A STUDY OF SOME ASPECTS OF NUMERICALLY CONTROLLED MACHINE TOOLS

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By

MURDOCH V. HEIDEMAN, B.Sc. (ENG.)

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AUTHOR: Murdoch V. Heideman, B.Sc. (Eng.) Rand.

SUPERVISOR: Professor M. C. deMalherbe

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SCOPE AND CONTENTS: This thesis is a study of numerically controlled machine tools (NCMT), and is divided into four sections.

Section A is a literature survey of current concepts, criteria and techniques in design of NCMT structures and drives. Several of the authors own ideas are also included.

Section B deals with NCMT manual and computer aided programming techniques. The structure and function of postprocessors is also covered.

Section C is a practical combination of computer design optimisation and numerical control manufacture. In an example the geometrical dimensions of a hydrostatic thrust bearing are optimised and used as an input to a generalized APT programme, written to produce a numerical control tape for manufacture of this bearing type.

Section D is the discussion and conclusion.

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I. INTRODUCTION

1.1 Background:

1.1.1 Historical Development:

In the last 25 years the concept of designing a machine tool "controlled with the output of a computing machine" has expanded to become one of the most significant technological developments in the metal working industry. During the mid 1940's aircraft manufacturers were finding it increasingly difficult to manufacture complex components such as aerofoil sections and turbine blades, with conventional machinery. In addition many repetitive calculations were needed to define each complicated contour within the tolerances specified by the aircraft industry, and any slight modifications in the design (which occurred frequently), could result in recalculating the whole component. Finally, in July 1949 Parsons Corporation and the U.S.A.F. jointly sponsored a study at M.I.T. to investigate the possibility of designing a NCMT* About 18 months later a two axis automatically controlled milling machine was designed and built at M.I.T., concurrently the development of computational techniques for preparation of input media was begun. The original NCMT were instructed by data coded on punched cards, similar to the ones used in the computer industry.

1.1.2 Applications of NCMT:

Initially NCMT were almost exclusively used in the aerospace industry, they manufactured components which previously could not be

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* NCMT numerically controlled machine tool.

machined by conventional tools, yet they were extremely unreliable and time consuming to programme. Most of the initial NC installations in the United States were partially financed by defence contracts that assisted industry engaged in military manufacture, to utilize these machine tools. In this last decade, however, machine tool builders have gained sufficient experience and knowledge so that the quality and reliability of their products have increased several fold. At the same time the demand for NCMT has increased and the prices have become more competitive because of the economy of mass production. NC has been applied to many other metal working processes such as tube bending, flame cutting, punching welding etc., and is now widely accepted in many other fields of industrial manufacture. Statisticians estimate that in September 1968 there were more than 14,000 NCMT in U.S.A. and almost 270 in Canada*. European and Japanese machine tool builders started working on NC somewhat later than their American counterparts, yet today they are producing some excellent NCMT, which is playing an increasingly important role in their metal working industry.

1.2 <u>Types of NCMT</u>:

NCMT can be divided into two different classes: a) point to point machine tools and b) continuous path machine tools.

A NCMT with a point to point (ptp) control performs a discrete machining operation at some specific location on the work piece. The path the tool takes in moving from one location to the

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* private communication Canadian Federal Department of Industry.

next, need not be defined, or be within any specified tolerance. Only the final position of the tool, before the machining operation begins, is critical. However, not only would it be extremely inefficient and time consuming if the machine tool took any random path between two points, but also there is the danger the tool could collide and damage the workpiece.

Consequently, the simpler ptp MT's move parallel to one co-ordinate axis at a time and at an inclination of approximately 45° to mutually perpendicular axes, while those with a more sophisticated control unit, move in a straight line between two points. These machine tools may be controlled in 2 or 3 mutually perpendicular axes as well as several rotational axes. This type of control system is frequently found on drilling machines, punch presses, lathes, flame cutting machines, tube benders and machining centres. (A machining centre usually can perform several different cutting operations e.g. drilling,tapping, boring and reaming). Some machining centres have an added facility of straight line milling, this refers to milling cuts parallel to the axes of the machine tool, and requires a slightly more intricate control system than the regular ptp control.

A NCMT with a continuous path, or contouring control (cpc) system performs a continuous machining operation in moving along some specifically defined path which is made up of numerous straight line increments - and in some cases arcs of circles. If the machine tool has the latter capability, it is said to have circular interpolation, as opposed to linear interpolation, where all contours are approximated by straight line increments. The velocity and displacement of the tool must be fully controlled throughout the machining operation, and motion on all controlled axes must be mutually synchronised. Continuous path controls are usually fitted to various types of milling machines, machining centres and lathes. Frequently cpc in only 2 axes is referred to as a profiling control, however, many systems have full cpc in 3 co-ordinate axes as well as 1, 2 or 3 rotational axes. Hence, the cpc system is usually described by the number of axes that are controlled. Some machine tools have cpc in 2 axes and only a linear velocity control in the third axes which is not synchronised to the other two axes. These contouring control systems are said to have 2-1/2 axes control.

The large complex 5 and 6 axes cpc machine tools can machine virtually any shape or surface that can be numerically defined.

SECTION A

THE NUMERICAL CONTROLLED MACHINE TOOL

It is interesting to observe the similarity between conventional machine tool shapes recently manufactured, with those manufactured 50 years ago. Although the power capacity of the drive motor and the dimensions of machine tools have increased considerably, and the machine tools today, are capable of cutting with greater accuracies, yielding higher production rates and cutting harder metal alloys, the basic forms of the classical metal cutting machine tools have remained unaltered. This, however, is no longer valid for NCMT shapes.

Initially NCMT were designed by merely adding a numerical control system to an existing machine tool design with a few minor modifications. This solution was soon found inadequate and careful consideration had to be given to the new design criteria. A fundamental difference in designing a NC machine tool, is that, it is no longer essential to keep the workpiece at waist height and to allow the operator a clear unobstructed view of the workpiece area. This permits the designer greater flexibility in satisfying other design requirements. Another factor is that NCMT are often cutting metal more than twenty hours a day, consequently, the machine tool components must be designed to withstand such taxing utilization.

CHAPTER 2

THE MACHINE TOOL STRUCTURE

2.1 INTRODUCTION

The performance criteria of NCMT are generally more demanding than those of conventional machine tools. Ideally a NCMT should be designed to machine both the hardest metal alloys and the free cutting metals at optimum rates of metal removal, without any compromise in workpiece accuracy and surface finish. The working accuracy of a NCMT is usually limited by the deflections of the structure, not the resolution of the measuring devices. Consequently, a good deal of the research and development activity carried out in various countries is concerned with improving analytical and other design techniques of machine tool structures.

In 1931 Krug first included static stiffness as a design parameter in MT construction. He proposed the ratio of load to deflection as a measure of stiffness. The load was assumed static and consisted of the weight of the workpiece, the weight of the moving parts of the MT and the cutting forces. This is not entirely adequate since the metal cutting and inertia forces frequently have a high rate of change, and the dynamic behaviour of the MT is also a critical design parameter. The various modes of vibration of the machine tool should be analysed fully and the stability of the machine tool verified.

2.2 STATIC STIFFNESS

2.2.1 Cross Sectional Areas:

Most individual elements in a machine tool structure are subjected to bending, torsional and shear forces due to the static loading. It is essential in designing a machine tool structure to limit the maximum deflections to well within the accuracy expected of the MT.

A simple comparison of various cross-sectional shapes, having the same cross-sectional area but different moments of inertia shows a hollow rectangular box to be best suited for machine tool elements [1]. Although the box section has slightly less torsional stiffness than a hollow tube, this is adequately compensated by additional strength in bending. The ratio of width to height should be between .5 and 1.0 for practical reasons. If an element is severely stressed in bending and torsion, designers ofen use a composite section. For example, in large MT a hollow tube mounted on gussets in a rectangular box section can be used advantageously.

Usually it is not possible to keep a uniform cross-sectional area along the length of a member. It is frequently necessary to cut apertures through a section for fitting or locating other components. The bending and torsional stiffness is reduced considerably when an aperture is cut in the section. By fitting a suitable bolted cover plate [1] almost 90% of the original stiffness can be recovered. This, however, is not true of the torsional stiffness. Diagonal stiffeners have been designed by Peters [1] give added torsional and bending strength to a cut element. Several research laboratories are carrying out strength to weight optimisation studies on various ribbing patterns for cast machine tool elements of non uniform cross-sectional area.

2.2.2 Steel or Cast Iron:

There is an unresolved controversy on the merits of steel weld-elements replacing cast iron elements in MT construction.

Figure 2.1 shows a simply supported rectangular beam with a concentrated load midspan, and dimensions as shown:

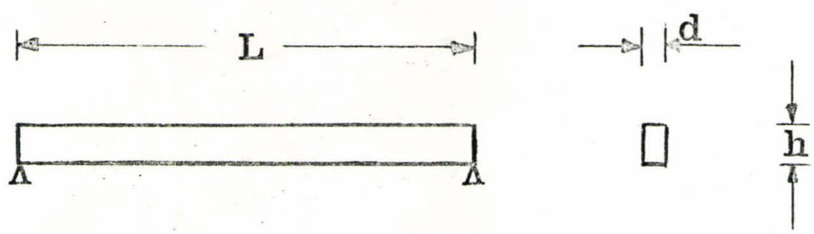


Fig. 2.1

To minimize the volume of material, V, given the permissible deflection, δ and permissable bending stress, σ_b, we have:

$$V = L \times h \times d$$

$$\delta = \frac{P \times L^3}{4 \times E \times d \times h^3} \qquad (1)$$

$$\delta = \frac{P}{4 \times E \times V} \times \left(\frac{L^2}{h}\right)^2$$

and

$$\sigma_b = \frac{3 \times P}{2 \times V} \times (\frac{L^2}{h})$$

Now plotting curves

$$V_1 = \frac{P}{4E\delta} \times (\frac{\ell^2}{h})^2 \quad \text{and} \quad V_2 = \frac{3xP}{2x\sigma_b} \times (\frac{\ell^2}{h})$$

Assuming the beam is designed for maximum deflections δ and maximum stress σ_b we find an optimum ratio $\frac{\ell^2}{h}$ for each material, point A and B (Fig. 2.2).

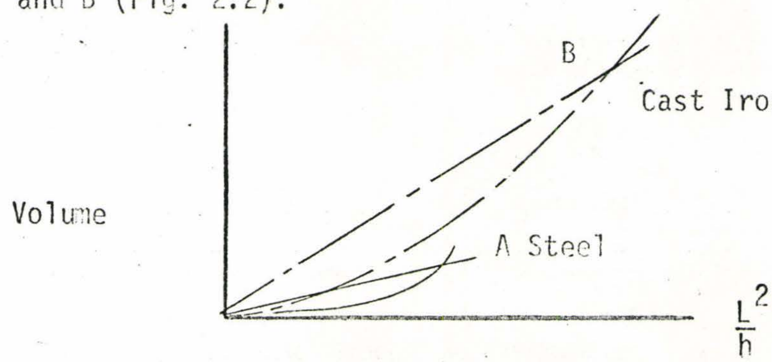


Fig. 2.2

Since Young's modulus for steel is almost twice that for cast iron, and the ultimate tensile stress is 30 to 60% higher, the optimum ratio for steel has a volume approximately 3 times smaller than that of cast iron. These conditions are usually not practicable as the steel section becomes very thin and deep. However, it serves to illustrate that the designer using structural steel (rather than cast iron) may select lighter and deeper sections for equal or smaller deflections [19]. Usually to achieve the stiffness required, the material is well within its load bearing capacity (far to the left of the curve in Fig. 2.2) and it is limited only by the value of Young's modulus (Eqn.1). Consequently higher grade steel alloys are never used in MT structures, as Young's modulus for steel does not vary by more than 5%.

2.2.3 Stiffness of Bolted Connections:

It is not sufficient to consider the deflections of individual elements only, but the deflection and stiffness of the machine tool as a whole, when fully assembled, must also be considered. Often for valid design criteria, elements may be bolted together. Thus, it would be desirable to be able to specify the parameters of a bolted connection to ensure the required stiffness is achieved. A rigid bolted joint is designed so that it does not part under load, and the stiffness of the joint interface then adds to the overall stiffness of the joint.

A theory has been developed [2] and [3] which shows a relationship between the mean interface pressure, p, of a joint and the normal elastic deflection λ_J of the joint.

$\lambda_J = \frac{1}{m} \log p + c$ where m and c are constants. This was found valid for $p > .02$ ton f/in^2 for the materials and finishes tested.

On differentiating we get $\frac{dp}{d\lambda_J} = mp$

The value of m is a measure of the surface stiffness dependent on the surface topography and the material of the mating surfaces. The paper goes on to show that although a bolt assembly consists of several joints in series (washers, threads, etc.) when the stress is above a minimum pre-load the bolt assembly may be considered solid. Then the actual bolt stiffness contributes a negligible amount to the overall joint stiffness (assuming the joint does not part under load). This is confirmed by Koenigsberger [1] who states, "if the pre-load (of a bolt) exceeds the minimum load, a further increase in the pre-load has only little effect on the bending stiffness, and no effect whatsoever on the torsional stiffness".

Connolly and Thomley [3] have analysed different bolted flanged joints with; normal load; bending moment; two fixed ends; hollow cross-section; computing the proportion of joint deflection to overall deflection. In each case they found that the joint deflection was highly significant for short structures, even with high values of m; as the surface quality deteriorated the joint deflections became significant for the longer structures (up to 3 feet) tested. Values of m were measured for different machining methods - the value obtained for good surface grinding was 14.85×10^4/in. which finally decreased to $.62 \times 10^4$/in. for rough slab milling. The authors refer to another paper containing the results of a survey of the values of m commonly found in industrial manufacture.

2.2.4 Changes in Static Stiffness:

Another difficulty is that the static stiffness is often dependent on changes, in the point of load application, and workpiece position, e.g. on a lathe the static deflections will vary as the cutting tool moves along the workpiece. In the case of a hydraulic ram drive, the stiffness decreases as the piston extends from the cylinder.

2.3 DYNAMIC STIFFNESS

2.3.1 Dynamic Disturbances:

Most machine tools today are limited by their dynamic performance. Consequently, MT designers are becoming increasingly aware that more attention should be devoted to the dynamic behaviour of the MT. Frequently the limiting factor to higher rates of metal removal is the dynamic rigidity of the MT structure. At the risk of over simplification, dynamic rigidity may be considered as the machine tools resistance to vibration. They may be transient vibrations, induced by the impact of the cutting edge and the work-piece, or forced vibrations,caused by out of balance rotating components, coming from within the machine tool, or from some external source, and transmitted through the MT foundation. Still another type of vibration which usually limits the depth of cut for a particular workpiece-tool combination, is known as chatter. The precise physical causes of chatter are not fully understood [6] although several authors have recently made significant progress in formulating analytical stability criteria for chatter free machining [7] and [8]. It occurs when a variety of cutting forces act simultaneously on the cutting tool. Often minor changes in tool position or geometry can remedy it. The analytical solutions for machine tool chatter are usually limited by the assumptions made to make the mathematics managable. In the past chatter has been stopped by simply reducing the rate of metal removal. Chatter has adverse effects on the surface finish, the machining accuracy of the workpiece and may also cause excessive wear of the cutting tool or the actual machine tool. In addition, the vibration is self excited, dissipates energy drawn from the MT drive, leaving less available at the cutting edge.

2.3.2 Classical Vibration Theory:

From classical vibration theory the following parameters influence machine tool stability:

M = Vibrating Mass

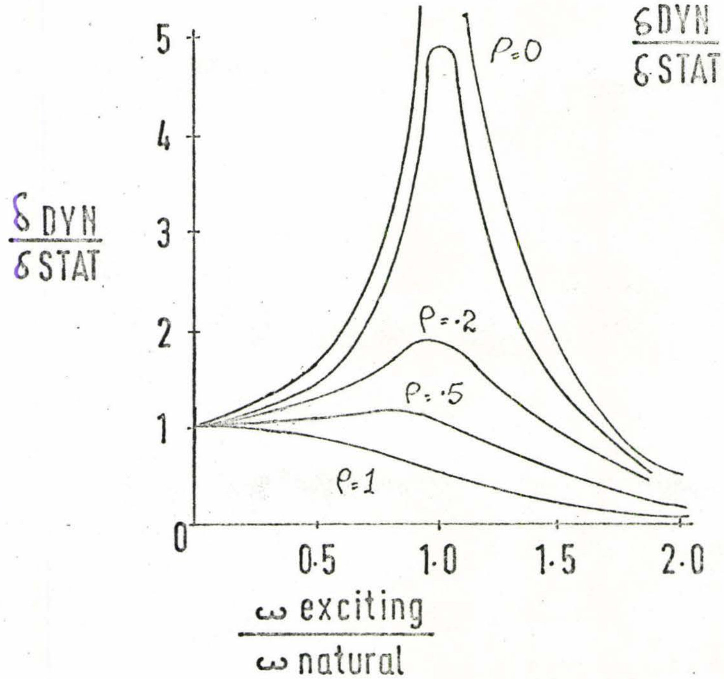
$k = p/\delta$: Static Stiffness = Force/Deflections

$\rho = \frac{C}{2\sqrt{Mk}}$: Damping Factor (C : Damping Constant)

$W_{nat} = \sqrt{k/M}$: Natural Frequency

The well known response curves for a single degree freedom system with viscous damping are shown in Figs. 2.3 and 2.4 for free and forced vibrations respectively. From these curves it is apparent that the dynamic deflections are minimal when the exciting frequency is far smaller or far larger than the resonant frequency, or when the damping factor is high. However, systems with several degrees of freedom have other resonant frequencies higher than the natural frequency, so often machine tool designers will attempt to

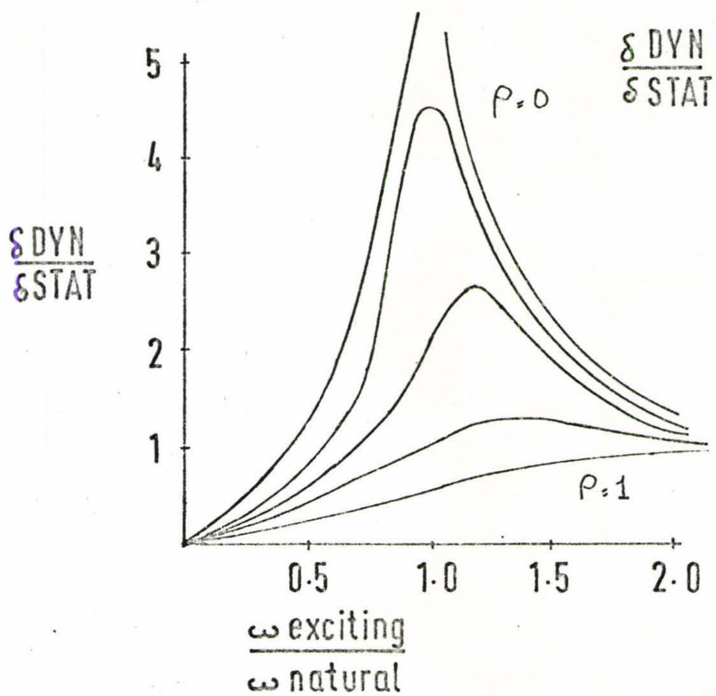
$$\frac{\delta DYN}{\delta STAT} = \frac{1}{[(1-(\omega/\omega_n)^2)^2 + (2\rho\,\omega/\omega_n)^2]^{1/2}}$$



Amplitude of Exciting Force, Independent of Exciting Frequency.

FIG. 2·3

$$\frac{\delta DYN}{\delta STAT} = \frac{(\omega/\omega_n)^2}{[(1-(\omega/\omega_n)^2)^2 + (2\rho\,\omega/\omega_n)^2]^{1/2}}$$



Amplitude of Exciting Force, Dependent on Exciting Frequency.

FIG. 2·4

design the MT with a natural frequency higher than the maximum exciting frequency anticipated. This is not always possible as a versatile machine tool must operate over a wide range of speeds and feeds. The natural frequency is proportional to $(\frac{K}{M})^{1/2}$ consequently to increase the natural frequency the designer must minimize the weight for maximum stiffness. Increasing the stiffness (K) alone, however, does not limit the deflections that occur in the range of resonant frequencies (and it is often impossible to eliminate MT resonance entirely). This is illustrated in a vector diagram of the forces acting on a simple single degree of freedom system at resonance, shown in Fig. 2.5. The spring force $k\delta$ and the inertial force $m\ddot{\delta}$ are opposing each other, in quadrature with only the damping force $c\dot{\delta}$, opposing the exciting force. Consequently, to limit the dynamic deflections at resonance a high damping constant is required. Peters [9] suggested the machine tool should have a damping factor between .5 and .7. A high damping factor ensures rapid decay of free self-excited vibrations and increases the dynamic stiffness against forced vibrations, but it is difficult to attain, and can introduce an undesirable phase lag.

