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THE COLLEGE OF AERONAUTICS
CRANFIELD

INCREMENTAL CONTROL

by

A. L. Watson and D. W. McQue

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SUMMARY

This Note describes the control of a centre lathe using stepping motors and a small computer. The mechanical conversion is low cost and the system described is readily adaptable to the simultaneous control of a group of machine tools.

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Summary

A small digital computer has been used to control precision turning on a modified lathe at the College of Aeronautics. Stepping motors were coupled to the leadscrews on the top and transverse slides to provide the power to position the slides accurately. The computer was originally used to simulate a cheap control unit for the modified lathe, but, as a result of this work, it became clear that the computer could be used as a cheap flexible control for the simultaneous operation of a group of machine tools. This type of control has been called Incremental Control, in order to distinguish it from Numerical and Program Control.

A component is machined by converting information, usually in the form of a drawing, into commands to a machine tool. In the case of a conventional machine tool, this conversion is made by the machine operator. Automation is applied to replace all or part of this task of converting information. No such automated control can be as versatile as a human operator since, for economy, it must have a limited repertoire of commands and so it does not usually have the ability to cope with unusual circumstances. On the other hand, such a control will faithfully repeat a task without becoming tired and thereby causing errors. Thus automation can be applied to reduce the monotony and/or simplify the complexity of a machining operation by taking over the routine tasks.

The control is usually made up of two parts, 'Software' and 'Hardware' (see Figure 1). The hardware consists of the electronic components in the control and is fixed at the time of manufacture. The software consists of the programs which are fed into the hardware to activate the control. The nature of the control can be changed by altering the software and a predominance of software in the control is an insurance against obsolescence, allowing rapid economic modifications and extensions to the control. A general purpose computer has this predominance of software control. Modifications to hardware are generally more expensive than modifications to software since hardware has to be rewired and meanwhile the control is out of service.

A comparison can be drawn between Numerical and Incremental controls. The scope of a NUMERICAL control system depends largely on the hardware of its control, which has to be evaluated when the control is designed. While the basic control hardware can be cheap and satisfactory, refinements such as information feedback are usually expensive and may still be inadequate.

The scope of an INCREMENTAL control system depends largely on the software used with the computer; thus, the system can be tailored to meet the individual requirements of each machine tool. The main cost involved in producing a control occurs in writing the computer programs, whereas the cost of enlarging the hardware in the interface is usually small. The control can be modified in most cases without putting the machine tool out of service. Service will be lost where modifications are made either to the structure of the machine tool or to the hardware of the interface.

Stepping motors can be fitted to a new machine tool or by modifying an existing one. Once the basic control has been fitted, additional control can be added according to the nature of the work planned for the machine tool. A number of specialised tools can be simultaneously controlled by the computer on a time sharing basis because the computer, as is shown later, can deal with control input and output commands much faster than the machine tools are capable of dealing with the commands. The cost of the control is reduced since the scope of the individual machine tools is limited. The combined scope of all the machine tools controlled by the computer is very large.

There is a limiting number of facilities that can be fitted to one machine tool. If this limit is exceeded, the cost of providing extra facilities that are rarely used cannot be recovered. All the machine tools on an incremental control system can be used at the same time, which means that better use can be made of the facilities provided.

At Cranfield the computer has reduced the costs of developing the incremental control system. It was found that the computer programs could be readily modified by the Mechanical Engineer, causing very little down-time since no hardware had to be modified (hardware modifications can seriously increase development costs). Also, no expensive hardware will be scrapped if the project is abandoned.

Incremental control can be adapted to other systems besides machine tool control. Essentially, the computer has been used to control a number of stepping motors, and can be used wherever stepping motors are used. Incremental control has been developed on a machine tool and this application is described in this report.

Co-crdinate Control of Two Stepping Motors

The simplest program is described below to illustrate the operation of the computer. This involves the control of a pair of stepping motors for two axes co-ordinate machining. There is no feedback.

A stepping motor is electrically controlled so that its shaft rotates in steps which have a fixed angle of revolution. For example, the motors used for this project move through 200 steps to turn through one revolution. By careful manufacture, the motors can be made to step through the same angle each time with high precision. There are two main types of stepping motors, one of which is the phase pulsed synchronous stepping motor which works on the same principle as a synchronous motor. A rotating field is set up in the stator, and this is followed by the poles on the armature. The field of the stepping motor is rotated by switching the polarity of direct current across the field windings. Each time the current is switched, the armature rotates through one pole pitch and the motor shaft rotates through the fixed angle. The other type of stepping motor uses a solenoid operated ratchet to turn the rotor. The solenoid is energised by a control circuit and the ratchet pulls the rotor through the fixed angle.

