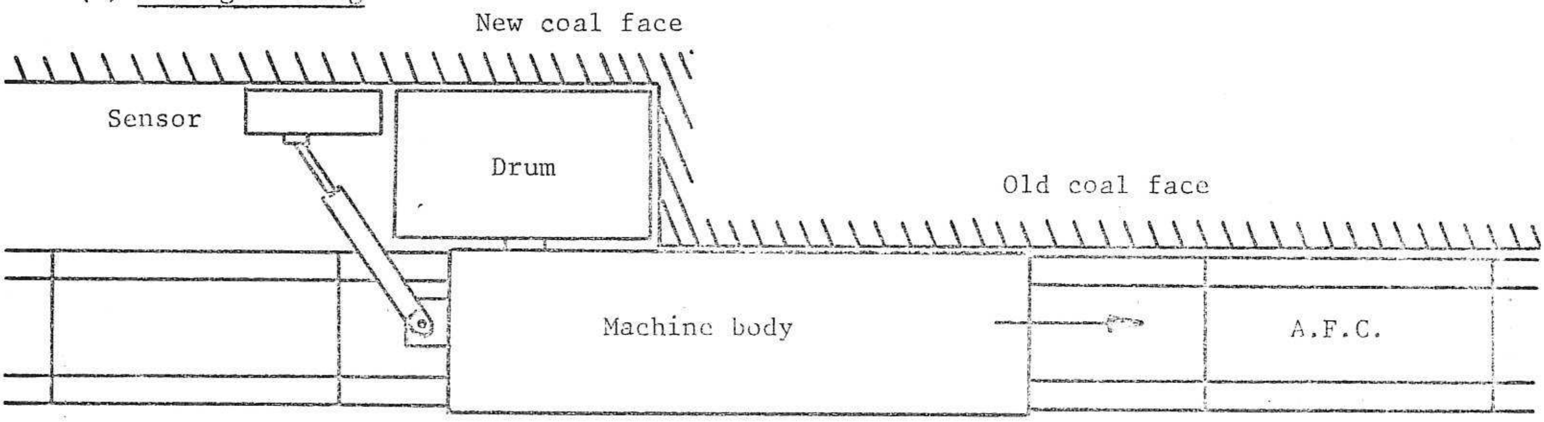
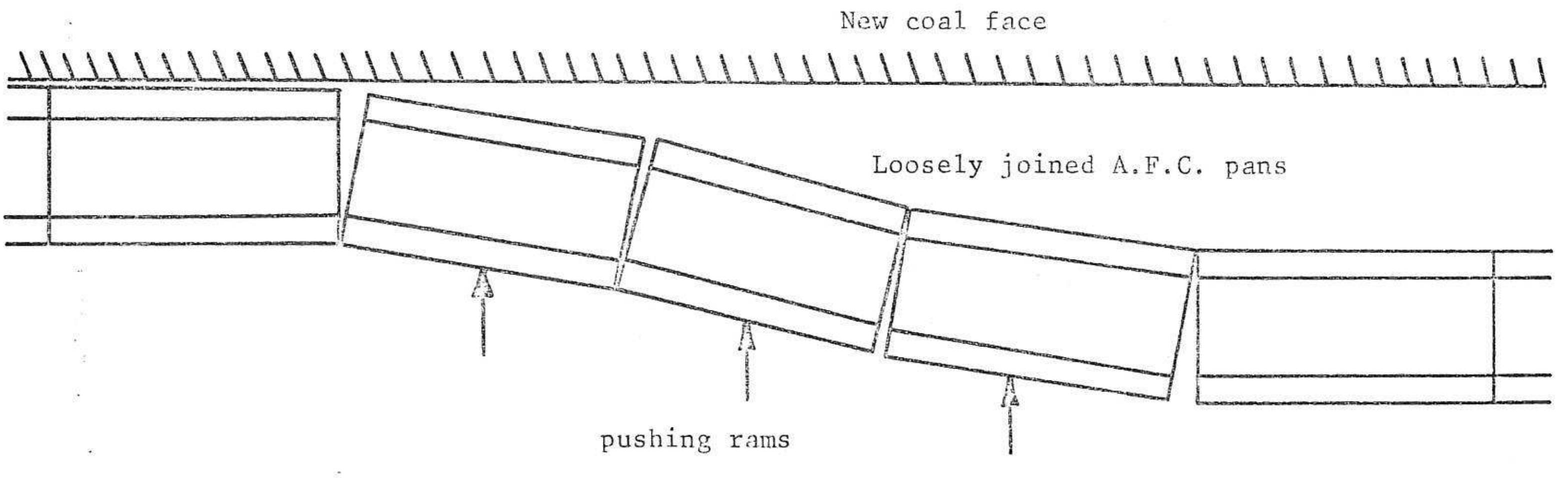