2.3.3 Structural Damping in Steel and Cast Iron:

For many years designers have prefered to make machine tool members from cast iron as it has a higher structural damping constant than steel (approximately .002 and .001 respectively) when the same stress is applied [10]. Recently several MT designers have used

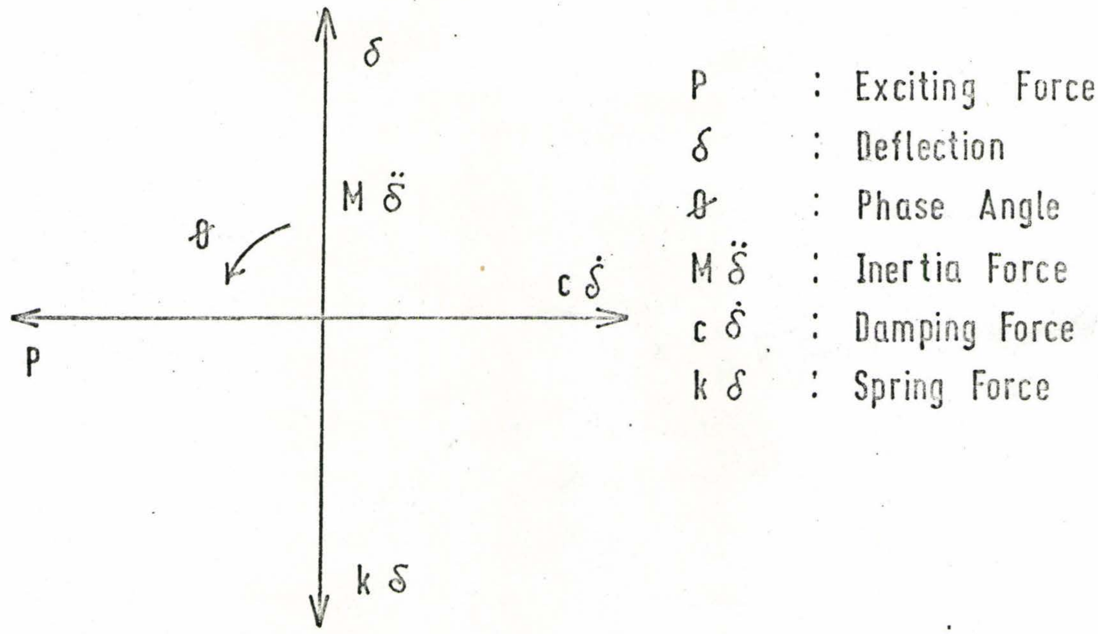


FIG. 2·5 Vector Diagram of Forces Acting at Resonance

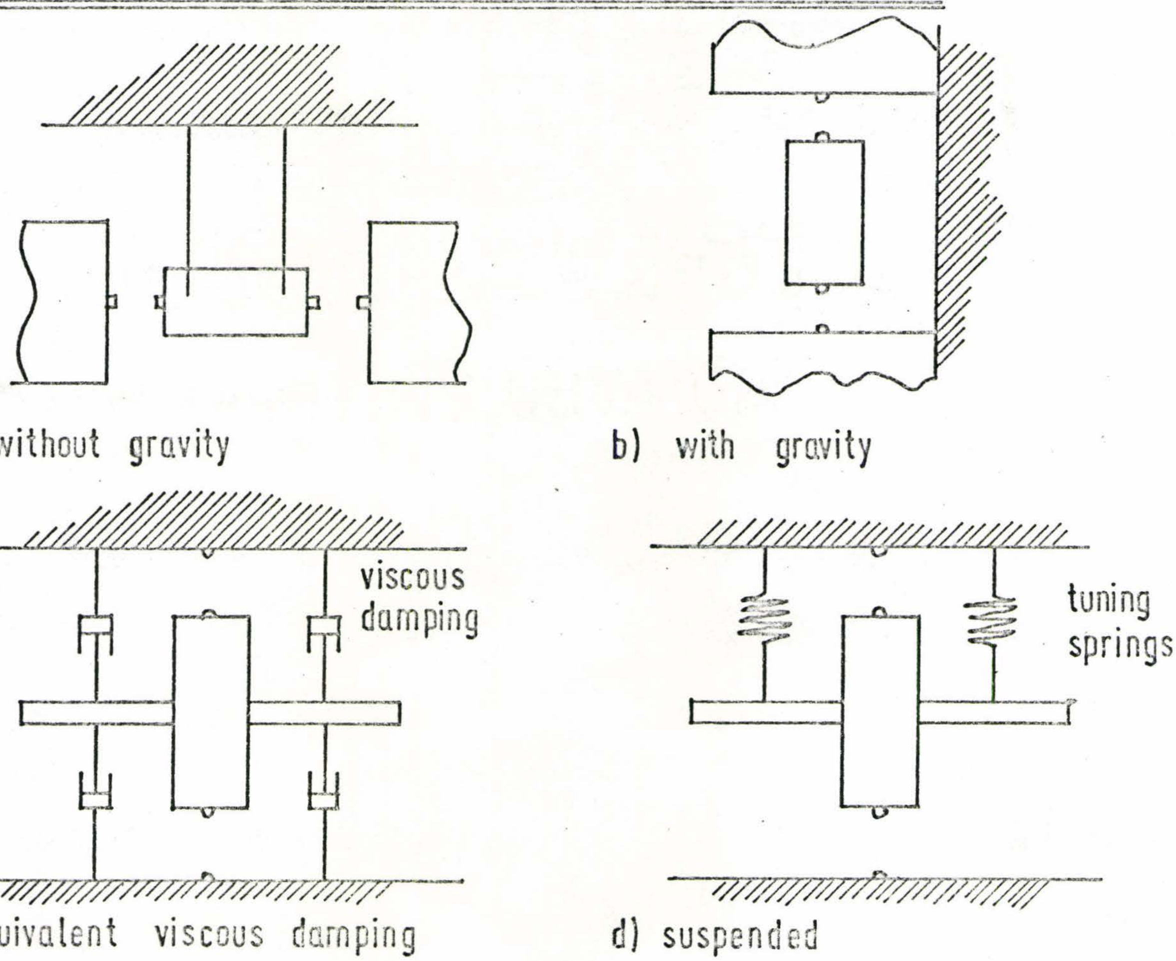


FIG. 2·6 Impact Dampers

steel elements welded together and have achieved higher damping factors, than with a cast member. In addition, the reduction in weight of the member for equivalent static stiffness, often results in a higher natural frequency, which is desirable. Opitz and Bielefeld more than doubled the natural frequency of a MT member from 340 cps for a cast element, to 695 cps for a weld element [9]. Structural damping increases with increasing stress and since steel can be more highly stressed than cast iron it is possible by designing thinner and lighter steel sections, to improve the structural damping of a steel element to equal that of cast iron elements.

2.3.4 Friction Damping:

Another type of damping that has been used is friction damping. This is characterised by a constant energy loss per cycle. It occurs when the energy of vibration is sufficient to cause relative movement between any two contact surfaces under pressure. There is a relationship between this pressure and the energy dissipated each cycle. Using this principle Peters [9] increased the damping of a lathe spindle from .0005 to .0261. The optimum contact pressure for maximum friction damping was obtained by using an interference fit between the spindle and the bearings. A steel structure fabricated with frequent interrupted welds may also exhibit a significant amount of friction damping. The contact pressure is caused by contraction of the welds on cooling, and the energy is dissipated by relative motion between the surfaces. Yet in most cases friction damping is not very satisfactory, the maximum amount of damping obtained is quite insufficient for MT structures, (especially near resonant frequencies) and there is always the problem of excessive wear on the mating surfaces.

2.4 DAMPERS AND ABSORBERS

2.4.1 General:

Alternatively the dynamic stiffness of the machine tool, may be increased by using various vibrational reducing devices. These may be classified as either absorbers, or dampers. Both have inherent disadvantages. The absorber, which transfers the vibrational energy to another system, e.g. Frahm absorber, has to be tuned for a particular frequency. Its operation is only efficient over a small band close to the tuned frequency, and often increases the amplitude of the vibrations of frequencies outside this band. On the other hand, dampers which actually dissipate the vibrational energy are effective over a wide range of frequencies, but are difficult to tune correctly. These dampers are usually placed in parallel to the main force loop of the machine tool.

Vibrating elements on the structure are sometimes mounted on visco-elastic material to isolate the rest of the structure from the excitation. The damping coefficient is dependent on;the type of material (PVC and other epoxy resins are frequently used), the geometric shape and the pre-load applied.

The difficulty in designing vibration limiting devices for NCMT is that they are required to be effective over a wide range of exciting frequencies, as NCMT are usually versatile tools and operate over a large range of feeds and speeds. Also the modes of vibration of the structure are not necessarily constant but may change with the location of the cutting tool or the workpiece. The vibration characteristics will also vary with different workpieces, which may or may not have dynamic stability.

2.4.2 Common Dampers Used in MT Structures:

The well known dynamic absorber has been used successfully on extended boring bars, which have little inherent damping, and vibrate predominantly in one mode. In this case the space available for the damper may be the limiting constraint for an efficient design. The impact damper is finding increasing application on machine tools, and has been used extensively for damping the vibrations of lathe tool holders. It consists of a mass oscillating in a container rigidly connected to the main vibrating system. The energy is dissipated on each impact with the walls of the container Sadek and Mills [11] have published several papers on impact dampers and MT applications.

Fig. 2.6 shows a schematic of 4 types of impact dampers. The experimental results indicated [11] that model d gives the best performance over a wide range of frequencies. The springs suspending the mass have to be tuned for maximum damping, which occurs at 2 impacts per cycle.

The concept of reducing the vibration of the MT structure using an electrohydraulic or electro-magnetic shaker has limited application because only a very large shaker mass would be effective.

Mathematical models of these common dampers and absorbers are readily available in any standard text or vibration [13]. Several assumptions have been made to simplify the mathematical analysis (Fig. 2.7). In most cases the main vibrating mass is considered to have only one degree of freedom, which is never true in actual MT applications.

2.4.3 <u>Self-Optimising Dampers</u>:

Currently several designers have proposed self-optimising dampers, Bonesno and Bollinger [14] developed the theory for dynamic absorbers, that will minimize the amplitude of vibration of any exciting frequency. The response curve for a dynamic absorber (Fig. 2.7) optimally tuned is shown in Fig. 2.8 by the dashed line. The damping in the main system of the MT is very low and conveniently assumed to be zero. This optimum tuning gives the lowest amplification factor* over a frequency band, PQ, about the natural frequency of the main system. This, however, is not true outside this band, and non optimum tuning will give the lowest amplification factor. The damping factor is given by $\rho = \frac{C}{2\sqrt{Mk}}$.

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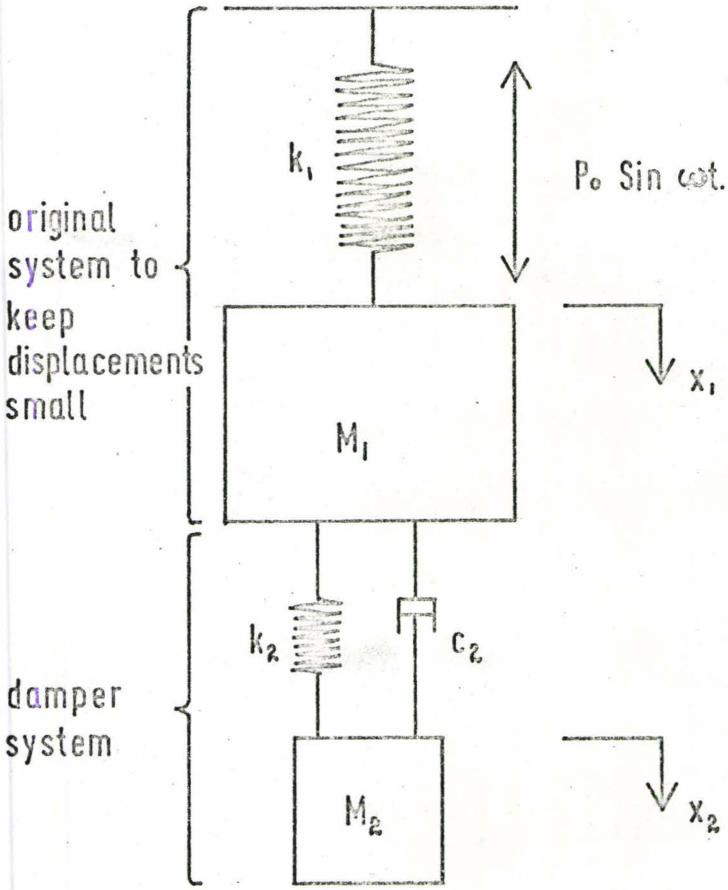
* $\text{Amplification} = \frac{\text{dynamic deflection}}{\text{static deflection}}$

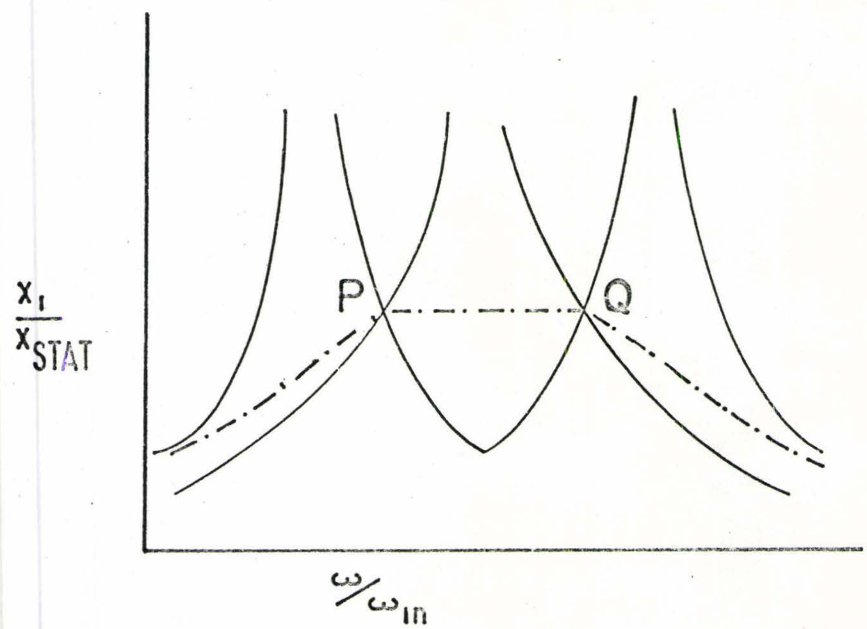


equations of motion

$$M_1\ddot{x}_1 + k_1x_1 + k(x_1 - x_2) + c(x_1 - x_2) = P_o \sin \omega t$$

$$M_2\ddot{x}_2 + k(x_2 - x_1) + c(x_2 - x_1) = 0$$

FIG. 2·7



$x_{STAT} = P/k_1$ static deflection

ω_{1n} $\sqrt{k_1/M_1}$ natural fre-quency mass 1

$u = M_2/M_1$ mass ratio

C_c $2M\omega_{1n}$

in optimum case

$$\frac{\sqrt{k_2/M_2}}{\sqrt{k_1/M_1}} = \frac{1}{1+u}$$

and $x_1/x_{STAT} = \sqrt{1+\frac{2}{u}}$

FIG. 2·8

Variation of one or two of the three parameters, m, k, C is sufficient to keep the amplification factor at a minimum for all exciting frequencies. Bonesno and Bollinger [14] decided to keep m constant and vary c and k by some control criteria to minimize the amplification factor. The displacements of both masses may be measured by an accelerometer, and integrating circuits. Instead of measuring the applied force or the frequency, which requires expensive equipment, only the phase angle was measured, and this indicated whether to increase or decrease the spring rate to keep the response at a minimum. Often the amplitude of vibration would have to be increased, before the minimum amplitude could be reached, thus it would not be sufficient to measure the displacement only. An analog model was used for a simulation study on a hybrid computer. The authors plotted the response surfaces of c and k. The optimum conditions for a steady state disturbance are $c = 0$ and $k = M\omega^2$, however, transient decay times will extend to infinity if c is permanently set at zero and it must be finite. Tests performed on an experimental model were very satisfactory. A cantilever beam was chosen as the main vibrating system. The absorber had manually adjusted friction pads for damping, (although the theoretical model was designed with viscous damping), and this proved adequate. The spring rate was varied by altering the effective spring length with a servo mechanism. The damper behaved as expected when the cantilever had only one degree of freedom, but became somewhat unpredictable when excited in several degrees of freedom [20].

It may prove somewhat easier to design a self-optimising impact damper. The damper performance could be controlled by changing the stroke length and the coefficient of restitution of the ends.

2.5 MACHINE TOOL FOUNDATIONS AND VIBRATION ISOLATORS

2.5.1 General:

The assumption is frequently made that a machine tool is rigidly mounted to the floor. This assumption is seldom justified. Usually it is desirable for impact type machines such as punch-presses or forging-hammers to be mounted as rigidly as possible. Consequently, their foundations are made of concrete several times the weight of the machine, and they are firmly attached to it. However, the most rigid mounting is still somewhat elastic, and most NCMT require periodic releveling and re-aligning to compensate for movement on the mountings.

A resilient type machine tool mounting is becoming increasingly popular. They can be designed with the appropriate amount of static stiffness, to limit the deflections under static loads to permissible deviations, yet eliminate the need for regular alignment checks. The resilient support acts as a vibration insulator, it protects both the MT and the surrounding area from mutual dynamic disturbances.

Frequently the supports are made of elastomers, plastics, steel or even cork, all of which have very little drift under static load.

and high damping properties. Nor do they deteriorate with age or under workshop conditions.

A rigidly designed MT may have softer, more resilient supports and sometimes is even mounted on metallic springs, whereas a MT that requires additional rigidity from the foundations would need a stiffer support. It is usually desirable to keep the natural frequency of the supports low (10 - 20 cps) so that the exciting frequency is far above their resonant frequency and large dynamic displacements are avoided. Often the height and the resilience of the supports are the limiting design constraints, which raise the natural frequency of the supports higher than desired.

2.5.2 A Self Adjusting Air Spring:

Self adjusting air spring mountings have received considerable attention from NCMT builders. A height sensing device is coupled to a servo valve, that exhausts or admits air to compensate for load changes, that would result in height variations. The advantages of this system is that it provides adequate static stability, having a quick response to load variation, and that it can also retain its height to within $\frac{1}{20}$ of a thousandth of an inch [15]. A schematic diagram of an air spring is illustrated in Fig. 2.9. From the analysis given it is apparent that the natural frequency of the system

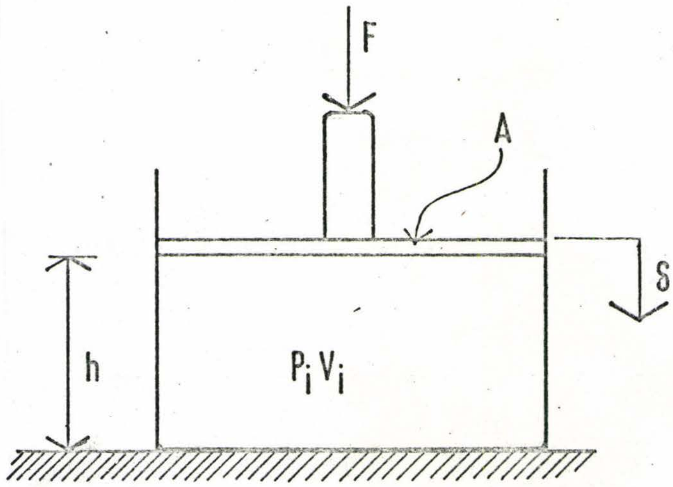


FIG 2·9 a Schematic Air Spring

P = pressure
V = volume
A = area
F = force
δ = displacement
n = ratio of specific heats c_p/c_v
K = spring constant
M = mass on piston
h = height of cylinder
ω_n = natural frequency $\sqrt{K/M}$
i = subscript initial

For An Adiabatic Expansion:

$$P_i V_i^{\,n} = PV^n$$

$$(P/P_i) = (V_i/V)^n \quad \ldots\ldots (1)$$

$$F = P/A \quad \ldots\ldots (2)$$

$$V = V_i - A\delta \quad \ldots\ldots (3)$$

Substitute (2) and (3) in (1):

$$F/AP_i = \left(\frac{V_i}{V_i - A\delta}\right)^n$$

$$F = AP_i(1 - A\delta/V_i)^{-n}$$

$$\frac{dF}{d\delta} = \frac{nA^2P_i}{V_i}\left(\frac{1}{1 - A\delta/V}\right)^{n+1}$$

Spring constant $k = \frac{dF}{d\delta}$ and for small δ

$$k = \frac{nA^2P}{V} \quad \ldots\ldots (4)$$

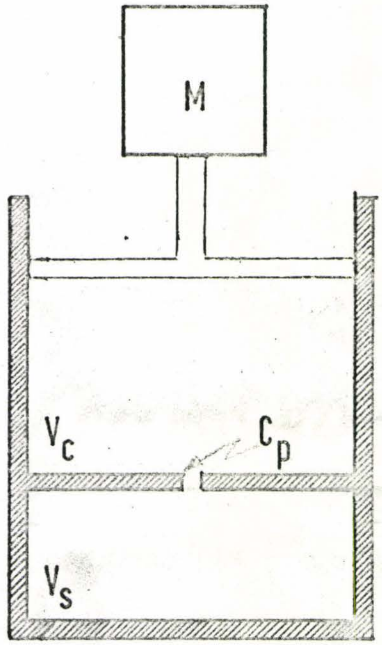
Assume F is a mass M on the piston then PA = Mg
and volume V = hA

$$K = \frac{nMg}{h}$$

Then $\omega_n = \sqrt{\frac{ng}{h}}$

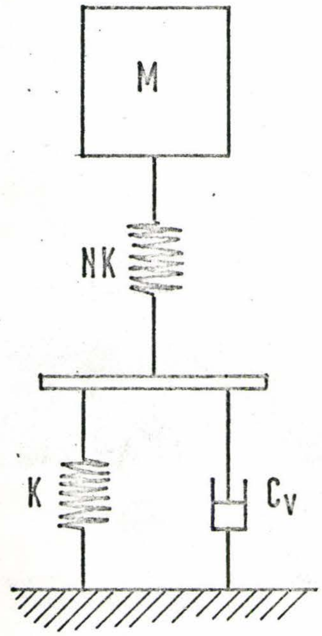
is constant for constant height above a given datum. To improve the dynamic stability at near resonance frequencies, the isolator may be connected to a surge tank through a small orifice. This is shown, together with a mathematical model of the system in Figs. 2.10 and 2.11.