The computer control of a phase pulsed synchronous stepping motor will be described in this report. A pair of bistable multivibrators is used to switch the current across the field windings in this motor.

The multivibrators are triggered by pulses which, in the case of computer control, are supplied by the computer. The motor with its drive circuits forms a digital to analogue converter.

The interface between the computer and the stepping motor consists of the drive circuits and a gate which controls the direction of rotation of the motor. By adding a second drive circuit and gate, two stepping motors can be controlled from the computer to perform any co-ordinate movement.

When a pulse is sent to a stepping motor that is coupled to the leadscrew on a machine tool slide, the slide moves accurately through a fixed increment, Any distance moved by the slide can be subdivided into a number of increments and, hence, represented by a number of pulses. The feed rate of the slide is controlled by the rate at which the pulses are sent to the stepping motor.

To control the motor, the computer has to process three items of information.

1. Direction code

   This operates the gate on the output of the computer and connects it with the peripheral (the peripheral in this case is the stepping motor). Another part of this code operates the gate on the interface and specifies which motor will turn and its direction of rotation.

2. Increments

   This is the number of pulses that the computer has to output in order to make the slide move through the required distance.

3. Feed

   This is the number which specifies the delay time between each pulse.

As mentioned previously, the computer can supply pulses at a much faster rate than the maximum rate that can be handled by the stepping motor. The computer is therefore under-utilised since it wastes time between each pulse. Instead of wasting time, the computer can be used to service other stepping motors between each pulse by the technique known as 'time sharing', which is described later in this report.

By using these three instructions, a co-ordinate path can be followed. The path shown in figure 2 can be split into the following sections: A - B, B - C, ... F - A. The three instructions are specified for each section and are listed to form a data program. This program is stored consecutively in the computer.

An octal debug program is initially stored in the computer. This allows data to be stored or output from the computer via the teletype.

A computer program is used to translate the data program into output signals in accordance with the flow charts which are shown in figure 3. The main part of this program copies the data for each section in turn into a subroutine which outputs the pulses. When one section has been completed in the output subroutine, the next section is installed. This process continues until all sections have been completed, whereupon a path will have been described by the motors in accordance with the data program.

Machine Tool Conversion

The conversion of the lathe at Cranfield formed the main part of a thesis written by one of the Authors. A brief summary of this work is given below.

A standard V.D.F. centre lathe with a two feet swing was converted with stepping motors to control precision machining of the blade slots in Steam Turbine rotors. The rotors are machined by hand at present and cause some anxiety even to a highly skilled Operator. The rotor cannot be scrapped since to replace it would seriously delay a turbine supply contract. Coupled with this, the added machining costs of the rotor is high and the machining tolerances on the blade slots are small. The subject of the thesis was to study the application of stepping motors to control a lathe with reliability when machining the rotors.

The conversion was made as follows. A new crossed-roller top slide was fitted to the lathe. This slide was designed with a ball recirculating leadscrew held in a double angular contact bearing and driven by a stepping motor. The ratio of the gearbox, between the stepping motor and the leadscrew, was selected so that the slide moved in increments of 0.00005 inches. This high precision slide could be positioned repeatedly within one increment.

Another stepping motor was fitted to the existing leadscrew on the transverse slide. This slide moved in increments of 0.00014 inches, and could be repeatedly positioned within 0.00025 inches.

The stepping motors were coupled to the computer using a similar interface to the one described in the previous section. There was no feedback of the position of the slides, so the lathe was controlled by an 'Open Loop' system.

The stepping motors could be controlled manually by pressing one of four buttons mounted on the interface. (Four buttons were required to specify which motor to operate and its direction of rotation). When a button was pressed a signal was fed back to the computer which then operated the appropriate motor - (further details of this control are given in the section on feedback). The cutting program could be interrupted by pressing one of the manual control buttons, so that if the lathe went out of control, for example - if the cutting tool began to chatter, the tool could be withdrawn by pressing a button. The motors could be run at two feed rates which were preset in the computer program. The fast feed was generally set at the maximum rate for the motor, whereas the slow feed was generally set for fine adjustment of the slides at about 4 puleses per second, which was equivalent to a feed on the compound slide of 0.0002 inches per second. This slow feed rate was very useful when setting the tools to a datum.