Fig. 2. Plan View of a Short Section of Coal Face

(a) During Cutting



(b) During A.F.C. Pushover



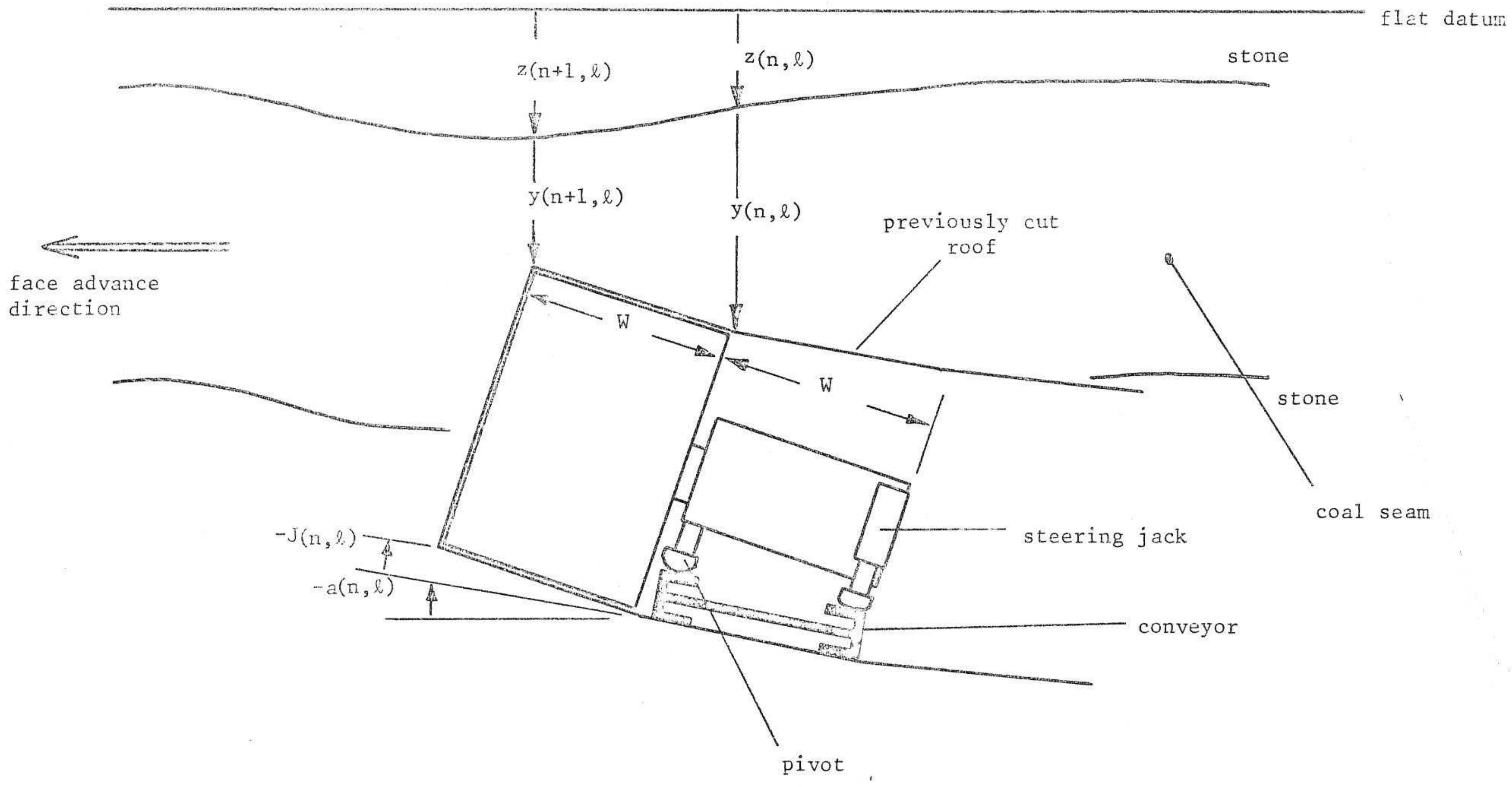


Fig. 3. End View of Roll Steering Machine (nth, cut)