The ratio of the surge volume to the capacity volume (N) is the characteristic parameter of the system. It has been shown that this system has low transmissability (stability at resonance) and a high rejection rate at high frequencies (12 db/octave compared to 6 db/octave for a viscous damped system).



Schematic Airspring Isolator and Surge Tank

FIG. 2·10



Mathematical Model

FIG. 2·11

As the orifice $C_p \to \infty$

The damping is zero

V_o = Volume at zero damping

$$V_o = V_c + V_s$$

For a closed orifice $C_p \to 0$

The damping tends to infinity

V_∞ = Volume at infinite damping

$$V_\infty = V_c$$

$$\frac{V_o}{V_\infty} = 1 + \frac{V_s}{V_c}$$

For zero damping $C_v = 0$

K_o = spring constant at zero damping

$$K_o = K \left(\frac{N}{N+1}\right)$$

For infinite damping $C_v = \infty$

K_∞ = spring constant at infinite damping

$$K_\infty = NK$$

$$\frac{K_\infty}{K_o} = N + 1$$

However from Fig. 2.9 equation (4) $K \alpha 1/V$

Thus equating V_o/V_∞ and K_∞/K_o to verify the model

$$1 + V_s/V_c = N + 1$$

Hence $$N = V_s/V_c$$

$$\frac{\omega_\infty}{\omega_o} = \frac{f_\infty}{f_o} = \frac{K_\infty}{K_o} = N + 1$$ where f = frequency

ω_o = Natural frequency at zero damping

ω_∞ = Natural frequency at infinite damping

$$f_\infty = f_o \quad N + 1$$

CHAPTER 3
NCMT DRIVES

3.1 INTRODUCTION:

In general a MT drive system requires a power supply to energise the prime mover; a transmission with discrete or continuous speed variation and in some cases a rotary to linear motion converter .

The parameters that influence the selection of NCMT drives may be divided into two categories, those dependent on the metal cutting process, and those dependent on the control and measuring systems used. In the former case, factors such as, the type of material and maximum dimensions of the work-piece, the feeds, speeds and horsepower requirements for efficient rates of metal removal etc, must be considered. Table 3.1 lists several of these parameters for lathes and for milling machines. The parameters dependent on the control system are for example; variable speed selection, feedback control systems, measurement devices etc. It is obvious that the overall performance of the machine tool will depend on the compatibility of both the criteria and often a compromise solution will be necessary.

This chapter deals with current design practice of NCMT drives.

TABLE 3.1

DESIGN PARAMETERS TO BE CONSIDERED FOR M.T. DRIVE SELECTION

CENTRE LATHE	MILLING MACHINE
Workpieces: (a) Materials Cut (b) Max. Turning Dia. Req'd. (c) Max. Length Between Centres	(a) Materials Cut (b) Max. Length Breadth Height
Tools: (a) Materials (b) Geometrical Dimensions Rake Angles (c) Life	(a) Materials (b) Min. & Max. Cutter Diameter (c) Max. No. of Cutter Teeth (d) Helix & Rake Angles (e) Life
Cutting Conditions: (a) Cutting Feed (b) Feed Rate (c) Depth of Cut	(a) Cutting Feed (b) Feed Rate (c) Depth of Cut (d) Width of Cut

3.2 DESIGN PARAMETERS FOR SPINDLE DRIVE TRAINS

3.2.1 General Requirements:

The majority of NCMT are designed for maximum flexibility in their metal cutting capability. Each machine tool should have sufficient torque over a wide speed range to maintain optimum cutting speeds and feeds for many different combinations of tools and workpiece materials.

Most NC metal cutting tools have a rotary cutting action (i.e. turning, boring , drilling, milling) as opposed to a reciprocating cutting action such as planing*. Consequently, the spindle speed is the ratio of cutting speed to tool diameter. Thus the fastest spindle speed is given by;

$$N\ max = \frac{\text{fastest cutting speed used}}{\pi \times \text{min diameter cutting tool}}$$

and similarly the slowest spindle speed by;

$$n\ min = \frac{\text{slowest cutting speed used}}{\pi \times \text{max diameter cutting tool}}\ .$$

Table 3.2 gives some indication of the range of cutting speeds recommended for different materials. A spindle speed ratio of 1:40 would be fairly typical of a NCMT capable of machining both very hard metals (rene 41) and the free cutting materials such as aluminum at an acceptable rate of metal removal.

It is important, however, to keep the transmission inertia low, and avoid excessive pitch line velocities of free running gears.

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* A German N/C. planing machine has been built

TABLE 3.2

CUTTING SPEEDS FEET/MIN. FOR MILLING CUTTERS

	High Speed Steel ft/min.	Carbide ft/min.
Carbon Steel up to 38 Ton/ins^2	50 - 100	160 - 400
Cast Iron	32 - 50	128 - 200
Light Alloy	640 - 1280	1280 - 2000

3.2.2 A Typical Spindle Drive and Transmission:

A schematic of the spindle drive and transmission system of a well known machining centre is shown in Fig. 3.1. The constant mesh transmission contains three electric clutches, each responsible for a discrete speed range, and is driven by a positive displacement hydraulic motor which has variable speed, controlled by the flow through an electro-hydraulic valve. Typical output characteristics of this system is shown in Fig. 3.3. It should be noted that the spindle horsepower drops below seven horsepower when the spindle speed is less than 400 rpm., between 600 and 1000 rpm and between 1600 and 3000 rpm. These limitations could be disadvantageous in machining the harder alloys with cutters of large diameters, however, using a carbide tool rather than one made of high speed steel will usually solve this problem. Similarly the restrictions on cutter diameter in machining hard steel or chilled iron in the 600 to 1000 rpm range can be avoided, if a carbide tool is used.

3.2.3 Torsional Strength and Stiffness:

In addition to the regular cutting forces the spindle is often subjected to forced vibrations from the periodic impulses of a milling cutter, or from the unbalance of a rotating part. The impact of the tool on the workpiece should also be considered, and generally the cutting forces may vary extremely rapidly, causing high stress peaks in the whole spindle assembly. Strength calculations are based on the minimum speeds, when the torque applied to the

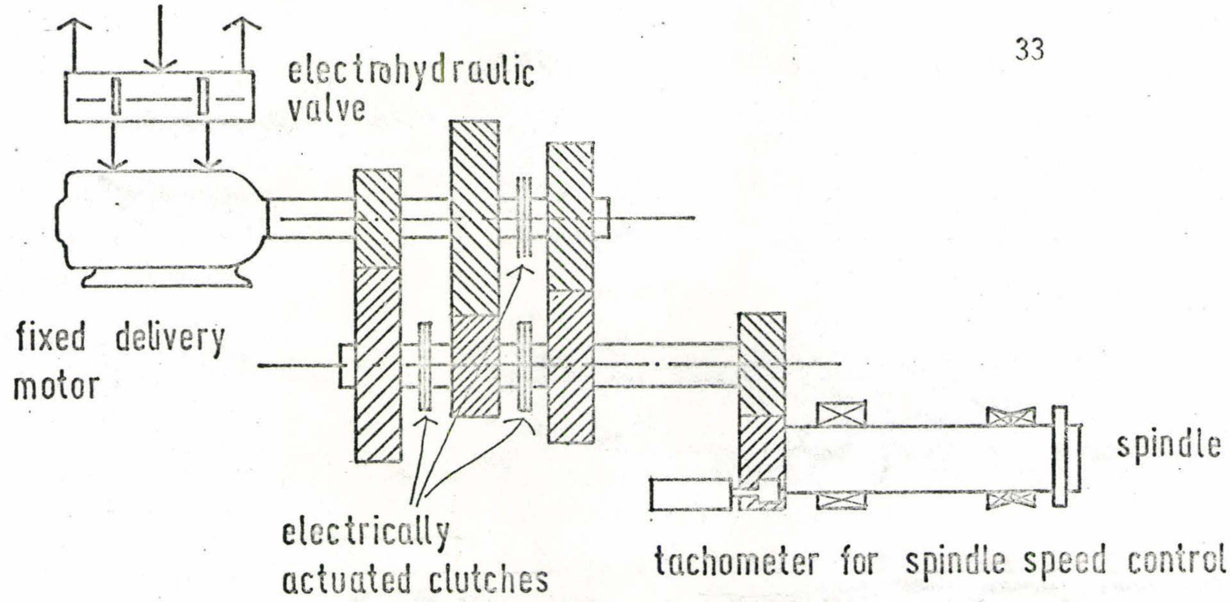

FIG 3:1

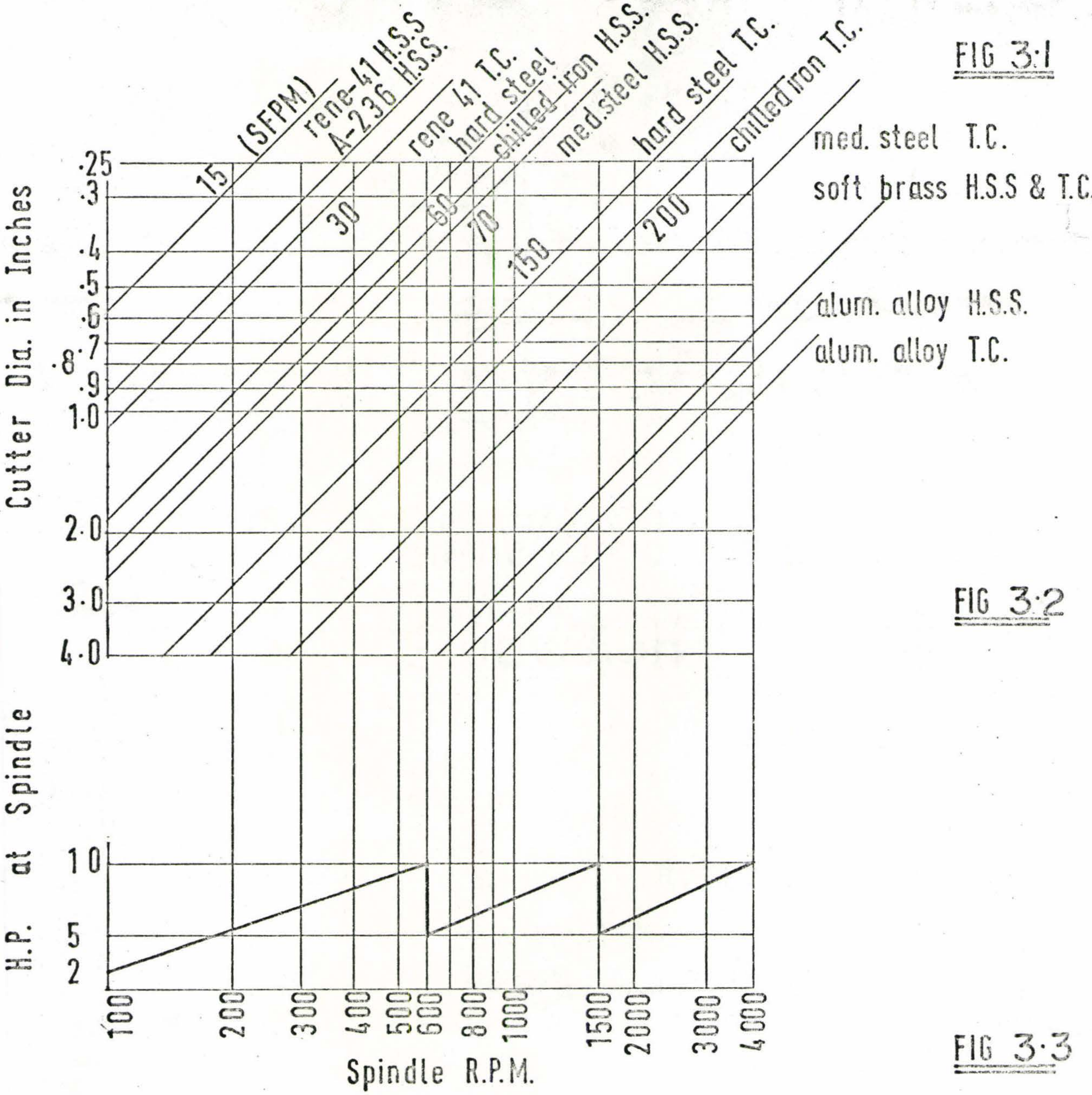

FIG 3·2

FIG 3·3

mechanical components is maximum. All transmission shafts should be short as possible to minimize torsional and axial compliance of the drive train. This is not always possible, because, to allow the tool maximum accessibility over the work-table area, the spindle should be a long slender projection. Torsional vibration occurs frequently in drive trains with insufficient torsional stiffness, and usually results in an undesirable phase lag between input and output. The torque variation can be partly absorbed by a fly wheel (could be driving gear) on the spindle which distributes the torque evenly over the entire cycle.

3.2.4 Additional Considerations:

Any spindle deflection will have a detrimental effect on the quality and accuracy of the work-piece, and can be responsible for excessive tool and machine tool wear. Another critical parameter is the inherent spindle damping particularly with reference to the natural frequency of the drive train and to the frequency of anticipated transient disturbances. Both these factors depend largely on the selection and the location of the spindle bearings.

Uncontrolled heat sources in the vicinity of the spindle bearings should be eliminated wherever possible, as irregular thermal expansion of the spindle may introduce appreciable errors in machining. Spindles are often designed of material with low coefficients of expansion (.e.g invar). Some MT builders provide temperature sensors with feedback to the control unit to compensate for any thermal growth, or to control heating elements mounted on the spindle assembly to keep the temperature and spindle length relatively static.

Added to these considerations are the usual requirements of high transmission efficiency, and freedom from backlash etc.

3.2.5 Spindle Speed:

It is not essential to have a continuous spindle speed range, most NCMT have discrete ranges incremented by 10, to 50 rpm per step. Nor it is necessary to calibrate the speed very accurately, a deviation of 5% of the programmed speed is sufficiently accurate. However, for tapping or screw cutting it is imperative that the spindle speed remairs constant, and is adequately synchronised to the feed motion to maintain an accurate thread pitch. Consequently, there is usually a spindle velocity feedback loop. Generally, it has a smaller gain (slower response) than the feed control loop, so to avoid a phase lag between spindle and feed motion, in tapping operations, the feed motors are synchronised to the spindle motors. In all other machining operations spindle motion is independent of the feed motion.

It is generally desirable to have spindle rotation in both directions, this is easily achieved in hydraulic and DC motors which are frequently used for spindle drives.

3.3 DESIGN PARAMETERS FOR FEED DRIVE TRAINS

3.3.1 Point to Point Feed Drives:

The basic distinction between point to point and continuous path NCMT is essentially in the design of their respective feed drives and feed control systems. Since point to point machining does not require the tool to follow a precise path in moving between two points on the work piece, the feed drives on mutually perpendicular feed axes are usually not synchronised, and do not need a continuously variable speed range or precise velocity control. In practice, point to point feed drives have several discrete speed levels, one for rapid traverse, a few intermediate levels and one for final jogging into position. Feed motion usually takes place independently along each axis, or at an inclination of approximately 45° to two mutually perpendicular axes (i.e. the feed drives move at roughly the same speed).

3.3.2 Continuous Path Feed Drives:

To direct the tool along a series of straight line increments, at any inclination to the feed axes (2,3,4 or 5) requires complete synchronisation of the feed drives in defined velocity ratios. It is desirable to have a wide, continuously variable, speed range on each feed axis so that optimum cutting feeds of different metal alloys are possible. However, often NCMT feed drives have many discrete speed levels very close together over the entire range. The cutting velocity is the vector sum of

TABLE 3.3

A COMPARISON OF DESIGN PARAMETERS FOR POSITIONING AND CONTOURING FEED DRIVES

CONTOUR DRIVE & TRANSMISSION	POSITIONAL DRIVE & TRANSMISSION
Maximum feedrate	Maximum feedrate
Size of Speed increments over entire range	Range of max. & min. feed and speeds
Required rigidity against cutting forces	Permissible speed regulation with increasing external forces
Required damping factor to transient disturbances quickly	Maximum permissible time taken for each co-ordinate setting
Minimum compliance and backlash in the drive and guideways	
Minimum friction in guideways especially non viscous	
Minimum hysteresis, backlash, dead zone, and other non linearities in the drive	
Minimum variation in temperature, supply voltage, viscosity (for hydraulic systems)	
CONTOUR MEASURING AND CONTROL SYSTEMS	POSITIONAL MEASURING AND CONTROL SYSTEMS
Range of positional error detector - maximum deviation in transient state	Null or coincident control for final positioning
Permissible insensitive zone	Maximum time permissible for co-ordinate setting
Required gain in positional control loop	

of the velocities of the feed axes. The feed drives usually have both positional and velocity feed back control.

3.3.3 Power and Torque Requirements:

The power requirements at the cutting edge along the feed axes is relatively low, since the tangential cutting force component (in the feed direction) is always less than the main cutting force and the ratio of feed speed to cutting speed is always less than .02 [1]. Thus the power needed for the feed drive is less than 2% of the spindle power. However, due to the transmission losses and the inherent stiffness of the drive train, to ensure static and dynamic stability, the feed drive motors may have as high as 25% the power capacity of the spindle drive motors.

Constant torque motors are well suited to overcome the high axial stiffness of feed transmissions. The maximum traverse speed usually determines the power requirement of the feed motors.

3.3.4 Additional Requirements:

The drives must have high dynamic and static stiffness and adequate damping to reduce the effects of transient disturbances. Non-linearities such as backlash, slip-stick friction, hysteresis losses should be prevented or minimized.

All rotating components in the drive transmission should have low inertias and the motors should be capable of rapid acceleration and deceleration to ensure fast response times to control signals. The power transmission should be both continuous and smooth in operation.

3.4 ELECTRICAL DRIVES AND METHODS OF SPEED CONTROL USED IN NCMT

3.4.1 A. C. Motors:

Conventional means of speed control of A. C. motors are often inadequate for NCMT drives. Usually only a few discrete speed levels are possible by varying the number of exciting poles of the motor. Consequently, A.C. motors used for NCMT drives are usually controlled by magnetic or eddy current clutches, however, these are inefficient at loads less than the maximum. A versatile 3 phase, 400 cps induction motor was used more than 10 years ago in the U.K. for NCMT feed drives. It had a peak output of .7 bhp at a speed of 10,500 rpm and an acceleration of 10,000 rpm/sec. These were used on large* milling machines, cutting light alloys, producing a maximum feed rate of 150 rpm (Ref. 29).

Some of the first positional NCMT used two phase feed drive motors. They have extremely high torque to inertia ratios which accounts for their fast response times. The output torque is proportional to the product of the two phase voltages, unfortunately,

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* Load capacity 4 tons and work table 24 ft. x 6 ft.

they have poor efficiencies. The final positioning was achieved by de-energising the motor at low speed before the specified location, and allowing the drive to coast to a stop. These systems were designed accurate to one thousandth of an inch but are infrequently used today because of the inherent inefficiencies of the system and the availability of more suitable alternatives.

A.C. motors are frequently used for driving hydraulic pumps which in turn supply hydraulic power to the main drive motors. These motors usually have 2 or 3 speed levels which are controlled by the number of poles excited.