The cost of this conversion was £1000. The estimated cost of a simple control system to allow two axes co-ordinate machining was £500. Machining tests have shown that the system is reliable as long as the stepping motors are not overloaded. The control system is cheap and is ideal for light precision machining.

Further conversion of the machine tool, using feed back or different types of stepping motors, is required in order to perform heavy machining. The following suggestions describe possible methods of conversion but these methods have not been tested at Cranfield.

When a stepping motor is subjected to excessive torque, it stalls. This can happen on a machine tool when the cutting tool becomes blunted, the control continuing to send pulses to the motor, these pulses being ineffective. A way in which this problem can be overcome is to fit a hydraulic amplifier to the stepping motor. This is a hydraulic motor which is servo controlled by the stepping motor, and heavy duty machining can be undertaken with these motors without fear of losing pulses. The disadvantage of these motors is their high cost, which is increased by the need for a power pack to supply the oil.

When a stepping motor stalls, the supply current rises. This rise can be used to send a signal to the control, which will either stop the program or issue another pulse to check whether the pulse has been lost because of freak conditions. Encoders provide another way of feeding back a signal. They are attached to the leadscrews and emit pulses when rotated. If there is a discrepancy between the pulses sent in and those emitted by the encoders then a pulse has been lost. Encoders have the additional advantage over current sensing devices in that a check can be kept on the position of the slide.

The low power and large gear ratio of the stepping motor drive means that the feed rate of machine tool slides is low. For example, the top slide fitted to the V.D.F. lathe at the College has a maximum feed rate of 0.6 inches per minute. The maximum speed of rotation of a stepping motor drops dramatically as the torque output rises. (See figure 4). A hydraulic amplifier reduces the torque loading on the stepping motor and much higher speeds can be achieved. High speed stepping motors have been developed commercially and are called 'multi-phase motors'. These motors have several stator windings fitted axially along the motor (usually about 6) and speeds of 17,000 pulses per second have been reached. At these high speeds, the motors can still manage a torque output of about 20 oz. in., which is adequate to control a hydraulic amplifier.

Accelerating and decelerating circuits have to be used to control high speed stepping motors. At maximum speed, the motor cannot be stopped in the time between adjacent pulses; the deceleration circuit slows the pulse rate as the final position is approached. This circuit is incorporated in the drive unit.

With the lathe conversion mentioned above, the feed rate of the slides is not related to the cutting speed of the workpiece, which means that the feed rates have to be respecified on the data program each time the cutting speed is changed. Change in cutting speed can be indicated by feedback of a signal which varies according to the speed of rotation of the headstock spindle. This can be done, for example, by using magnetic pick-ups situated next to a gear wheel on the headstock spindle. When a tooth of the gear wheel passes the pick-up, a pulse is generated, the pulse rate depending on the speed of the gear. Another way in which this can be accomplished is to couple to the headstock spindle a tachometer which will produce a voltage proportional to the spindle speed. The speed signal is used to control the delay time between the pulses and, hence, the feed rate of the slides. The method by which this is done is discussed in the next section.

Tests have not yet been made on the application of hydraulic amplifiers, high speed motors, or the feedback systems mentioned above. It is impossible to say which is the most economic system since this will obviously depend on the machine tool and the situation in which it is used.

Feedback and the Interface

Feedback to a computer allows decisions to be made and action taken according to the state of the machine tool. A computer can make decisions on only one fact at a time and the answer is either 'Yes' or 'No'. The action taken may or may not involve another decision. Several requests can be made to the computer for decisions and these must be taken in order of importance, otherwise incorrect action may be taken.

When a signal is generated on a peripheral, a request is relayed to the computer to interrupt the program on which it is engaged. When this is possible, the computer control is diverted to a priority list. The computer scans the priority list until it finds which peripheral generated the interrupt, this being specified by the peripheral. If two peripherals request an interrupt, then the most urgent request is dealt with first, the priority of an interrupt being determined by the Programmer. The computer jumps to a servicing program, which has been prepared by the Systems Engineer to deal with the situation, and works through this program in order to take the necessary action.