Fig.4

Height potentiometer

Tilting mechanism

Datum ceiling

Cutting drum

A.F.C. pan

Inclinometer

Drum-drive motor

Fig.5

Servo drive motor

Height potentiometer

Launching platform

expanded polystyrene

Haulage motor

Interrupt switch

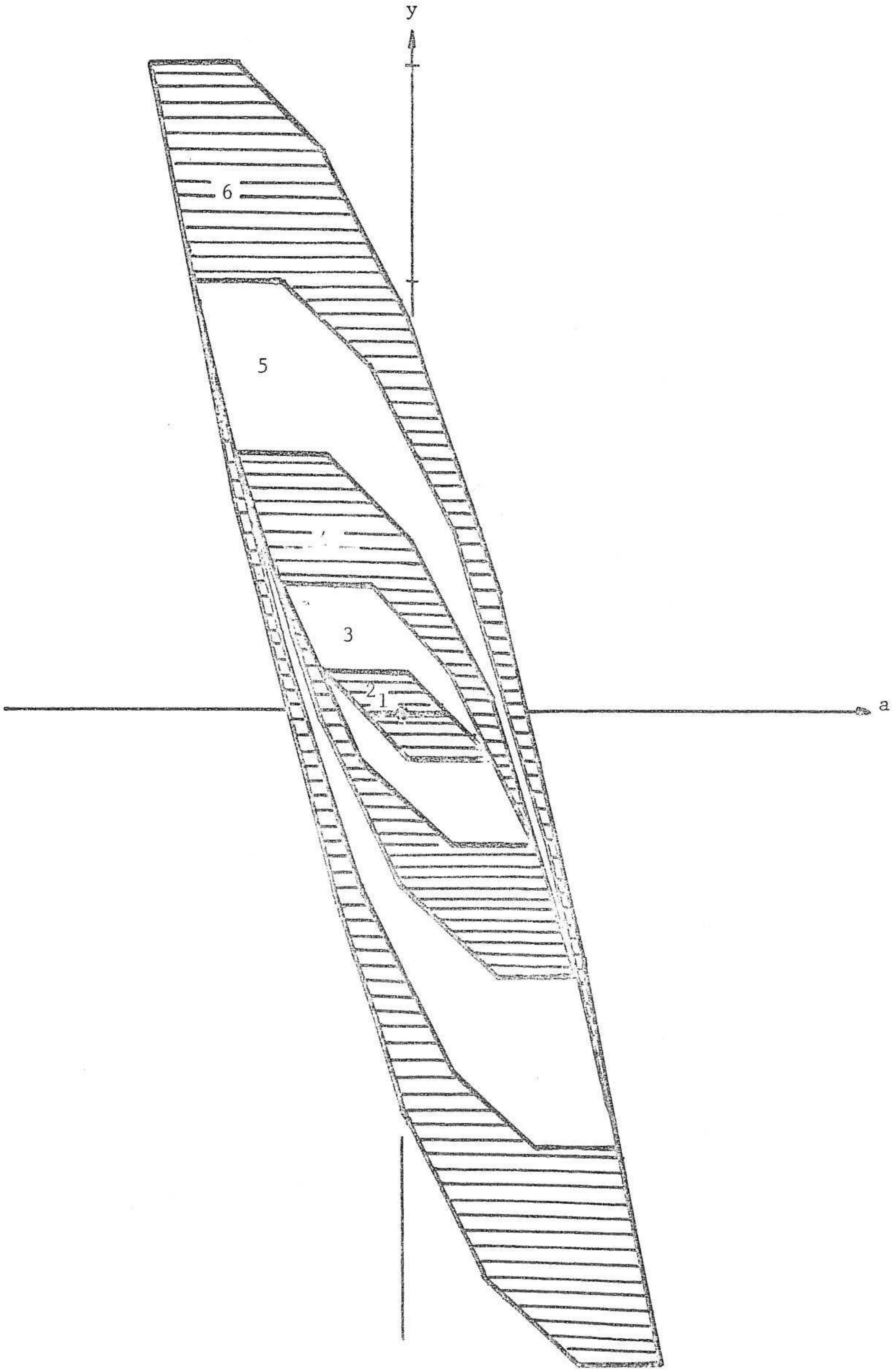


Fig. 6. Domains of Controllability

Fig. 7. Response, $y(n,\ell)$, of $\frac{1}{4}$ Scale Model

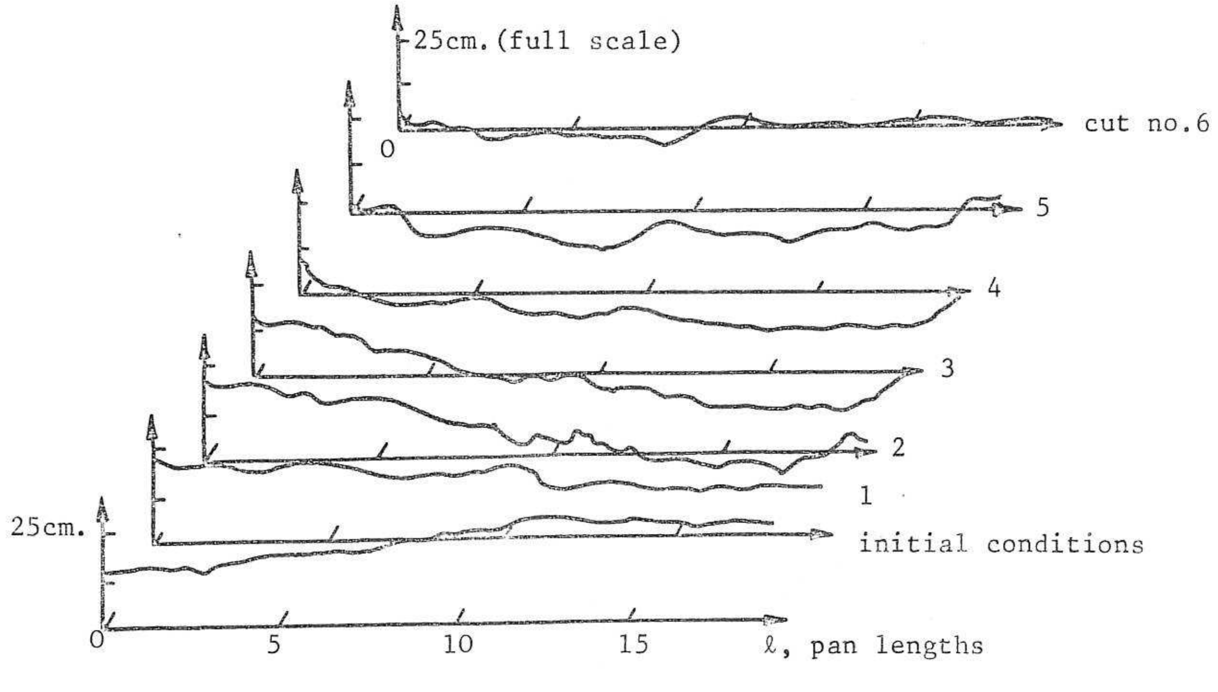
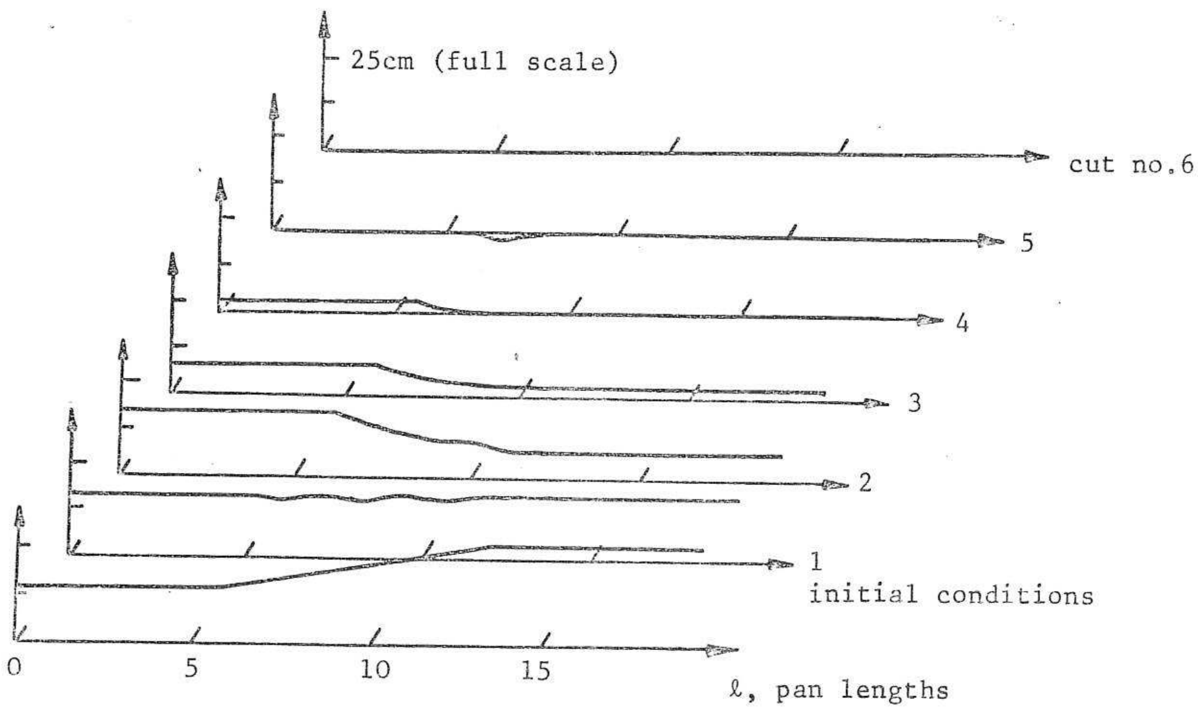