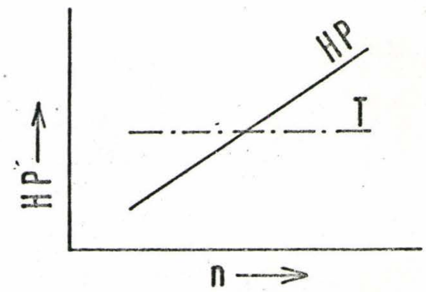
3.4.2 D. C. Motors:

3.4.2.1 General:

There are several methods of maintaining continuous speed control of a D. C. motor. The most efficient means and the one used most frequently in NCMT design, is by controlling the armature voltage, (see Figs. 3.4 and 3.5). Consequently, the problem is resolved into generating a variable voltage.

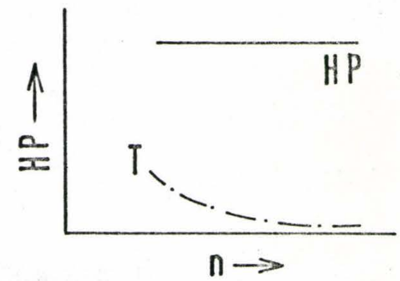
3.4.2.2 Ward-Leonard Motor Generator Sets:

A motor generator set provides excellent speed control, however, has relatively poor acceleration and a slow response (of the order of one sec [27]) on account of the high rotary inertia of the generator, the D.C. motor and the leadscrews combined. It is mainly used for large horsepower (above 25 horsepower) spindle drives and is rather expensive. A circuit



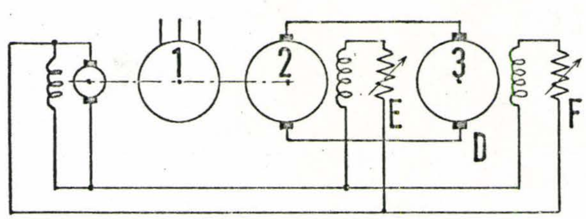
Speed adjustment of the d.c. shunt motor by changing the rotor voltage.

FIG. 3·4



Speed adjustment of the d.c. shunt motor by changing the field current.

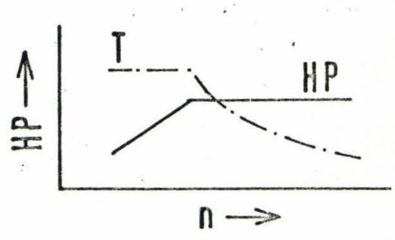
FIG. 3·5



1) A.C. Motor
2) Generator
3) D.C. Drive Motor

Circuit of a Ward-Leonard set

FIG. 3·6



Speed adjustment of the Ward – Leonard set.

FIG. 3.7

diagram of a Ward-Leonard set used in spindle drives is shown in Fig. 3.6. A wider speed range is obtained by reducing the field current of the spindle drive motor D with resistance F without diminishing the output power. The characteristics of a similar motor generator sets are shown in Fig. 3.7. At low speeds the output torque does not exceed the design torque strength of the transmission, and the power requirement is less than the maximum power. At a specific speed the maximum power is reached which stays constant over the rest of the speed range as the output torque decreases.

3.4.2.3 Silicon Controlled Rectifiers (S.C.R):

Silicon controlled rectifiers (S.C.R) have only recently been manufactured for industrial use, yet they have become one of the most popular devices for A.C. rectification in applic-ations such as NCMT, drive motors, and have influenced some NCMT designers in using electrical instead of hydraulic drives [28].

The SCR has the same rectifying properties as a diode, but in addition it can control the flow of electric current. It has 3 terminals a cathode, anode and a gate, which does not permit current to flow in either direction until triggered by a low power control impulse. Once the impulse is received, and the voltage is in the forward direction, the gate loses control and allows current to pass until it drops below a threshold value. When this occurs, the SCR reverts to its nonconducting state, until the next impulse is received. When connected to an AC supply the current is in the forward direction each half cycle and by suitable timing of the control pulses the SCR can be made conducting for any fraction of that half cycle, (see Figs. 3.8 and 3.9). This provides a variable D.C. voltage and is particularly suitable for NCMT because several control units generate electrical signals in the form of digital pulses which may be integrated by the SCR into an analog displacement.

The SCR has a response time less than half a cycle, however, motor overloads must be immediately detected and the firing pulses changed to prevent excessive currents in the circuit. It is not possible to change the current polarity in a transistorised circuit to decelerate or reverse the rotation of the motor, as it is when using a motor generator set. Although two similar rectifying circuits are often provided and the direction of current flow is changed by switching from one circuit to the other. The SCR controller is small light, very efficient (approx. 1 volt drop across the circuit) and requires no maintance. It has been used for large DC motors (60 HP) but is excellent for medium size NCMT feed drives which are seldom larger than 3/4 HP. The DC motor selected would be a shunt or a compound-wound motor depending on the torque speed requirement of the drive. Recently a DC servo-motor with SCR control was reported to accelerate to 3600 rpm in less than 10 milisec. Similar motors are available in sizes

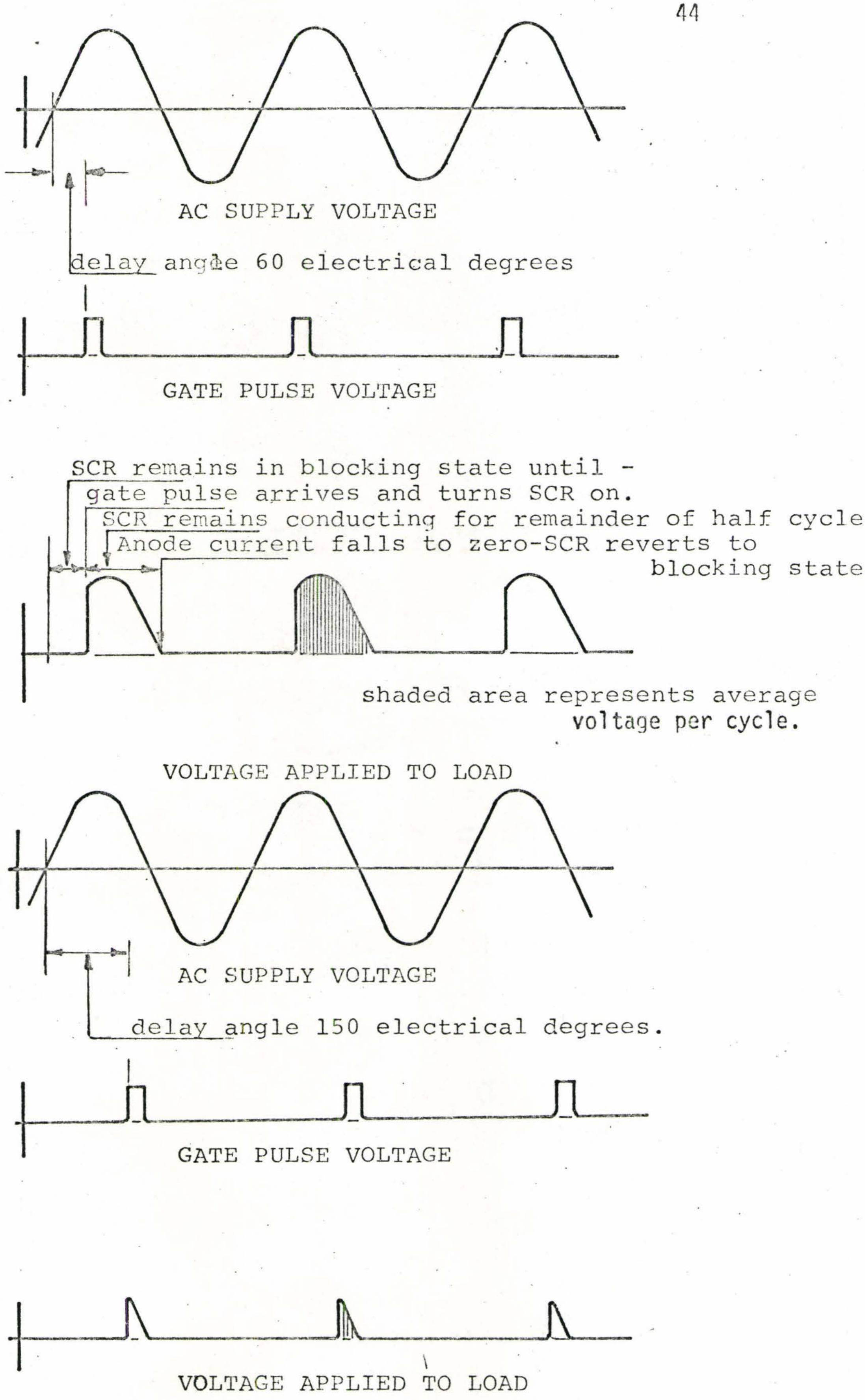


FIG. 3.8 EFFECT OF PHASE SHIFT ON GATE PULSE

(extracted from Ref. 28)

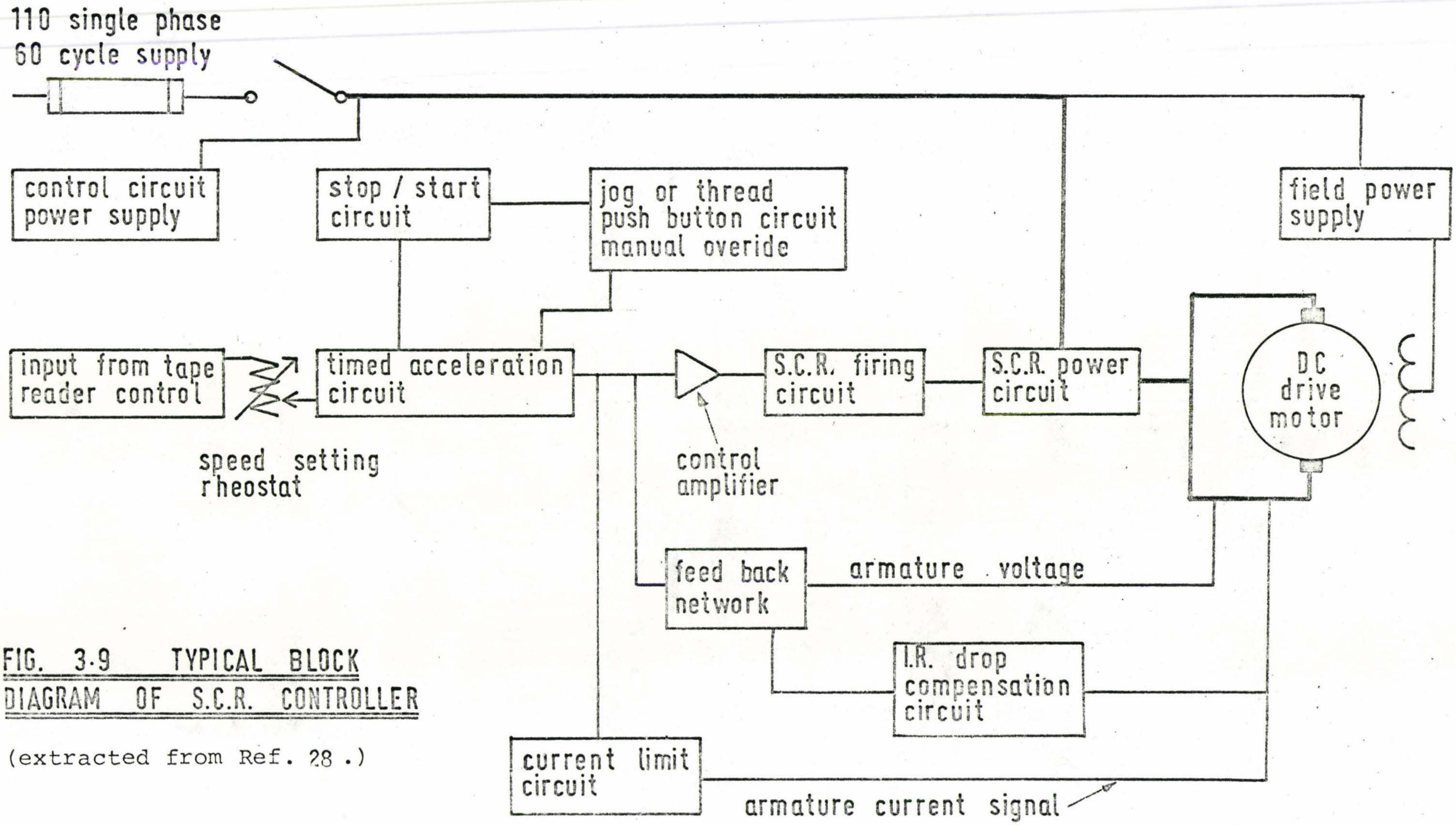


FIG. 3·9 TYPICAL BLOCK DIAGRAM OF S.C.R. CONTROLLER

(extracted from Ref. 28 .)

Shows a block diagram for an SCR controlled drive. The forward voltage drop across the SCR is usually only about 1 volt at full load current.

from 1/4 HP to 4 HP with a constant torque output. The operation is smooth and low speed pulsing is eliminated [32]. A good DC motor should be capable of a speed range of at least eight to one.

3.4.2.4 Electromagnetic Couplings and Dog Clutches:

The output of a constant speed AC motor transmitted through an electromagnetic eddy current coupling is sometimes used in NCMT spindle drives. The coupling is a slip device, it dissipates excess power as heat energy, but has several advantages; namely, it has no rapidly wearing components, it provides a wide speed range, any speed can be maintained accurately, it operates smoothly and acts as a buffer (discontinuity) to impact loading. The main disadvantage is that it reduces the torsional stiffness of the transmission and usually is only suitable for spindle drives.

The prime mover could be an induction*, synchronous or squirrel cage motor which operates at almost constant speed. The principle of the coupling is that a magnetic flux is established by eddy currents between a drum rotated by the input shaft and the excited field windings of the rotor mounted on the output shaft. The flux causes the output shaft to follow the rotating drum ("an inside out squirrel cage motor" [27]). The amount of slip permitted can be varied by varying the (D.C.) excitation of the rotor field windings. A tachometer is often used for velocity feedback and the clutch has adequate speed response and speed

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* Slip increases with load but the output speed can be kept constant with closed loop velocity control.

regulation [29]. This device has a constant torque output, however, in cases where constant horsepower is required an oversize coupling has to be used to withstand the maximum torque at low rotational speeds. This is often uneconomical.

Electrically actuated multiple dog clutches are still favoured for NCMT transmission systems because their positive locking action ensures high axial stiffness, which is frequently a critical design parameter.

3.5 HYDRAULIC DRIVES AND METHODS OF SPEED CONTROL USED IN NCMT

3.5.1 Introduction:

Hydraulic power transmissions have always been closely associated with machine tools. The table 3.4 illustrates various applications of hydraulics in feed drives. Hydraulic drives may be divided into two groups: hydrostatic and hydrodynamic. The latter mainly utilize the kinetic energy of the flow, however, poor efficiencies at low speeds, slow braking and reversal times restrict their use in NCMT applications. The hydrostatic drives on the other hand, utilize the potential (pressure) energy of the fluid and enjoy wide popularity in NC machinery.

Apart from a few exceptions the feed axes on most NCMT are rectilinear. Thus the hydraulic ram drive would be an obvious choice. Other considerations however, often result in using a rotary drive motor coupled, to a lead screw or a rack and pinion, on the feed axes.

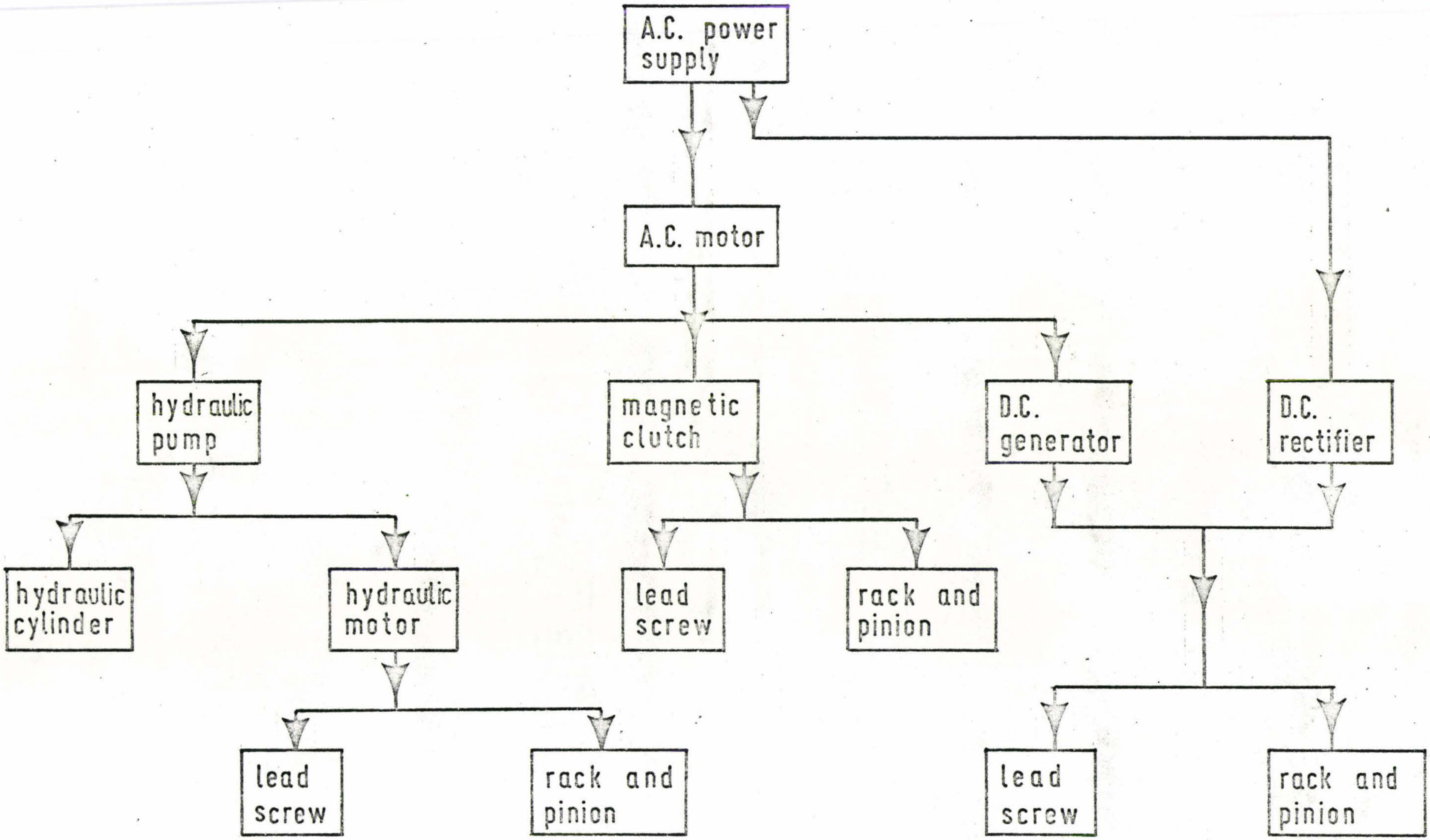

TABLE 3.4 VARIOUS FEED DRIVES FOR NCMT FROM AN A.C. POWER SUPPLY

Usually NCMT hydraulic circuits operate between 500 and 2000 psi. The upper pressure is limited by; the bulk modulus of the oil (it is usually taken to decrease .45% of its volume per 1000 psi compression); as well as the rapid increase in pipe friction with increasing fluid velocity. The pipe velocities are usually limited to less than 30 ft/sec [23].

3.5.2 The Hydraulic Ram:

The hydraulic ram is most commonly used on short stroke feed axes. The length of stroke is limited by; the stiffness; the buckling strength; and the sag of the piston rod when extended from the cylinder. It is considered good practice to design the piston rod in tension on the working stroke (normal feed direction) so that the piston rod is not subjected to severe buckling forces. Added to this, the compressibility of a large volume of oil required for long stroke hydraulic cylinders, has an appreciable effect on the positional accuracy of the piston, and the axial stiffness of the transmission. Several authors recommend that hydraulic cylinders for MT feeds should not exceed 30 inches [30] in length*.

A convenient parameter may be defined by the product of the moving mass and the length of the stroke. It can be shown** for constant crossectional piston area, the natural frequency of the ram decreases with increasing mass stroke factor.