Extra hardware is required in the interface to relay feedback signals, but this is not extensive. It consists of a gate to collect the signal and code it so that it can be identified by the computer.

The buttons fitted to the converted lathe at Cranfield for manual operation of the motors use the above feedback technique. When a button is pressed, the interrupt line to the computer is 'pulled down', and the computer scans a priority list. The second line (skip line) directs the computer to the service program. In this program, the computer first checks whether a motor pulse is still required and, if one is, the computer identifies the motor and the direction of rotation. This information required to make these decisions is sent from the buttons to the computer. Choice of feed rate of the motor is set by a switch. By examining the state of the switch the computer selects the correct feed rate and sends a pulse to the motor. The computer returns to the start of the program when the next pulse is due and determines whether another pulse is required.

All feedback signals can be relayed to the computer in the same way. All decisions and actions taken must be programmed in the computer.

Time Sharing

As has been explained in a previous section, the computer is under-utilised when controlling one machine tool. Instead of time wasting between each pulse, the computer can be used to service other machine tools. The small digital computer with a four thousand word store capacity that is used at Cranfield has a basic operation time of 8 microseconds. On this machine it has been estimated that it is possible to control 20 stepping motors at one time (or say 8 machine tools). To service this number of motors, the control technique has to be changed; otherwise, available computer time is quickly used up.

The first requirement is to extend the interface to handle the control of the feed rates of the slides. When a machine tool is following a particular section of a cutting path, the computer can be used to specify the feed rate to the control in the interface before the section is started. When the motor is ready for another pulse, it interrupts the computer. Only when a section has been completed does the computer have to give full service to a machine tool in order to set up the next section of the path. Priority and service routines are again used to specify which machine tool requires service most urgently. The output of increments to the machine tools is a fast operation and these are given high priority. Even if an operation is given low priority, delays will not be noticeable on the machine tool.

Tests have been made on turning a part with the data program stored on paper tape. Even with a very slow reader (10 chars/sec. and 6 characters to specify a section) no serious delay occurred. If the time spent at a change point is critical, the information can be buffered before the change point is reached and released to the peripheral very quickly.

The interface requires a further modification when high speed stepping motors are used. The pulse rate sent to these motors is of the same order of time as the speed of operation of the computer, which could mean that one motor would occupy all the computer time so that no other motors could be serviced. High speed operation is only required when 'cutting air', which is not a priority function and the interface would be modified to control the motors during such an operation. The computer would output the number of increments required on this operation to the interface.

The computer is programmed with general subroutines which can be used by all the machine tools. Specialised routines are also stored for individual machine tools to control special feedback signals.

Taper and Contour Control

Tapers and contours are generated by fitting the increments of a slide to the required path. Very small increments have to be used if an accurate curve is to be produced with a good surface finish. Tests have been made at Cranfield on machining a taper, and Figure 5a shows how increments are fitted to the line of the taper. Although the profile looks jagged, the response of the machine tool is not fast enough to follow the profile exactly and the corners are blurred, as shown in Figure 5b. In practice, an acceptable surface finish is achieved.

Two directions have to be specified to machine a taper and, except for the taper cut by simultaneous operation of both motors, one motor has to output more increments than the other. This motor is moved first and continues to move until the distance between the tool and the path just exceeds half an increment on the other motor, at which point an increment is supplied from the other motor and the tool point crosses the line. The process is repeated and a taper is generated.

The specification for a taper section in the data program is enlarged in the following manner:

Identification code

This tells the computer that the next section is a taper and can be represented by the letters TAP.

Contangent

This is the contangent of the taper angle and is converted into a form which can be used in the taper output subroutine.

The two directions

These use the same code as for co-ordinate turning.

The number of increments and the feed rate are specified as for co-ordinate turning.

A contour is machined in the same way as a taper, but the output subroutines are more complex. The equation of the curve is solved each time an increment is made by a motor, and the discrepancy between the curve and the tool position is found. The tool is then moved in the appropriate direction to reduce the discrepancy while still moving the tool along the path.

The simple co-ordinate interface described earlier can be used for taper or contour control. This interface enables pulses to be sent to a motor, this being all that is required.