Fig. 8. Response $y(n,\ell)$ - Simulation



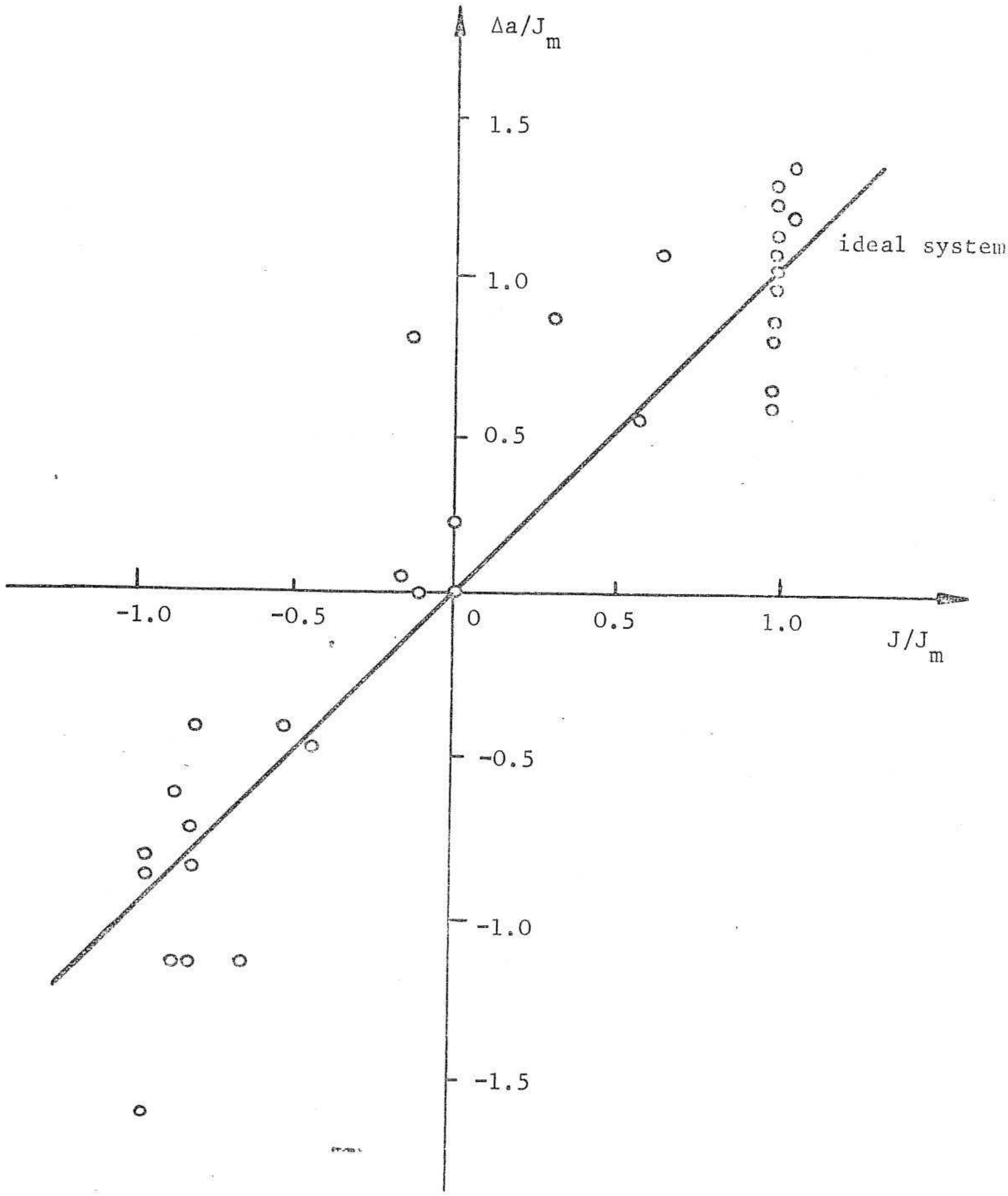


Fig. 9. Steering Characteristics of $\frac{1}{4}$-Scale Model