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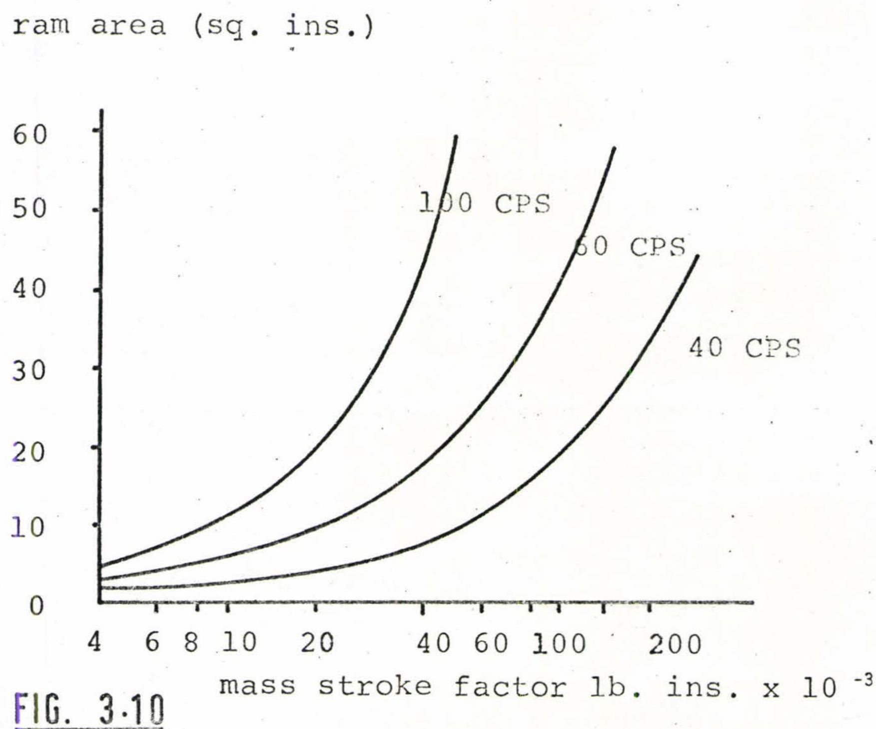
* [1] recommends 40 inches should not be exceeded.

** In section 3.5.6. the compliance λ of a hydraulic cylinder is shown proportional to L/Ae where L is the cylinder length, A crossectional area, e oil bulk modulus. Then from $\omega nat = \sqrt{1/M\lambda}$ we have ωnat proportional to $\sqrt{LA/Me}$.

The plot given in Fig. 3.10 [22] is based on a double sided ram with back pressures set above 500 psi. Ogden [22] claims the minimum natural frequency of the drive should not be less than 60-70 cps. Ram drives with mass stroke factors up to 10,000 lbs. ins. are most frequently found, although, in some cases rams are used for rather large machines with mass stroke factors of up to 40,000 lbs. ins (see Fig. 3.11).

Sometimes a dummy piston rod, of equal diameter to the actual piston rod, is used to equate the crossectional areas on each side of the hydraulic ram. Cylinders with equal crossectional area on both sides of the piston are called symmetrical, whereas those with unequal areas; unsymmetrical. The theoretical ram speed is proportional to the pump flow rate and inversely proportional to the piston crossectional area, and these have to be carefully balanced to obtain adequate feed-rates, and axial feed transmission stiffness. Unsymmetrical pistons have been used in the design of vertical feed drives, where the larger effective area is used to counterbalance the gravitational force acting on the drive mass.

By controlling the flow to a hydraulic ram the speed variation should be continuous from zero to the maximum. At low speeds, however, the motion is irregular and this is attributed to slip-stick friction. It may cause inaccurate positioning of both open and closed loop positional controls, and is often



$$\lambda = \frac{L}{4Ae}$$

$$Fres = \frac{1}{2\Pi}\sqrt{\frac{1}{M\lambda}}$$

$$Fres = \frac{1}{2\Pi}\sqrt{\frac{4Ae}{ML}}$$

M = moving mass
A = cross sectional area
e = bulk modulus of oil
L = cylinder length

FIG. 3·10

PLOT OF RAM AREA AGAINST MACHINE MASS AND STROKE FOR A GIVEN RESONANT FREQUENCY. [22]
1.2×10^{7} freq.^{2} x (mass x stroke)
(C.P.S. lb. in.)

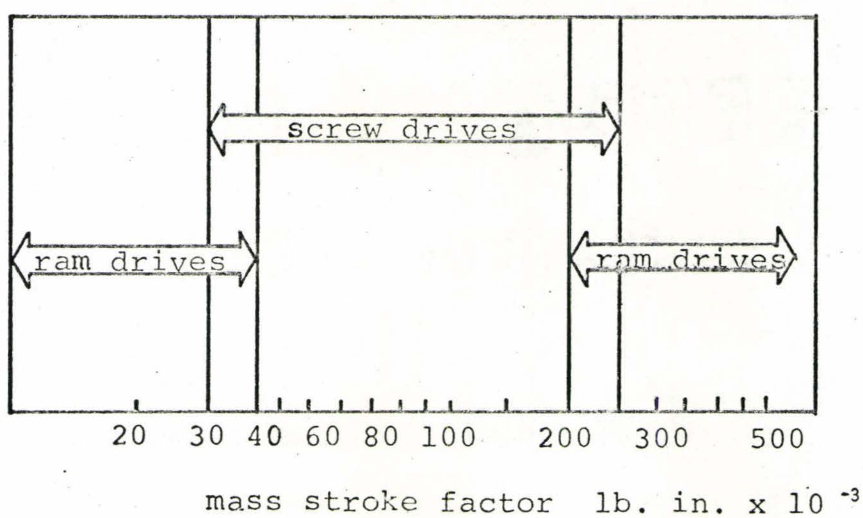


FIG. 3·11

RANGE OF DRIVE POSSIBILITIES RELATED AGAINST MASS STROKE FACTOR [22] responsible for dynamic instability of the latter. The phenomenon of slip-stick friction is well known, it occurs when the friction force, velocity relationship has a negative gradient (see Fig. 3.12) and it may also occur on machine tool slideways with much the same effects. It has been found [25] that by rotating the piston slip-stick friction can be eliminated*, although it is doubtful whether this theory is practicable in NCMT design.

3.5.3 Rotary Hydraulic Drives:

Positive displacement piston motors (and pumps) are preferred in NCMT since they operate with greater consistency and higher mechanical and volumetric efficiency, under varying loads, pressures and temperatures than both rotary (centrifugal), gear and vane motors (and pumps). Chiappulini [25] claims that most piston hydromotors (and pumps) have a "cyclic displacement (or velocity) irregularity", which diminishes as the number of pistons (in the motor) increases. A motor with an odd number of pistons generally has less irregularity than one with an even number. However, a particular radial motor with a specifically designed camshaft, exhibits no such inconsistency (i.e. velocity is constant with constant delivery). Radial piston motors are generally hydrostatically better balanced than axial piston motors, and this improves the efficiency and linearity of the motor by reducing internal leakage.

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* The gradient of the friction velocity curve becomes positive.

Rotary hydraulic drives are frequently used for long traverse feed axes (see previous section and Fig. 3.11) with either a rotating ball screw or a rack and pinion transmission. The total inertia of these rotary components limits the acceleration of the drive. On the other hand, hydraulic ram drives have no rotating components; the table mass and axial transmission compliance determine natural frequency and speed response of the drive. Zelleny [24] designed a three axis continuous path lathe capable of accelerating (and decelerating) to 500 ipm in less than .05 secs. He considered various alternative drive combinations (hydraulic motor and lead screw, DC motor and lead screw, and a hydraulic cylinder) and concluded that the hydraulic cylinder was the only feasible design. The other two were limited by their rotary inertias. However, the rotary inertia of hydraulic motors are quite comparable to the inertias of electric motors. In addition, hydraulic feed drives have far quicker response times than the equivalent electrical drives, and consequently are preferred for continuous path feed axes. NCMT spindles may also be driven by hydraulic motors.

3.5.4. Hydraulic Losses and Nonlinearities:

Internal leakage, fluid and mechanical friction, and oil compressibility are usually responsible for most of the power losses in hydraulic drive systems. The effective bulk modulus of oil is often reduced by almost 20% because of the inclusion of air particles in the oil which may occur in low pressure areas (i.e. at high oil velocities). Provided the leakage is laminar, the speed, torque (pressure) curve remains linear with a negative gradient. This characteristic increases the damping of the transmission, which in turn improves the stability of a closed loop control system. However, other factors such as changes in oil viscosity and temperature always introduce undesirable nonlinearities into the system. Often hydraulic circuits have auxiliary make-up pumps of the leakage become excessive.

Mechanical friction within the motor (slip-stick) can be responsible for unstable operating characteristics at first take off and low velocities. A particular swash plate motor has hydrostatic lubrication at the piston head pads, against the swash plate to eliminate slip-stick friction.

3.5.5 Types of Velocity Control Circuits and Total Systems:

The basis of speed control of hydraulic positioning servo systems is the control of the direction and quantity of fluid flow. This may be done by several alternative methods, a variable delivery pump and fixed delivery motor give a constant torque output, and the speed and the power are proportional to the delivery rate. The wide continuous speed range possible, makes this system suitable for continuous path feed drives. Although, apart from the expense of a variable delivery pump the system has another disadvantage; the variable delivery pump is

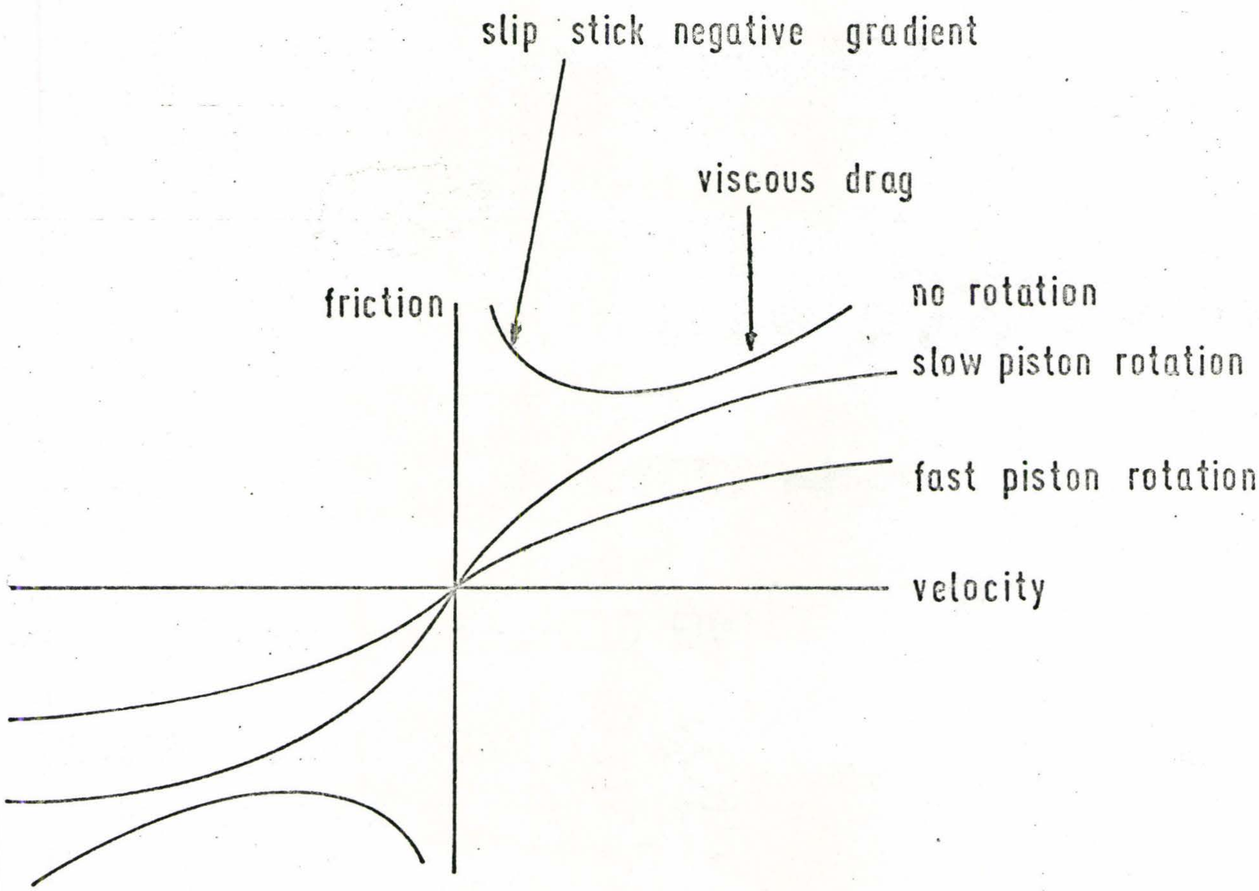


FIG. 3·12 FRICTION vs VELOCITY FOR HYDRAULIC CYLINDER within the servo loop and consequently the dynamic response is relatively poor. An equivalent system using a fixed delivery pump and motor controlled by an electrohydraulic bleed valve has excellent speed response but is extremely inefficient at low speeds and loads. In addition, a vast amount of pressure energy is dissipated as heat energy as the flow is throttled through the electrohydraulic valve. Usually a constant pressure relief valve is included in the circuit and provided the flow demand does not exceed the pump delivery rate, the pump may be considered as a constant pressure source.

A NCMT using a hydraulic power supply can be a single pressure system, or have several independent systems. The former design is usually preferred yet it is often practicable to have a few auxiliary systems as well as one main pressure source A typical medium size machine (work table capacity 4000 lbs.) has a large (50 HP) electric motor driving a variable displacement pump. An accumulator is always included in a hydraulic circuit to provide an immediate oil supply for rapid changes in demand. The accumulator would either be nitrogen filled, to prevent contamination of the oil, or air filled, with the oil contained in a rubber sac, which prevents contamination and inclusion of gas particles in the oil, which effectively lower the oil bulk modulus. In any hydraulic system, oil cleanliness is of prime importance, any minute particles of dust can cause erratic behaviour of the servo-valves. Therefore, all hydraulic fluid is filtered through a fine filter (say 10 microns) before entering any servo-valve. Heat exchangers may often become necessary to keep the oil temperature and viscosity within the design limits.

3.5.6 Electrohydraulic Servo-Valves:

The performance of the electroservovalve in a hydraulic positioning servo is critical to the overall performance of the whole machine tool. Basically the electrohydraulic servo-valve regulates the flow in the hydraulic circuit, in the same proportion as the current signal applied to the valve. The valve may be a '3' way or '4' way type having respectively 3 or 4 external connections.

The 3 way valve has 2 metering edges and is used to control an unsymmetric ram drive. The side of smallest effective piston area is permanently connected to the supply pressure. The other side is connected through the valve either to the pressure supply or to the return tank, depending on the spool position. When the spool is in the neutrallocation the ram is 'locked' in position, and the axial stiffness of the drive is limited by; the expansion of the pipes and the cylinder and the compressibility of the oil under high pressures. The valve is actuated by supplying a control signal to one of the electromagnetic coils on either side of the spool. This causes the spool to move in a particular direction through a distance proportional to the signal applied (assuming the value linear). This allows the oil to flow into the cylinder moving the ram in the same direction as the spool.

The spool is usually spring loaded and when the control signal is no longer applied, returns to the neutral position, and oil flow to the ram decreases.

Zelleny [24] claims that the side of an unsymmetrical piston connected to the supply pressure has infinite compliance. Thus the compliance, when the ram is at half the stroke length, $\frac{L}{2}$, is twice that of an equivalent symmetrical piston, see Fig. 3.13. This can be appreciably improved using one way valves in the supply circuit, however, the compliance of a symmetrical hydraulic ram is generally greater than an equivalent unsymmetrical one.

A four edge electrohydraulic servo-valve is used for control of a symmetrical ram, or a piston hydromotor, which is also considered symmetrical. The symmetrical ram is generally stiffer than an unsymmetrical one, and is easier to design but the length of the piston rod assembly is twice as long as the distance travelled, which is often inconvenient and impractical. The operation is similar to the two edge valve; the piston is 'locked' in position when the spool is in the neutral position, and moves in the same direction as the spool when the solenoids are excited by a control signal (see Fig. 3.14).

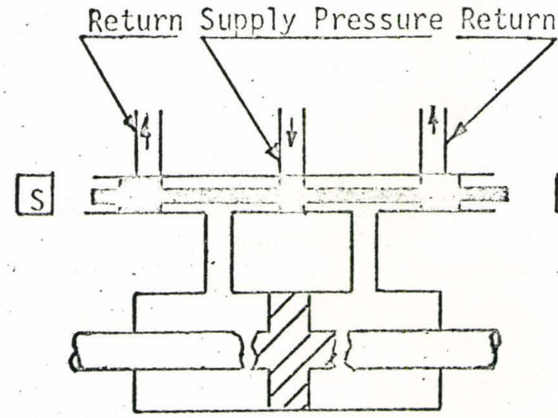


FIG. 3.14

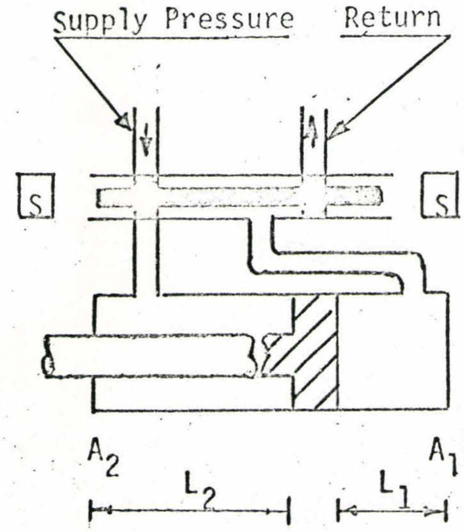


FIG. 3.13

The compliance of a four edge control value and a symmetrical piston

The compliance of a two edge control value and a unsymmetrical piston

using the following symbols

e, bulk modulus	V_1, V_2, effective volumes	$\lambda_1 \lambda_2$, compliance $\frac{\partial(\delta)}{\partial F}$
A_1, A_2, effective areas	P_1, P_2, pressures	$L_1 L_2$, piston lengths
$\delta_{(L)}$, piston displacement	F, arbitary force	L, total piston length

By definition $e = V\partial P/\partial V$

$$e = AL\partial F/A^2\partial L$$

The compliance $\lambda = \partial(L)/\partial(F)$

For each side of the piston $\lambda_1 = L_1/A_1e$ and $\lambda_2 = L_2/A_2e$

Total compliance $1/\lambda$ total $= 1/\lambda_1 + 1/\lambda_2$

<u>For Zero Lap Conditions</u>

4 edge valve

λ_{max} when $L_1 = L_2 = L/2$

$$\lambda_{Tot} = \frac{L}{4Ae}$$

2 edge valve

$$\alpha = L_1/L$$

$$\lambda = L/e\ [A_1/4 + A_2(1-\alpha)]$$

$$\lambda_{max}: \partial\lambda/\partial\alpha = 0 \quad \alpha = 1/(1 + A_2/A_1)$$

$$\lambda_{max} = L/A_1e\ (\frac{1}{(A_2/A_1+1)}^2)$$

Both these valves are ideally 'closed centre' (i.e zero lap), however, to increase the stability in the neutral position [24] and the linearity [30] the valve is frequently underlapped. It then becomes an 'open centre' valve. The underlap also increases the valve gain for small displacements about the neutral position since for example, with a rectangular port value gain is proportional to the instantaneous orifice width and similarly for a circular port the gain is proportional to the instantaneous orifice chord length. Underlapping, however, increases the quiescent leakage, which in turn increases the system stand-by power consumption. An overlapped valve introduces a dead-zone and is rarely needed in NCMT applications.

Frequently to increase the loop gain two-stage valves are used, these are especially useful in NCMT feed drives where the delivery rates and pressures are relatively high. The first or pre-amplification stage is usually another spool valve, or a flapper-nozzle arrangement, while the second stage is either a two or four edge spool valve. The flapper-nozzle pre-amplification stage has a low stand-by power requirement high static gain, and can operate at fairly high frequencies. Small two-stage valves respond to a maximum frequency of the order of 900 cps, however, this decreases with increasing oil flow. A typical two stage valve with a maximum flow rate of 45 gpm has a maximum frequency response of 80 cps and a time constant of 3 milisecs. In some cases the land-stems on the spools are contoured to reduce the reactive fluid forces that oppose spool motion, this permits the use of smaller solenoids and improves the operating characteristics of the valve.

SECTION B

PROGRAMMING NUMERICAL CONTROLLED MACHINE TOOLS

In reviewing the development of manufacturing technology it is apparent that the division or the specialization of labour created the necessity for men to communicate ideas and details of manufacture. The classical means of technical communication; pictorial representation; written description; and oral explanation, today are still being utilized in conventional manufacture, yet even these are often found inadequate.

The development of NCMT has added a new dimension to the communication difficulty. The only means of communication between man and the NC machine are coded alphanumeric instructions. Writing these instructions for manufacture of a component is known as NC programming. The machine tool will perform each instruction exactly as it appears in the programme, and has no capacity to interpret the intentions of the designer or the programmer. This means that a programme must contain precise and detailed instructions for each machining operation and this obviously makes the communication problem far more acute.

CHAPTER 4

PROGRAMMING TECHNIQUES

4.1 INTRODUCTION

4.1.1 General:

Programming NCMT may be done manually, however, when parts manufactured are complex and require many machining operations, the many calculations needed to programme the machine tool make manual programming impractical. Consequently computer aids to programming have been developed to perform the bulk of the routine calculations. There are a large number of computer assisted NC programming languages available today. They vary considerably in their uses, the ease with which they may be used, and the size and complexity of general purpose computer they require.

4.1.2 Sequential Programming:

Each instruction is performed in sequence as it appears in the programme, and the operation is completed before the next instruction is read. The instructions appear in a defined format and contains all the information necessary for that operation. All manually prepared programmes and a few computer programming languages are of this type. They are usually used for point to point (ptp) machining and have limited contouring capability.