The computer receives instructions from the data program so that it can determine whether a co-ordinate, taper, or contour movement is required. The data concerning the movement is then put into the appropriate output subroutine. A stock of output routines can therefore be built up to handle any machining operation and the number of these is only limited by the store space available in the computer.

Modes of operation of the Machine Tools

Methods of converting and controlling machine tools for computer control have been mentioned in this report. Two methods of actually operating a machine tool using these techniques are given below.

The cutting path of the machine tool can be programmed in the normal way by using a special program language to prepare a punched tape. The methods shown in this report for producing a data program are laborious, and the task can be eased by using a computer program to convert simple instructions denoting the path of the cutting tool into the machine language of the computer.

An example of the complexity of converting information is given by the conversion of a component dimension into the instruction for the number of increments. To store this number in the computer, the dimension has to be subdivided into the correct number of increments and this number has to be converted from a decimal to an octal base. Many errors can occur during this conversion, but the possibility of errors occurring could be reduced by the use of an interpolative language which would allow the computer to do this conversion for the Programmer. Such a language also reduces the risk of errors in data programming.

Another way of preparing a data program is to record the movements made on a machine tool when manually machining the component. This recording can be made by coupling encoders to the leadscrews and storing the number of pulses moved by the leadscrews in each direction. The machined component can be measured and the data program corrected for any errors in the dimensions of the component, this information being transferred directly into the computer store in the teletype. The recorded program can be dumped from the computer store on to paper tape, providing a permanent record of the program.

The advantage of this system is that the data program can be prepared by a skilled craftsman operating the machine tool. Such a craftsman allows for backlash in the leadscrews and tool deflection, and he can also set up the correct cutting conditions for the material. To allow for these factors in a data program prepared by conventional programming is very difficult since the factors vary according to the condition of the machine tool. The computer does not record the slack time during manual machining, so that the operator can machine the component slowly and carefully without affecting the machining time of the data program.

If a group of machine tools is programmed by the latter method, a skilled operator could look after the machine tools and prepare new data programs as necessary. When a machine tool requires attention, such as tool changing, suitable warning signals may be given to attract the attention of an operator. Whatever programming system is used an operator will have to be present to look after the machine tools. The duties of the operator will depend on the amount of automation and feedback fitted to the machine tools.

Conclusions

Incremental control can provide a flexible control system which overcomes the difficulty some manufacturers have found when attempting to adapt work to a general purpose machine tool with automatic control. This is because the system is so flexible. The advantages of the system have been shown in this report but there is, as yet, little practical proof of the cost of developing machine tools under this system. Tests at Cranfield have shown that a small digital computer can provide a cheap flexible control for the simultaneous control of different peripherals; this has been done using peripherals other than machine tools.

The basic stepping motors can provide cheap 'open loop' control for a machine tool to carry out light machining. The cost of this conversion rises sharply when heavy machining is required but even this cost is well below the cost of many comparable control systems (see appendix A for costs). Stepping motors are expensive and form a large part of the cost of converting a machine tool.

There is need for further work to determine the minimum amount of control required for general machine tools under Incremental control to give satisfactory performance.

Recommendations for Future Work

Another machine tool, preferably with three axes control, could be converted with electro-hydraulic stepping motors and operated simultaneously with the converted lathe at Cranfield. This lathe could be modified further by fitting encoders to the leadscrews. It would then be possible to make the following tests:

(a) The operation of electro-hydraulic stepping motors could be tested under heavy machining. The lathe could be used to test the different modes of programming a machine tool.

(b) Tests could be made on time sharing the machine tools on co-ordinate, taper and contour control.

Further work would enable a stock of standard general purpose programs to be written. Investigations could also be made into the design of standard interfaces which can be readily modified for feedback.

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Mr. P.E. Galgut for taking the initiative to try and further this work and also for prompting the authors to write this report.

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2. H. Opitz — An Investigation into the Performance of Stepping Motors and their Application to Machine Tool Feed Drives. 7th International M.T.D.R. Conference, Birmingham University, September 1966.

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Appendix A

Costs for equipment (these are the current prices quoted at the time of writing).