4.1.3 Generalized Symbolic Computer Aided Programming:

A generalized computer language allows the geometry of the component to be defined in symbols representing various surfaces such as planes, cylinders, conics and several other geometrical shapes. Machining instructions are then defined in terms of the geometrical symbols assigned previously in the programme. Generally, these languages require two passes through the computer, the output of the first pass is machine tool independent, and only in the post processing stage (2nd pass) are the instructions editted for a specific machine tool. There are, however, several generalized languages which incorporate the two programmes together in a single pass through the computer, they can only be used for a specific machine tool.

4.1.4 Special Purpose Symbolic Computer Aided Programming:

A special computer language may be written to programme a particular family of complex, geometrically similar components such as turbine blades or pump impellers, which are difficult to programme in a generalized language. This practice is avoided where possible, yet it does have some application in certain industries.

4.2 MANUAL PROGRAMMING

4.2.1 Introduction:

In this age of computer science, manual programming of a NCMT may sound rather antiquated. Many jobbing shops, however, find Manual Programming the most economical means for part programming geometrically simple components, which require only a few machining operations. Most manually written programmes are for point to point machine tools. Statistics show that at least 80% of the NCMT that have been built are positional machines. In a recent survey carried out in the U.S., 68% of the participants replied that they were using manual programming, and would continue to do so in the forseeable future [21].

Computer aided programming can save considerable time and effort, if many repetitive calculations are required to programme a particular part. Consequently, for point to point work with a high degree of symmetry, and many machining operations manual programming may no longer be economical.

4.2.2 Input Media And Manual Tape Preparation:

Today the majority of manually programmed NCMT accept a one inch wide punched tape which complies with the specifications established by the Electronic Industries Association(E.I.A.) for digital computers (Fig. 4.1), N.C. tapes may be manually punched on standard computer peripheral equipment (e.g. a flexowriter). The standard Binary Coded Decimal format for N.C. tapes are shown in Fig. 4.2.

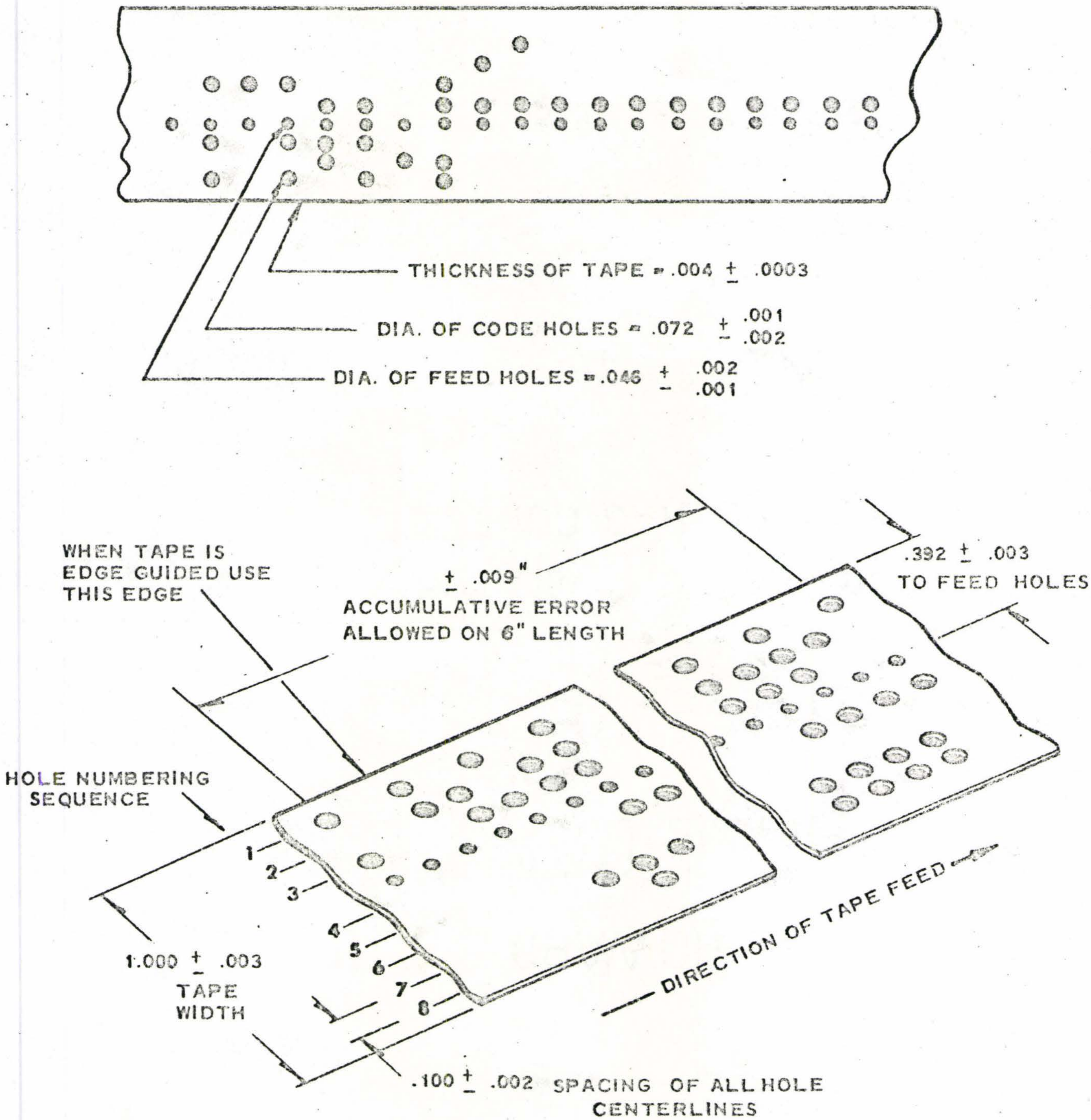


FIG.4.1

E.I.A. STANDARD 1" WIDE EIGHT – HOLE PUNCHED TAPE SPECIFICATION.

TAPE									CHARACTER	
8	7	6	5	4		3	2	1	DIGIT OR CODE	DESCRIPTION
		●			•				0	DIGIT 0
					•			●	1	DIGIT 1
					•		●		2	DIGIT 2
			●		•		●	●	3	DIGIT 3
					•	●			4	DIGIT 4
			●		•	●		●	5	DIGIT 5
			●		•	●	●		6	DIGIT 6
					•	●	●	●	7	DIGIT 7
				●	•				8	DIGIT 8
			●	●	•			●	9	DIGIT 9
	●	●			•			●	a	ANGULAR ROTATION AROUND X– AXIS
	●	●			•		●		b	ANGULAR ROTATION AROUND Y– AXIS
	●	●	●		•		●	●	c	ANGULAR ROTATION AROUND Z– AXIS
	●	●			•	●			d	ANGULAR ROTATION AROUND SPECIAL AXIS OR 3RD. F.F. *
	●	●	●		•	●		●	e	ANGULAR ROTATION AROUND SPECIAL AXIS OR 2ND. F.F. *
	●	●	●		•	●	●		f	FEED FUNCTION
	●	●			•	●	●	●	g	PREPARATORY FUNCTION
	●	●		●	•				h	UNASSIGNED
	●	●	●	●	•			●	i	DISTANCE TO ARC CENTER PARALLEL TO X
	●		●		•			●	j	DISTANCE TO ARC CENTER PARALLEL TO Y
	●		●		•		●		k	DISTANCE TO ARC CENTER PARALLEL TO Z
	●		●		•	●			m	MISCELLANEOUS FUNCTION
	●				•	●		●	n	SEQUENCE NUMBER
	●		●		•	●	●	●	p	3RD. RAPID TRAVERSE DIMENSION PARALLEL TO X *
	●		●	●	•				q	2ND. RAPID TRAVERSE DIMENSION PARALLEL TO Y *
	●			●	•			●	r	1ST. RAPID TRAVERSE DIMENSION PARALLEL TO Z *
		●	●		•		●		s	SPINDLE SPEED
		●			•		●	●	t	TOOL FUNCTION
		●	●		•	●			u	SECONDARY MOTION DIMENSION PARALLEL TO X *
		●			•	●		●	v	SECONDARY MOTION DIMENSION PARALLEL TO Y *
		●			•	●	●		w	SECONDARY MOTION DIMENSION PARALLEL TO Z *
		●	●		•	●	●	●	x	PRIMARY X MOTION DIMENSION
		●	●	●	•				y	PRIMARY Y MOTION DIMENSION
		●		●	•			●	z	PRIMARY Z MOTION DIMENSION
	●	●		●	•		●	●	.	DECIMAL POINT **
		●	●	●	•		●	●		UNASSIGNED **
	●	●	●		•				+	POSITIVE SIGN
	●				•				–	NEGATIVE SIGN
			●		•				SPACE	UNASSIGNED (USED AS LEADER WITH PARITY)
	●	●	●	●	•	●	●	●	DELETE	ERROR DELETE
●					•				CAR. RET.	END OF BLOCK
		●	●	●	•	●	●		TAB	TAB **
				●	•		●	●	STOP CODE	REWIND STOP
					•				TAPE FEED	LEADER
		●	●		•			●	/	SLASH CODE

* WHERE d e p q r u. v. and w are not used as indicated, they may be used elsewhere

** IGNORED by the MCU during actual operation

FIG.42

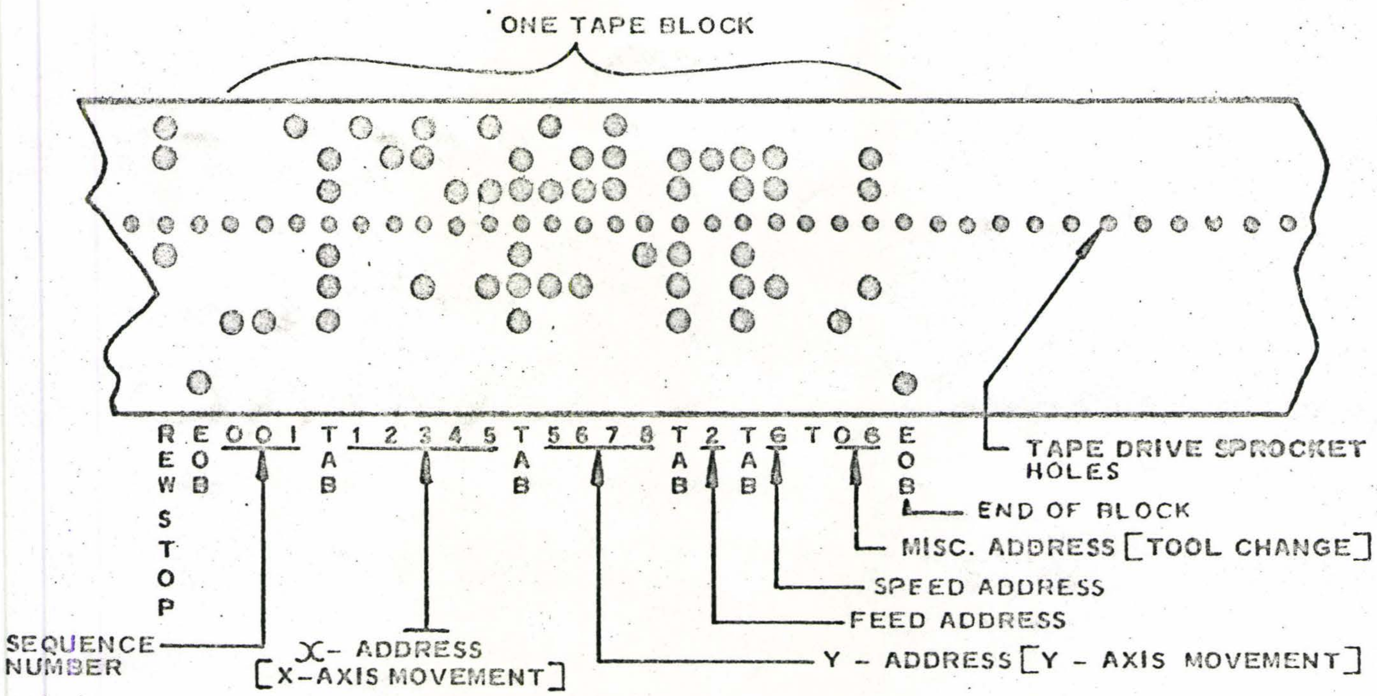
STANDARD TAPE CODE AND FLEXO WRITER CHARACTERS

Several types of tape are available, paper tape is the least expensive and can be used satisfactorily 200 to 600 times. A laminated paper-mylar-paper tape, which is considerably more expensive, has been used up to 15000 times. (Estimates from Cimtrol Cincinnati Milling Machine Co. Cincinnati).

4.2.3 Tape Formats:

Each machine control unit (M.C.U.) is designed to accept information from the tape reader according to some given format. The most frequently found today are Tab Sequential and Word Address formats. The former requires the data in a fixed sequence with a Tab code (see Fig. 4.2 and 4.3) between each piece of information. The data punched on tape is modal; it remains in memory until specifically altered. Tab codes between each piece of information indicate to the M.C.U. which address is being read by the tape reader. This means that an information block may contain a variable number of characters; it has a variable length block. The Word Address format may also have modal instructions and a variable length block, but each address has a symbolic word preceding it so that it may easily be identified. The data has to be kept in a prescribed sequence. Both these formats are illustrated in the following figures (4.3 and 4.4). Fixed Sequential and Block Address formats have also been used although they are not very popular today, since the instructions are not modal and this leads to inconvenient repetition. Both

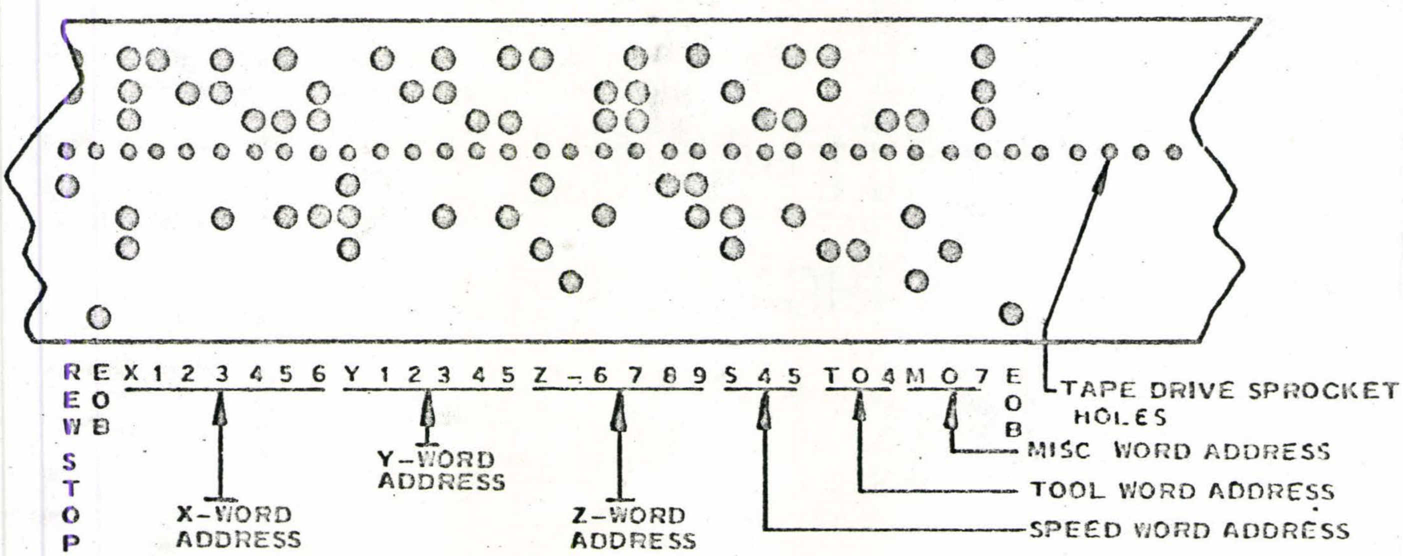
TAB SEQUENTIAL TAPE FORMAT:



PROGRAMMER'S MANUSCRIPT											
SEQ. NO.	TAB	± X-AXIS	TAB	± Y-AXIS	TAB	FEED	TAB	SPEED	TAB	M CODE	E.O.B.
001	T	12.345	T	5.678	T	2	T	6	T	06	E.O.B.
002	T		T	3.256	T		T		T	91	E.O.B.
003	T	1.245	T		T		T		T		

FIG.43

WORD ADDRESS TAPE FORMAT



PROGRAMMER'S MANUAL						
± X-AXIS	± Y-AXIS	± Z-AXIS	FEED	SPEED	TOOL	MISC.
12.3456	1.2345	-6789		45	04	07
	12.1112		415			

FIG.44

these formats have a fixed block length. Each control unit is wired to accept only certain alphanumeric characters, these are called the legal codes of the machine tool. Usually, some checking facility is incorporated in the control unit to guard against obvious programming errors such as illegal codes or insufficient information in a block.

4.2.4 Dimensional Words and Addresses:

The desired co-ordinate positions for machining operations may appear in incremental or absolute values depending on the design of the M.C.U. and the measuring system used on the M.T. An incremental distance is the distance the tool should be moved from it's present position to the desired position, whereas an absolute dimension is the desired location with respect to a fixed origin. Often an absolute system will not accept a positive or a negative sign, and all dimensions given must then be positive with respect to the origin. Generally using inches as a basic unit,the smallest programmable dimension is one thousandth of an inch, and all distances are given in units of thousandths of an inch consequently no decimal point need be programmed. There are various restrictions concerning leading and trailing zeros, generally neither may be omitted in a dimensional address. Each dimensional word in a Word Address format is preceded by a letter representing the direction of travel (x,y,z for a three axis machine).

4.2.5 Preparatory and Miscellaneous Functions:

A list of Preparatory Functions is given in Table 4.1 They are often called G codes and those used for manual programming are referred to as 'Canned Cycles'. These codes are used for the internal manipulation of data for various machining operations. For example G84 is a tap cycle, this one code will instruct the tool to rapid* just above the part surface, feed down to the programmed depth at the specified feed rate, reverse the direction of rotation, feed back up through the programmed depth at the same feed rate, and reverse the spindle rotation once again so that the tool is ready for the next instruction. In most ptp machine tools only a few G codes are wired into the control unit. Some of the older machine tools do not have any canned cycles at all, and every tool motion statement requires a separate statement in the part programme. This same list of G codes is also used for continuous path M.T.

The M codes or the Miscellaneous functions are listed in Table 4.2. They are used by most machine tool and control builders in their systems to activate ON-OFF relays controlling the actual machine tool and its accessories. Again the M.C.U. will only be wired to accept some of these codes, which are specified by the M.T. builder.

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* 'rapid' commonly used as a verb in the machine tool industry, and has the meaning to move in rapid traverse.

PREPARATORY FUNCTIONS

CODE	FUNCTION
G00	Point to Point Positioning
G01	Linear Interpolation (normal Dimensions)
G02	Circular Interpolation ARC C.W.
G03	Circular Interpolation ARC C.C.W.
G04	Dwell
G05	Hold
G06 & G07	Unassigned
G08	Acceleration
G09	Deceleration
G10	Linear Interpolation (Long Dimensions)
G11	Linear Interpolation (Short Dimensions)
G12	Unassigned
G13 - G16	Axis Selection
G17	XY - Plane Selection
G18	ZX - Plane Selection
G19	YZ - Plane Selection
G20	Circular Interpolation ARC C.W. (Long Dimensions)
G21	Circular Interpolation ARC C.W. (Short Dimensions)
G22 - G29	Unassigned
G30	Circular Interpolation ARC C.C.W. (Long Dimensions)
G31	Circular Interpolation ARC C.C.W. (Short Dimensions)
G32	Unassigned
G33	Thread Cutting, Constant Lead
G34	Thread Cutting, Increasing Lead
G35	Thread Cutting, Decreasing Lead
G36 - G39	Reserved for Control use
G40	Cutter Compensation Cancel
G41	Cutter Compensation - Left
G42	Cutter Compensation - Right

TABLE 4.1

.... fwd ....