(a) Conversion of Lathe at Cranfield

	£	£
Compound slide complete with stepping motor	650	
Transverse Stepping Motor	100	
Inter-changeable Tool Holder	100	
Interface and Drive Circuits	30	
Total for Initial Conversion		880
New Ball recirculating transverse leadscrew		256
Total for full conversion to date		£1,136

(b) Cost of Electro-Hydraulic Stepping Motors

2 Stepping Motors (Average) £400 each	800
2 High Speed Drive Circuits £400 each	800
Hydraulic Power Pack (approx.) £500	500
	£2,100

NOTE

The advantages gained by fitting electro-hydraulic motors is in proportion to their cost. The basic motor for the cost shown can provide good facility for slow speed light machining. The electrohydraulic motors give facility for high speed heavy duty machining.

(c) Cost of Computer

The basic cost of the computer and teletype, with adequate facilities for machine tool control, is £4,100. It is considered that light machine tools can be controlled with fairly crude programs. A standard interface would probably cost £500, so that the cost of control for each machine tool would be about £1,000.

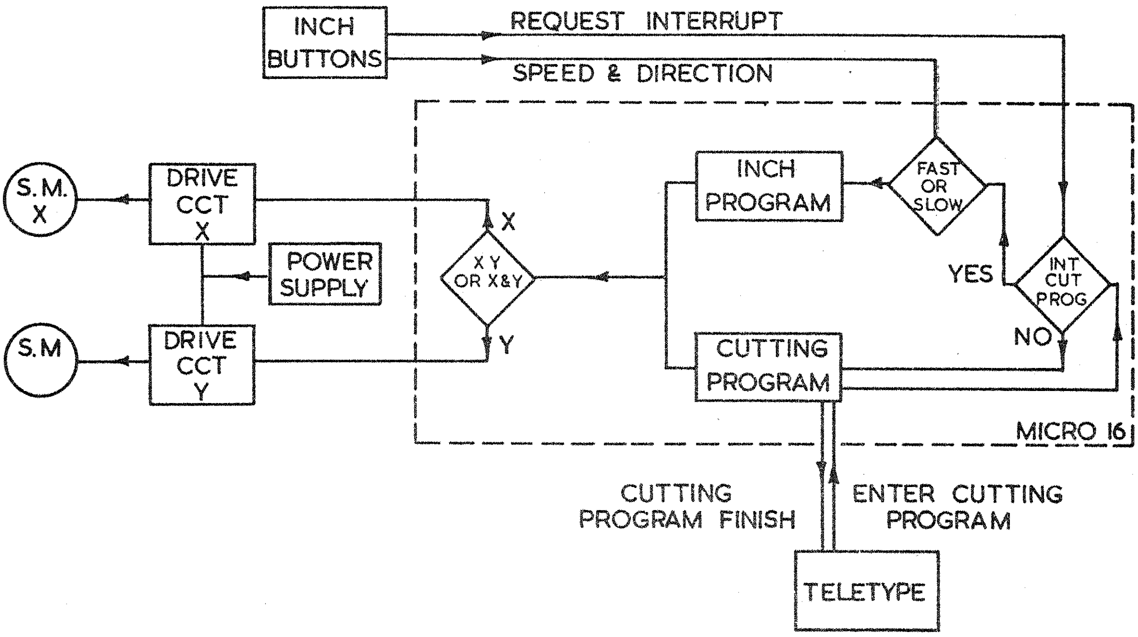

FIG.1. BLOCK DIAGRAM OF COMPUTER-INTERFACE HARDWARE-STEPPING MOTOR FOR THE LATHE CONVERTED AT CRANFIELD. THE BUTTONS FOR MANUAL OPERATION ARE ALSO SHOWN.

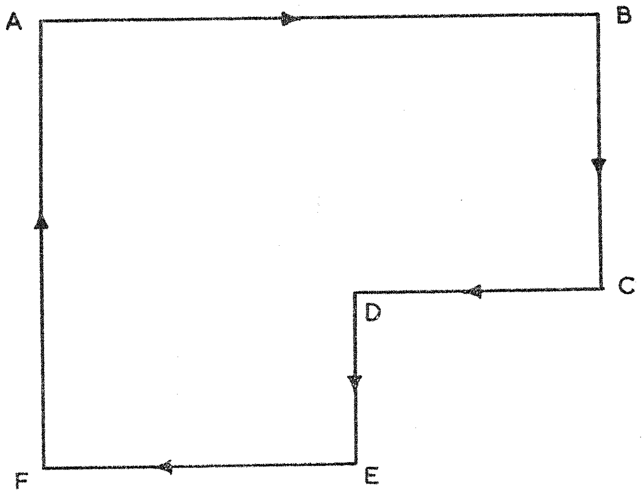

FIG.2. A CUTTING PATH.

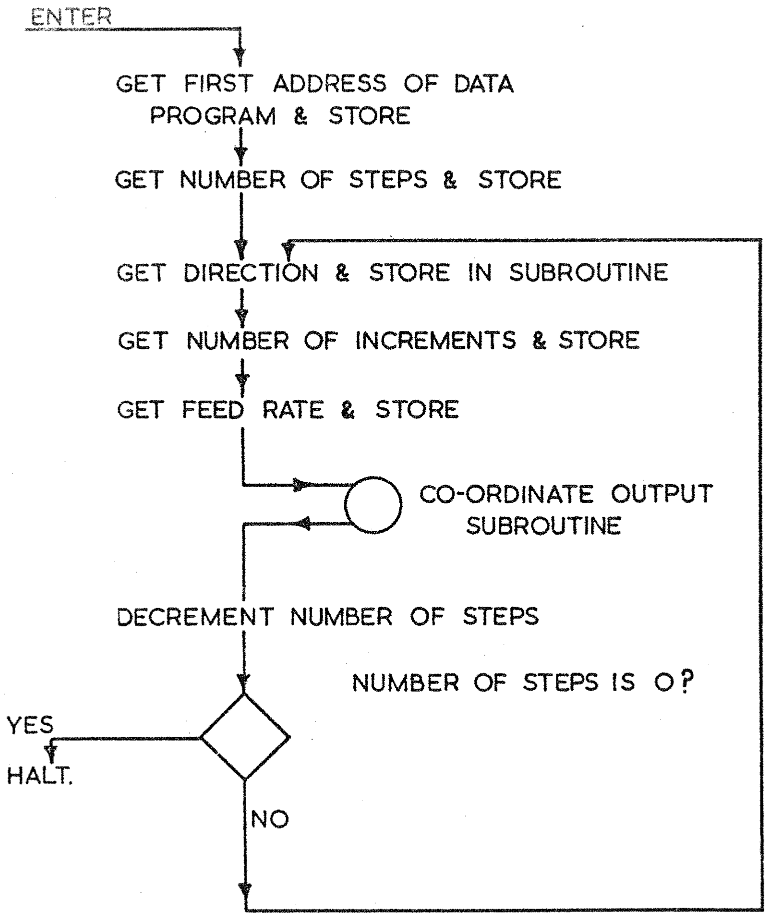

FIG.3a. FLOW CHART-CO-ORDINATE TURNING.