G43 - G49	Cutter Compensation if used, otherwise Unassigned
G50 - G59	Unassigned
G60 - G79	Reserved for Positioning Only
G80	Fixed Cycle Cancel
G81 - G89	Fixed Cycle Nos. 1 - 9
G90 - G99	Unassigned

TABLE 4.1

STANDARD MISCELLANEOUS FUNCTIONS

CODE	FUNCTION
M00	Programme Stop
M01	Optional Stop
M02	End of Programme
M03	Spindle on C.W.
M04	Spindle on C.C.W.
M05	Spindle off
M06	Tool Change
M07	Coolant on (mist) No. 1
M08	Coolant on (flood) No. 2
M09	Coolant off
M10	Clamp
M11	Unclamp
M12	Unassigned
M13	Spindle C.W. & Coolant on
M14	Spindle C.C.W. & Coolant on
M15	Motion
M16	Motion
M17 - M29	Unassigned
M30	End of Tape
M31	Interlock Bypass
M32 - M35	Constant Cutting Speed
M36 - M39	Unassigned
M40 - M45	Gear Change if Used
M46 - M49	Reserved for Control use only
M50 - M99	Unassigned

TABLE 4.2

4.2.6 Feeds And Speeds:

E.I.A. have set a standard procedure for coding feeds and speeds it is known as the "Magic Three". (Computer assisted programming languages usually allows feeds and speeds to be written in absolute values). The first digit of the "Magic Three" is the absolute sum of the number of digits of the feed or speed to the left of the decimal point plus three for example

4.0 would have a first digit of 4

400.0 would have a first digit of 6

0.04 would have a first digit of 1

The remaining two digits are the actual feed rate or spindle speed rounded off to two significant figures. In the Word Address format all feed rate codes are preceded by the letter F. These are in inches per minute for feeds independent of spindle speed, or in inches per revolution, or r.p.m. in the cases of linear feed dependent on spindle speed, or rotary feed dependent on spindle speed respectively.

Spindle speeds are always in R.P.M. before coding, and are preceded by a letter S in the Word Address format. As an example: -

an example: -		Coded in Magic Three for a Word Address Format
Spindle speed 1200	R.P.M.	S712
Feed rate 35	i.p.m.	F535

4.2.7 Tool Selection:

Some machine tools have automatic tool changing devices, and depending on the complexity of the control, the tools may have to be loaded in a prescribed order, or may be chosen at random.

In both cases, and also for manual tool changing operations, each tool is allotted some identifying number which can be referred to throughout the programme.

4.3 A CASE STUDY OF A CINTIMATIC TURRET DRILL WITH AN ACRAMATIC 330 CONTROL

4.3.1 Introduction:

It is extremely difficult to describe manual programming adequately without referring to a specific machine tool. Consequently a case study of a manually programmed turret drill is included in this report to serve as an illustrative example. Programming other M.T. may differ considerably but the basic considerations will remain similar.

4.3.2 The Operating Specifications:

4.3.2.1 General:

The machine selected has a three axis positional control and is capable of drilling, tapping, milling and boring operations. The turret has eight indexing positions and the tool may be selected at random. The control has a mechanical tape reader capable of reading 60 characters per second, it accepts a Word Address format.

Tab codes may be inserted between data to make the print out neater and more readable. An end of block (E.O.B.) character must be used to indicate the end of each information block.

All dimensions are given in absolute units with respect to origin which is located at the front left hand corner (facing the M.T.) of the work-table. The origin can be translated manually on the control panel, however, since positive and negative signs are not legal format all programmed dimensions are assumed positive with respect to the origin. The limits of travel and the feed rates for the axes are given below:

AXIS	MAX. TRAVEL	MIN. FEEDRATE	MAX. FEEDRATE	RAPID MODE
X	39.999 ins	1.0 ipm	99 ipm	200 ipm
Y	19.999	1.0	99	200
Z	9.999	0.5	99	140

4.3.2.2 The Reference Work Plane:

In programming a component the highest point above the work table (in the Z direction) is usually selected as a reference point. The turret has eight tool spindles, and there is a decade switch on the control panel associated with each of these spindles. These decade switches permit the operator to dial in accurate tool length compensation for each tool, by nulling an ammeter when the tool is set exactly .100" (on a gauge block) above the reference point. This automatically establishes a reference work plane .100" above the reference point and parallel to the X-Y plane. All tool motion that occurs above this reference plane, or gauge height, is carried out in rapid mode. A safe tool change height is set manually with another switch on the control panel by adding an additional inch clearance to the tool compensation setting (of the respective decade switch) of the longest tool in the turret.

4.3.2.3 Legal Codes:

Only certain alphabet codes are legal, each has a specific meaning and may appear in the programme followed by a numerical word of a defined number of digits, associated with that address. The following table is a list of acceptable address codes indicating the length of the numerical word that follows the address and the meaning of the symbol.

LETTER	NO DIGITS	MEANING	REMARKS
F	3	Feedrate instruction	Magic three code
G	2	Preparatory function	See List:table 4.1
H	3	Sequence number	Complete information block
M	2	Miscellaneous function	See List table 4.2
N	3	Sequence number	Partial information
R	4	Reference work plane	0 - 9.999
S	3	Spindle speed	Magic three
T	1	Tool & turret number	1 - 8
X	5	Absolute X position	0 - 39.999
Y	5	"Y"	0 - 19.999
Z	4	"Z"	0 - 9.999

The control unit checks for legal parity and stops if an illegal code is read.

4.3.3 THE TAPE FORMAT

4.3.3.1 Sequence Number:

Each block of information should have a sequence number for the programmer's and operator's convenience. A block of complete information has an H word preceding the number. It is mandatory to use an H block at the beginning of each programme, and after every tool change. The control unit has a feature to search the tape for H blocks. It is considered good practice to programme an H block at least every 10 blocks of tape, so that if the programme was stopped, the tape could be realigned at the last H block in the programme without rewinding the tape to the initial block. A block that does not have complete information, has the code N preceding the sequence number. The sequence number must always contain three digits.

4.3.3.2 Preparatory Functions:

The G codes in manual programming are sometimes referred to as 'Canned Cycles'. It prepares the data for the following machining operation. The G codes listed are accepted by this machine:

G79	Mill Cycle	G80	Cancel Cycle
G81	Drill Cycle	G82	Dwell Cycle
G84	Tap Cycle	G85	Bore Cycle

These are explained in greater detail later in this report.

4.3.3.3 The Absolute Co-Ordinates:

The next three word address codes are the absolute X,Y, and Z co-ordinates that define the location of the machining operation, indicated by the G code in this information block. They appear in the following order:

X : 5 digits   Y : 5 digits   Z : 4 digits

Both leading and trailing zeros may not be omitted. For example, assume the absolute X co-ordinate is 9.6 inches, which should be programmed as X09600 (where one unit is one thousandth of an inch). If the leading zero is omitted the word address appears as X96000 which the machine control unit interprets as 96 inches. This will stop the machine as it is beyond the X limit of travel. Alternatively, if X0960 were punched omitting the last zero the M.T. will oscillate about that point unable to null the thousandths digit. The Z address has only 4 digits as it is never larger than 9,999 inches, however, the same rule applies. Motion in X and Y is done simultaneously and they are completed before any motion in the Z direction will begin.

4.3.3.4 Feedrate:

This normally applies to feed in the Z direction, however, using the milling cycle (G79) the X and Y motions are also carried out at the programmed feedrate. The feedrate, in inches per minute, is converted to the appropriate 'Magic Three Code' and is preceded by the address F.

4.3.3.5 Z Rapid Position:

As mentioned earlier a reference plane is established .100 inches above the highest point of the workpiece in the Z direction. This allows all tool motion in the Z direction above this plane to be done at rapid mode. This plane, however, can be lowered to any other convenient level in the Z direction by using the R address. When the plane is in the original position, or at gauge height the value of R is 0.000. This dimensional word also requires 4 digits to be fully specified.

4.3.3.6 Spindle Speed:

This machine has only sixteen discrete spindle speeds. The one required is coded into 'Magic Three' which is then preceded by the letter S in the programme.

4.3.3.7 Tool and Spindle Number:

The spindle turret is numbered from one to eight. A tool may be selected by using the address T followed by the turret number in which the tool is loaded.

4.3.3.8 Miscellaneous Functions:

The following M codes are acceptable to this control.

M02	End of Programme	M06	Tool Change
M03	Spindle on, Clockwise	M09	Coolant off
M04	Spindle on, Counterclockwise	M13	Spindle Clockwise and Coolant on
M05	Spindle off	M14	Spindle Anticlockwise and Coolant on

These are usually executed after the other instructions in the block have been completed.

4.3.3.9 End of Block Code:

This is a specific character that must be punched on the tape to signify the end of each instruction block.

4.3.3.10 Modal Properties:

A complete block of information contains values for each of the above words and addresses. Since this machine has modal properties, if values of one or more of these codes are unchanged from the previous block of information, they may be omitted. These are incomplete information blocks and have the word N preceding the sequence number. (see section 4.3.3.1)

4.3.4 PROGRAMMING A TOOL CHANGE

The tool change code (M06) must appear in the programme preceding the block that calls for a tool change. This miscellaneous function brings the turret up to tool change height (dialled in on the control panel, 4.3.2.2) after all other instructions in that block have been completed. Then the new tool number that appears in the following information block is read, and the turret is rotated so that the spindle containing the required tool is engaged in the spindle drive. After this has taken place the rest of the instructions in the block are executed. The tool must be at gauge height before the M06 code will function correctly. This is best illustrated in an example explained in section 4.3.5.6.

4.3.5 PREPARATORY FUNCTIONS

4.3.5.1 G81 The Drill Cycle:

The M.T. satisfies the X and Y co-ordinates first, in rapid traverse, then rapids in the Z direction to the reference plane. It feeds at the programmed feedrate through the reference plane (.100 ins.) to the workpiece surface, and then through the distance specified in the Z address. The turret rapids back to the reference plane height, and rapids to the next X and Y co-ordinates given in the following block.

In drilling a blind hole of a certain depth, an additional allowance must be made for the angle of the tool tip. Most conventional drills have a tip angle of 118°, and the extra depth needed to compensate for this is approximately .3x tool diameter. If the hole is intended to break through the other side in addition to the allowance for the tool tip angle a further .025 ins. is added to the Z dimension to make sure that no burrs are left in the hole.

4.3.5.2 G82 The Dwell Cycle:

This cycle is similar to the drill cycle except that the tool dwells at the programmed depth for a given time before the rapiding up to the reference plane. The dwell time is preset in the control unit in the range of 5 milisecs to 5 secs. This cycle is used for spot facing and counterboring operations, which require a smooth surface finish on the face cut.

4.3.5.3 G84 The Tap Cycle:

Again this is similar to the basic drill cycle. Once X and Y motions have been completed (in rapid), the turret rapids to the reference plane, and feeds to the programmed depth. At the desired depth the spindle reverses its rotation and the turret feeds back to the reference plane at programmed Z axis feedrate. Then the spindle again reverses rotation and the table moves at rapid to the next X and Y co-ordinates.

Usually the first three to five threads are considered bad, and the programmed depth should be increased by an equivalent distance to those bad threads (viz. thread pitch x number of bad threads).

The tapping spindle speeds are given in tables, and the feedrate is directly proportional to the product of spindle speed and thread pitch (Feedrate = spindle rpm x thread pitch).

The tapping tools are generally spring-loaded to allow for a finite response time for the spindle to change direction of rotation, before it starts feeding out of the hole. If there was no resilience in the tool, the threads could easily be stripped especially if a high feedrate was used.

4.3.5.4 G85 Bore Cycle:

The bore cycle is the same as the tap cycle, except the spindle does not change its direction of rotation at the bottom of the hole, before it feeds back to the reference plane. If the boring tool were removed in rapid traverse the tool would mark the bore surface with a spiral line.

4.3.5.5 G80 Cancel Cycle:

This function ignores any programmed Z axis feed depth; the tool rapids to the R word in the Z direction only. It performs no useful machining operation but is used together with other G codes to increase the machine tool effectiveness.

For example, changing the work plane from a low level to a higher level is usually done with a G80 cycle (see Fig. 4.5), the instructions would read:

H010	G81	X01000	Y03000	Z1000	F520	R1000	S718	T6	M13	(Position 1)
N011	G80					R0000				
N012	G81	X12000								(position 2)

Upon completion of block H010 the tool is instructed by the G80 command in block N011 to rapid to R0000, and ignore any feed in the Z direction. In this instance this instruction is needed to raise the tool prior to movement along the X and Y axes, to avoid collision with the work piece.

Changing Work Plane (Low to High Level) With a G80 Cancel Cycle

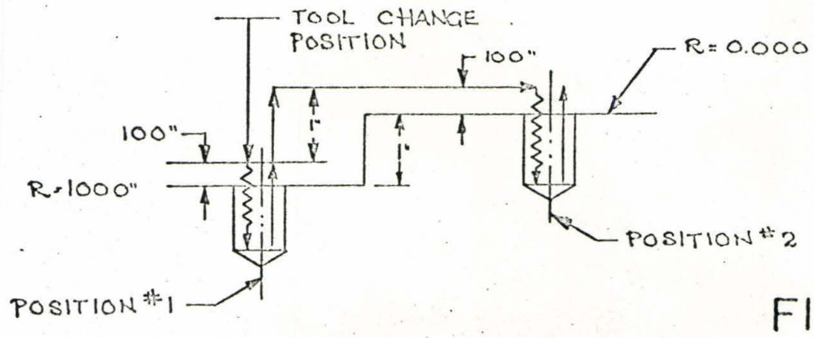


FIG. 4·5

Standard Mill Cycle (Rapid to Depth)

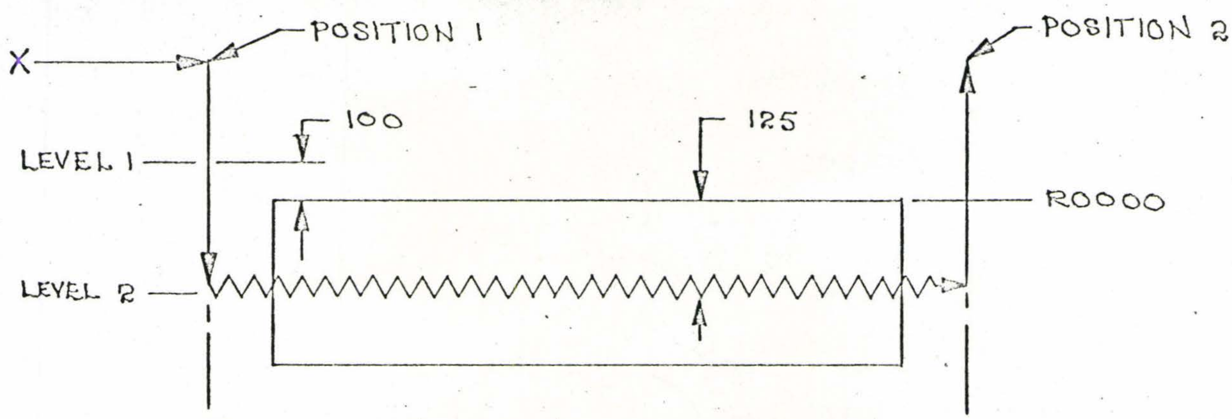


FIG. 4·6

Milling Cycle (Feed Rate Control)

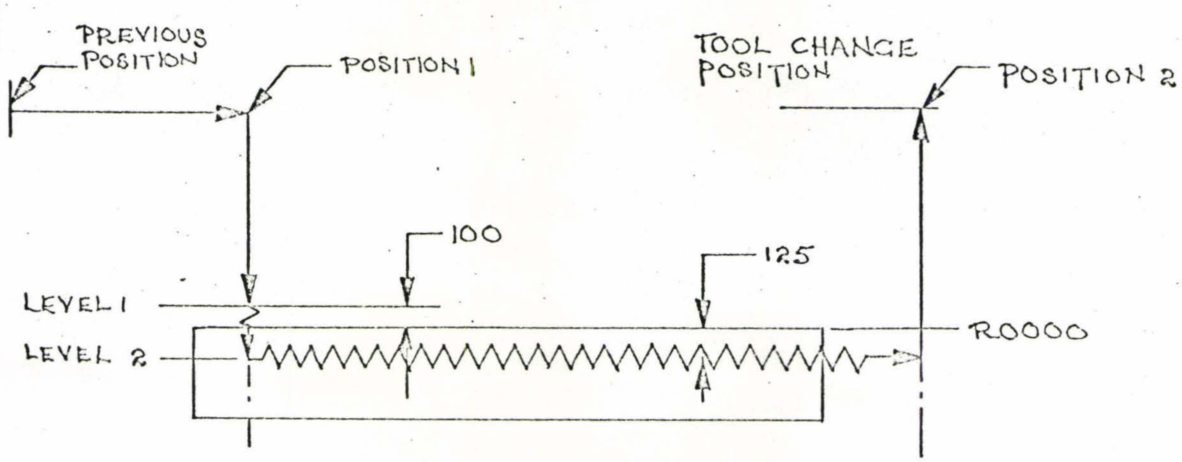


FIG. 4·7

4.3.5.6 G79 The Basic Mill Cycle:

The G79 code executes the X and Y motion first at the programmed feedrate, chosing the shortest path between the initial and the desired positions. Once these are satisfied the tool rapids to the reference plane, and then feeds to the programmed depth. In the example below block H025 indicates a .5 inches deep milling cut. (Z address). Milling with this cycle is then achieved on the following block, N026, which retains the G79 code (modal), and makes the tool move in the X and Y directions at the same feedrate. Since the R and Z values are unaltered from the previous block, they are already satisfied, and there is no further tool motion in the Z direction. The following block removes the tool at rapid back to the reference plane.

```
H025   G79   X03000   Y13000   Z0500   F450   R0000   S610   T2   M13
N026         X07000   Y15000
N027   G80                                    R0000
```

This method of milling is inefficient, since the X and Y traverse motion in the first block (H025) are done at the milling feedrate while the tool is cutting through air. Assuming it is possible to rapid to the cut depth (e.g. face milling), the following improvements can be made: (see Fig. 4.6).

```
H010   G80   X02000 Y09000  Z0000   F440   R0225   S620   T6    M13
                                                         (position 1)

N011   G79   X07000

N012   G80                                 R0000               M06
                                                         (position 2)
```

The first block (H010) has a G80 code, this ignores the Z word and just rapids to R after X and Y motions are satisfied. Since there is no feed in the Z direction the programmer has to compensate for the .100 inches height of the reference plane. This may be done by increasing the R value by .100 inches above the desired cut depth Consequently, the tool rapids a total distance of .225 ins. in the Z direction but this is only .125 ins. below the surface of the workpiece. The next instruction performs the milling operation, and finally the G80 code is used to raise the tool up to gauge height, so that the tool change (M06) code can then lift the turret to the tool change position, and the tool programmed in the next block will be selected. Both the R0000 and the M06 codes are necessary to retract the tool to the tool change position, as stated earlier, the M06 code is only effective when the tool is at gauge height.

It is also possible to feed the tool into the workpiece at one feedrate, and use another feedrate for the actual milling operation, as shown in the next example;

The instructions are:

H001	G80	X12000	Y10000	Z0000	F410	R0000	S615	T2	M03 (position 1)
N002	G79			Z0125					
N003		X15000			F450				
N004	G80					R0000			M06 (position 2)

These instructions can easily be followed with reference to Fig. 4.7. It should be noted, that in this case there is a feed in the Z direction at the programmed feedrate, and this automatically compensates for the height of the reference plane (.100 ins.)

There are many other cycle combinations used for tool manipulation and performing other machining operations and several other 'canned cycles' (e.g. deep hole drilling etc.). The effectiveness of the machine tool is largely a function of the programmer's experience, skill and imagination.

4.3.5.7 Profiling In The X-Y Plane:

Since the motion of the X and Y axes are performed simultaneously and the shortest route between two points is always taken, (i.e. a straight line), a limited amount of profiling (in the X and Y planes) is possible by approximating the contour by a series of straight line increments. The size of the increments is limited by the speed at which successive blocks can be read, and the necessary control signals generated by the machine control unit. The manufacturers recommend that an increment less than .01 ins. should not be used. They claim that smaller increments would not improve the workpiece finish, and cause excessive wear of the tape reader. This method of profiling will often give the workpiece a step-like appearance, especially profiling small radii of curvature. Nevertheless, it is extremely useful to have this capability.

It is also possible to estimate the machining time, from standard times for various operations and distances of travel, which are supplied by the machine tool builder. This machine tool can also be programmed with a N.C. computer language.

4.4 INTRODUCTION TO COMPUTER AIDED PROGRAMMING

4.4.1 General:

The original idea of calculating complex component shapes, for conventional manufacture, on a General Purpose Computer developed into the concept of a machine tool controlled by the numerical output of the computer. During the mid 1940's several industries involved in aircraft component manufacture (notably Parsons) were using the existing data processing machines to handle the vast amount of calculations required to define the contours of propellers and turbine blades. In 1944 a prototype programme was written for the M.I.T. Whirlwind computer to do these calculations, this was called the 'Automatically Programmed Tool' system. Later, with the development of the first NCMT (at M.I.T.) this programme was modified to programme a NC tool, and became known by the acronym, APT.

4.4.2 The Growth of Other Computer Aided Languages:

Over the last decade NC has been applied to numerous metal working processes, and has become increasingly popular in industrial manufacture. Consequently, several computer corporations, machine tool builders and machine tool control builders, have developed a wide variety of computer languages for NC programming. Some corporations have developed their own in house languages suitable for their particular needs (e.g. Rolls Royce). Today, there are so many computer languages for NC machines with different levels of capability, computer requirements and ease in programming, that manufacturers should pay considerable attention in selecting a language best suited to their needs.