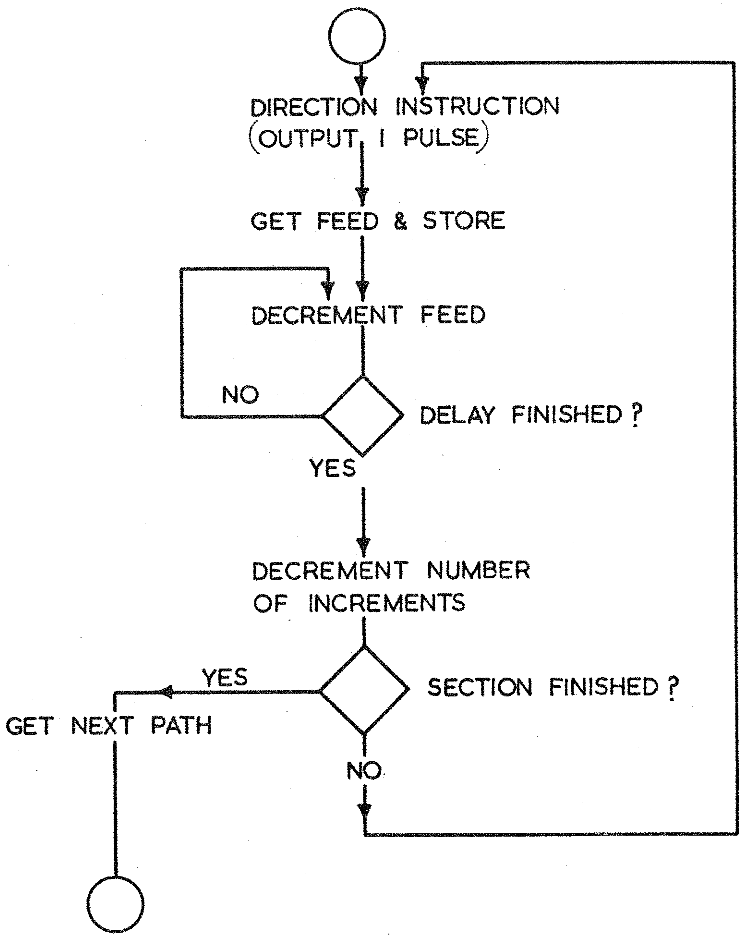

FIG.3b. CO-ORDINATE OUTPUT SUBROUTINE.

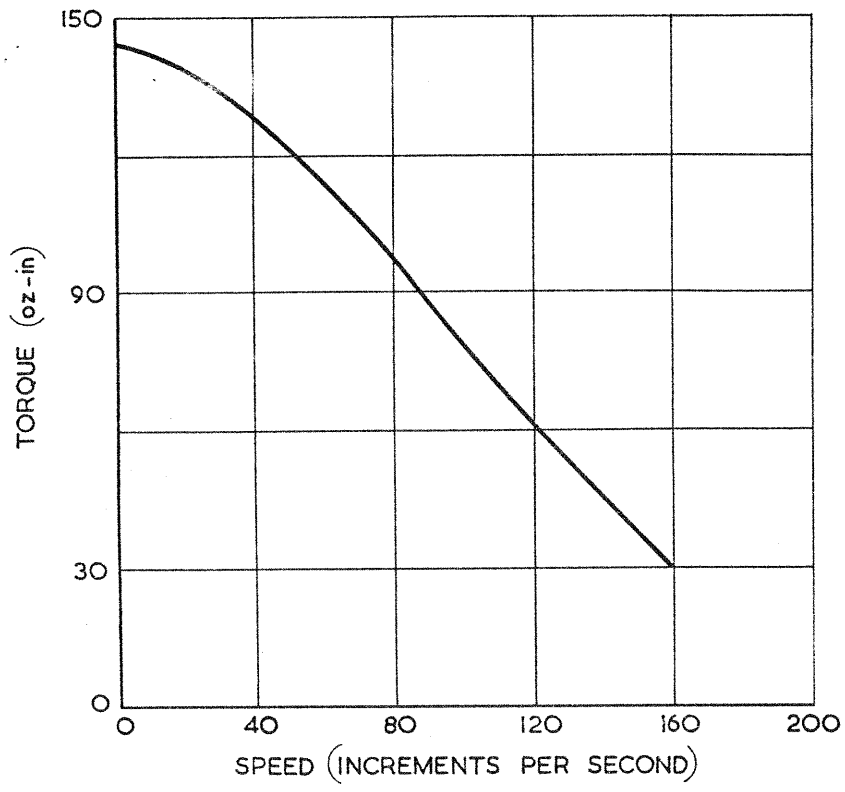

FIG.4. TYPICAL TORQUE/SPEED CURVE FOR A BIFILAR STEPPING MOTOR.

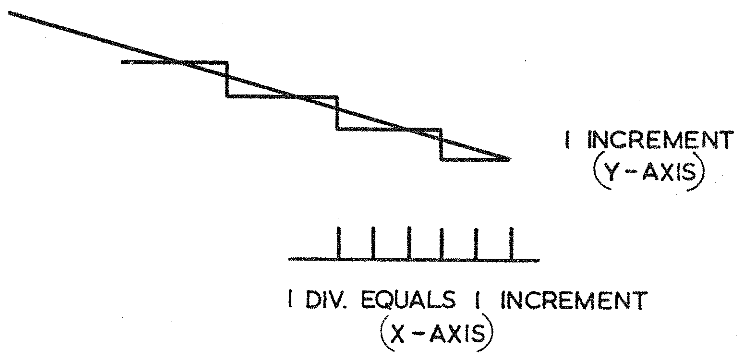

FIG.5a. FITTING INCREMENTS TO A TAPER.

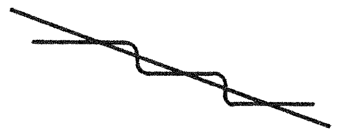

FIG.5b. BLURRING EFFECT CAUSED BY SLOW RESPONSE OF SLIDES.