Some of the early languages such as WALDO and COMPAC have a fixed format output, which eases the computer load but limits the manufacturing capability of the language. On the other hand APT, which can be used for almost any metal cutting operation (basically for milling) and has up to five axis capability, requires an extremely large computer memory core (e.g. smallest IBM computer; 360/40, with 256k bytes). There are other languages that can be run on smaller computers, but do not have the flexibility of APT. For example, AUTOPROMPT is designed for ball-cutter milling, AUTOSPOT for two or three axes point to point machining; ADAPT for profile milling (two axis contouring control); CAMP IV for up to five axis point to point operations.

4.4.3 <u>Computer and Machine Tool Independence of NC Languages</u>:

As explained previously in this chapter, most NC languages are machine tool independent on the first pass through the computer, only on the second pass, using a post processor-programme do they become compatible with a particular machine tool and control combination. The post-processor programme for a specific M.T. and control unit, and the NC compiler programme, have to be written for a specific computer. Even though the APT processor output format (the cutter location tape) is similar for various computers, it is not computer independent. There are variations in computer word length, and address systems. For example the IBM 360/series is a character address machine with 32 bit words consisting of 8 bit bytes, whereas the General Electric 400 series is a word address machine with four, six bit bytes in each word. To achieve a higher degree of computer independence it is current practice to write postprocessor in FORTRAN IV, and only minor modifications are needed for interdependence between computers.

4.5 APT

4.5.1 Introduction To APT:

4.5.1.1 General:

In 1957 the Aerospace Industries Association (A.I.A) undertook further developments of the original APT programme and in the following year a second version, APT II, was released. Three years later APT III was completed, it is currently the most widely used NC language, and has been modified several times during the last seven years.

Shortly after the first version of APT III was written, the A.I.A decided to establish the APT Long Range Programme (ALRP). Various industries participating in the project formulated the programme, and they appointed Illinois Institute of Technology Research

Institute (IITRI) to administer it. IIRTI is still responsible for updating and expanding the APT language today. Members of the ALRP decide the direction of future activities, and they have access to all the latest developments and modifications, in return they subscribe to the programme maintenance costs. Two years after a system has been released to ALRP members it is made available to the public.

4.5.1.2 Recent Developments:

The original APT III programme had various short-comings, one of the first projects undertaken by IITRI was to restructure the APT language. This was completed in 1965 and is referred to as the 'New System'.

The 'new system' is open ended so that any technological improvements can easily be incorporated in the programme as soon as they are developed. An assembly approach (similar to FORTRAN) in the compiler is used instead of the old interpretive approach. This means that the programme is compiled completely in ASSEMBLY LANGUAGE before any calculations are made. Whereas with an interpretive system the calculations are made with calls to various subroutines as each statement is read. The former system diagnoses syntax errors on the first run through the computer whereas the latter system may calculate almost the whole part-programme before it discovers an error(in the last statements)which will prevent the calculations from being completed. Apart from this in larger programmes an assembly approach utilizes the storage more efficiently and has faster execution speeds.

The APT language is the most widely used NC language in the world, it is almost a 'de facto' standard, although recently developed languages on the continent are becoming increasingly popular in Europe. There has been discussion whether APT should be made an official U.S. standard and be placed in the hands of a Government Agency for maintenance. In addition there are many different subsets of the APT language; ADAPT and AUTOSPOT are the best known of that group. At present APT IV is almost completed, however, it is expected that APT III will still remain in use, and only gradually will be replaced in new installations or cases where APT III is inadequate.

4.5.2 PROGRAMMING IN APT

4.5.2.1 General:

The APT vocabulary consists of over 300 words which are made up of 6 characters or less. The words can be divided according to the function they perform;

1. Geometrical Definitions
2. Tool and motion statements
3. Machine Tool functions
4. Systems commands

Parts are represented, in terms of the surfaces which define their shape, using APT Geometrical statements. All machining operations take place along two intersecting surfaces, this allows any cutter path to be uniquely defined in three dimensional space.

The surface being cut is called the part surface, the one guiding the tool - the drive surface, and finally the cutting motion ends on or at the check surface (see Fig. 4.8).

4.5.2.2 Vocabulary:

The APT programme usually begins by assigning symbols to each geometrical shape of the part, until the part is completely unambiguously defined. There are several ways of specifying geometrical shapes in the APT language, each is recognized by a particular format. Table 4.1 shows the number of ways that each of the listed geometrical shapes can be defined in the APT language. The statement is of the form;

Symbol = APT surface word/descriptive modifier

The symbols may not be another vocabulary word, or larger than six alphanumeric characters and must contain at least one alphabetical letter. For example, PT 1 = POINT/1,2,3: PT 1, is a point with coordinates in x,y and z equal to 1,2, and 3 respectively.

C1 = CIRCLE/ 1,2,3,4.

C1, is a circle with centre coordinates, 1,2,3 in x,y and z respectively and a radius of 4. If P1 was already defined in the programme C1 could alternatively be defined by;

C1 - CIRCLE/PT1, 4, or both could be defined with one statement;

C1 = CIRCLE/CENTRE, (P1 = POINT/1,2,3) RADIUS, 4

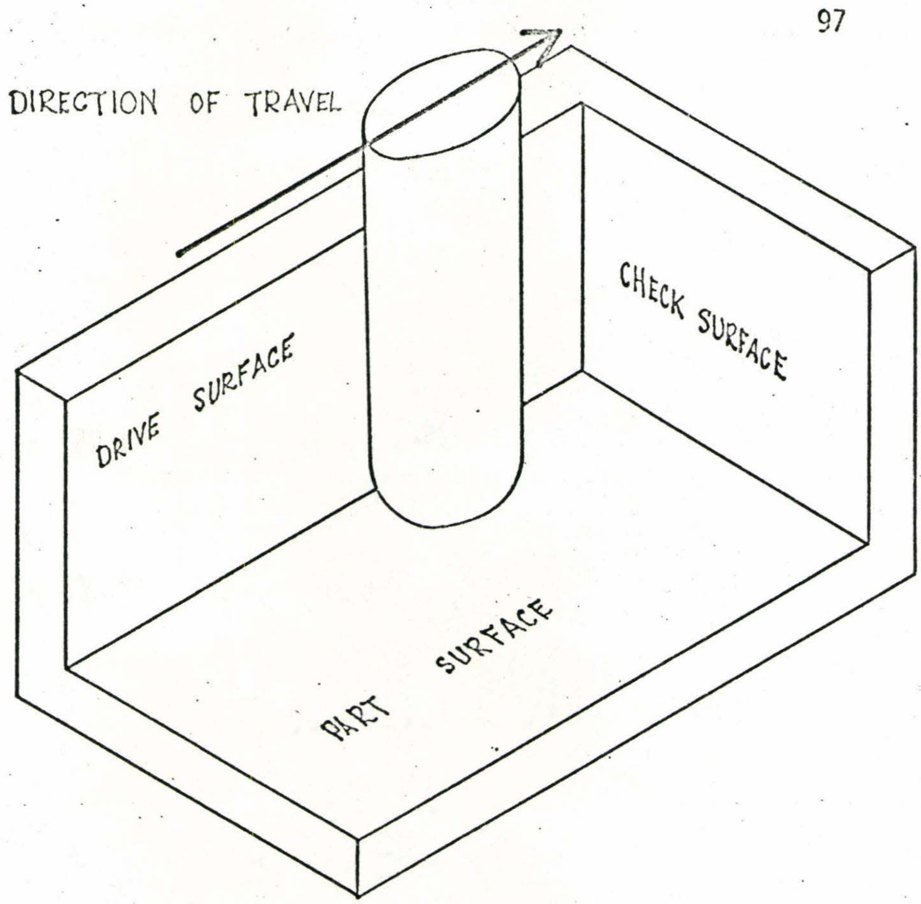


FIG. 4·8

C1=CIRCLE/X LARGE,L1,Y SMALL,L2,R

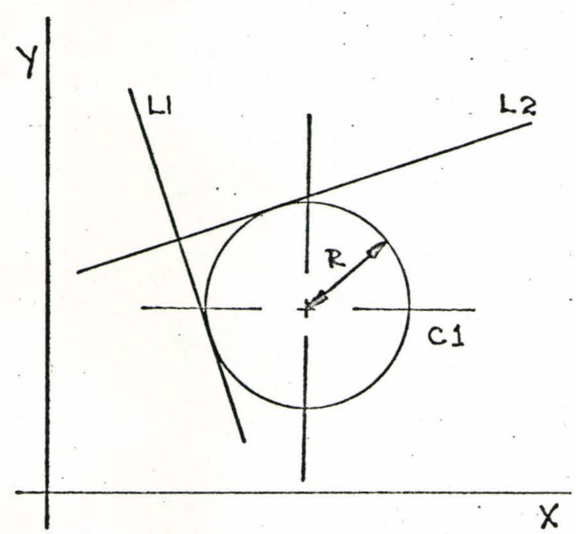


FIG. 4·9

APT GEOMETRICAL TYPES		
Apt. Word	English	No. of Definitions
CIRCLE	circle	12
CONE	cone	2
CYLINDR	cylinder	1
ELLIPS	ellipse	3
G CONIC	general conic	1
L CONIC	left conic	3
LINE	line	13
PLANE	plane	8
POINT	point	10
QUDRIC	general quadratic surface	1
RLDSRF	ruled surface	4
SPHERE	sphere	5
TABCYL	tabulated cylinder	3
VECTOR	vector	9

TABLE 4·1

In defining a CIRCLE tangential to two lines L1 and L2, it is obvious that 4 circles could satisfy this condition of tangency. So in order to be specific, modifier words are to be used:

X LARGE, X SMALL, Y LARGE etc. Using these modifier words, C1 in figure 4.9 is explicitly defined by:

C1=CIRCLE/X LARGE, LI, Y SMALL, L2,R

4.5.2.3 Representation of Surfaces:

Non-mathematical surfaces can often be specified by a generatrix, which is a line moving parallel to itself along a space curve, using a TABCYL statement. This is extensively used in describing free form contours that occur in automobile bodies, aircrafts and other components. Alternatively, non-mathematical surfaces can be represented by a mesh of surface points. The programme can then interpolate between these points to fit a smooth curve. (General Electric have developed a special language for this purpose called GEMESH).

Surfaces can be defined in parametric form as follows:

$x = f_1(u,v)$; $y = f_2(u,v)$; $z = f_3(u,v)$; as u and v vary, a set of points are generated which define a specific surface. The APT system assumed only linear interpolation on the control unit, and any surface is approximated by a series of straight line increments. The language provides an INTOL/n and OUTOL/n statements, in which n limits the maximum inner and outer tolerances of the part respectively.

These are discussed at greater length in Section 4.5.3.5.

4.5.2.4 Cutting Tool Specifications:

In the CUTTER statement, there are seven parameters that can be used to define the geometrical proportions of the cutting tool as shown in figure 4.10 . Every programme has to have a CUTTER statement for each different cutting tool, which contains at least one of the 7 parameters.

4.5.2.5 Initial Motion Statements:

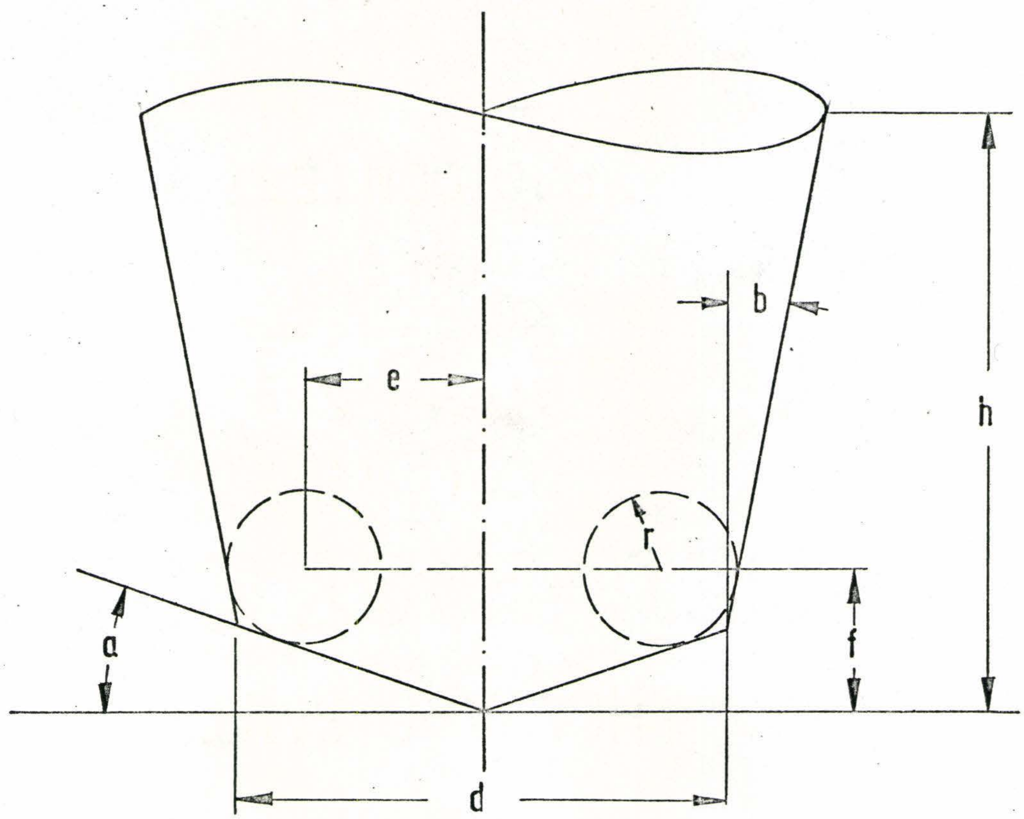
A statement giving the initial starting position of the cutter path in ptp programming is mandatory and has the form:

	FROM/1,2,3	where 1,2 and 3 are coordinates in x,y and z respectively
or	FROM/PT1	where PT1 is a point previously defined
or	FROM/SETPT	where SETPT is a point previously defined

Both the CUTTER and the FROM/statements must precede the first motion statement. The cutter path is always defined with respect to the tool-end, which is the intersection of the tool axis and the bottom of the cutting tool.

In the case of cpp, the tool must be brought within the specified tolerances to a set of controlling surfaces before it can follow any defined surface path.

Analogous to the FROM/statement in ptp programming, cpp also requires an initial starting statement which must appear in the programme before any contouring may begin. It has the form;



CUTTER /d,r,e,f,a,b,h.

FIG. 4·10

GO/TO,DS, TO,PS, TO, CS.

Where the GO/ is the special APT word for initial continuous path motion, TO, is a modifier and may be replaced by PAST or ON in any of the three locations it appears in that statement (see Fig. 4.11). DS, PS and CS, are drive, part, and check surfaces respectively. However, in some cases it is not necessary to define a check surface, so only the drive and the part surfaces are programmed.

The motion initiated by the GO/statement does not have a specific drive surface. The CUTTER moves along the shortest distance to the intersection of the three defined surfaces, until it is within the tolerances limits specified by the OUTOL/statement in the programme, or if there was no such statement an OUTOL will be assumed internally by the machine control unit.

4.5.2.6 Subsequent Tool Motion Statements:

The drive and part surfaces defined in the GO/statement apply to the subsequent tool motion statements that appear in the programme. There are a number of APT modifier words to specify where the motion of the tool should terminate. Four of them;TO; ON; PAST and TANTO, are adequately explained in the Figure 4.11. Once the drive and part surfaces have been defined, the cutter is then directed to:

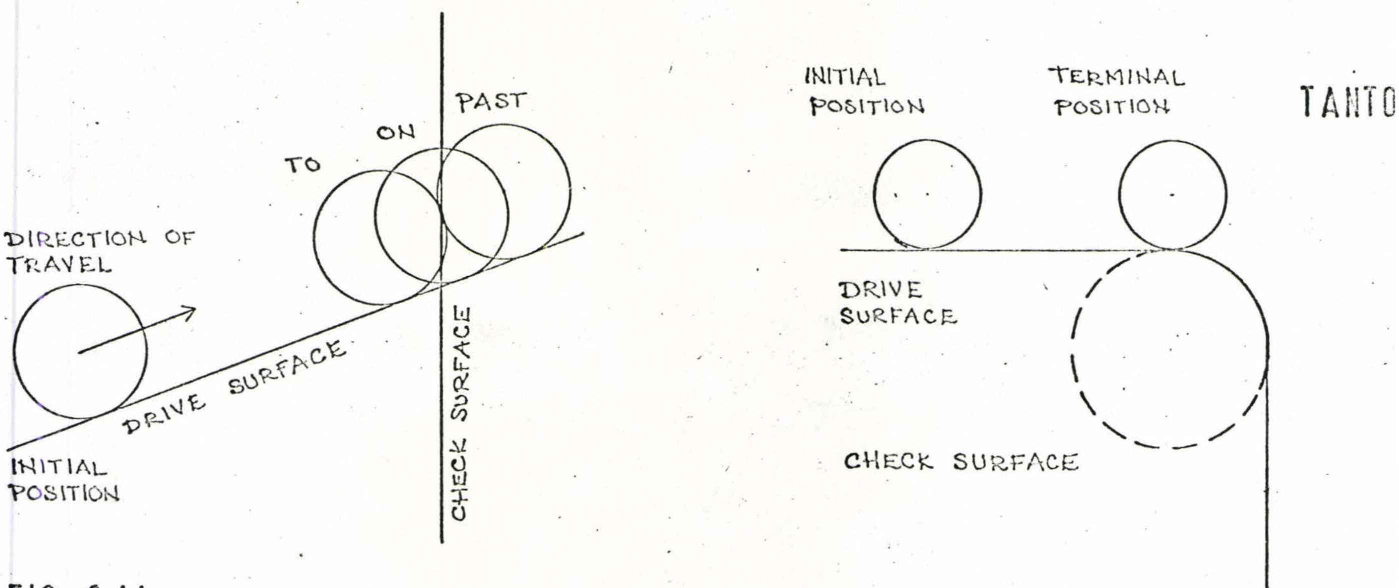


FIG 4·11

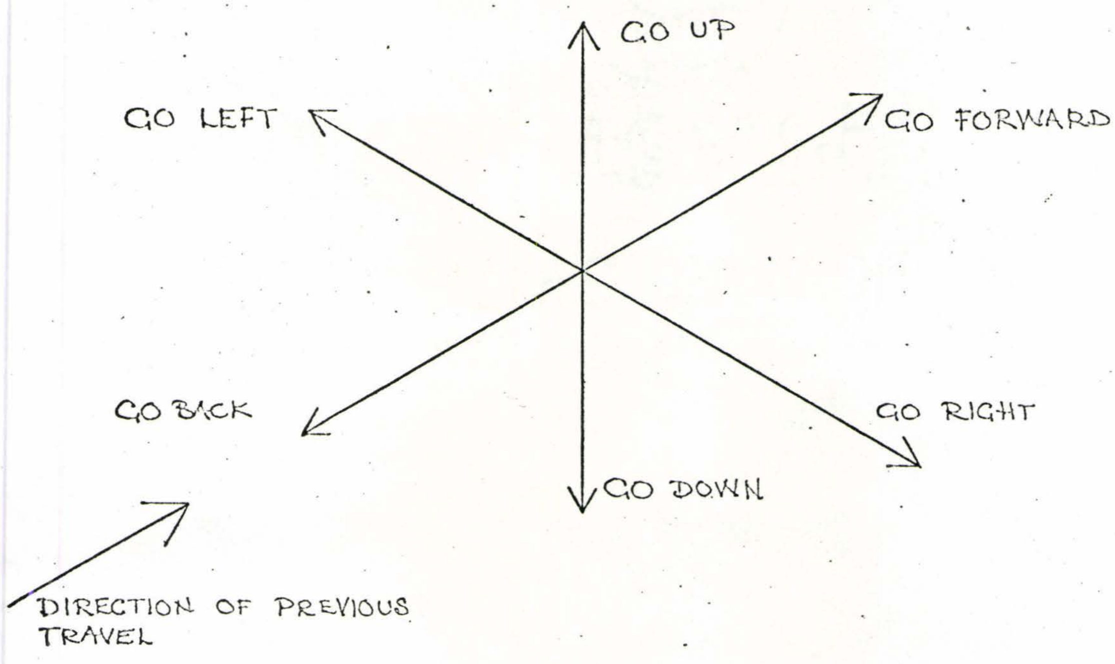


FIG 4·12

GOFWD	go forward
GOBACK	go back
GOLEFT	go left
GORGT	go right
GOUP	go up
DODOWN	go down

by the above modifiers.

The GOFWD direction is the direction of previous travel (in the APT system the part is always assumed stationary, while the tool moves about the parts contours), and the other directions are apparent (see Fig. 4.12). The programmer may have to use a certain amount of discretion in cases where the direction is not quite clear. The programmer can define a vector and instruct the tool to move in that vector direction. After the tool reaches a check surface, the check surface becomes the new drive surface, in the next programmed tool motion instruction. However, the part surface remains the same unless it is re-defined. This can be done by a PSIS/statement, which becomes effective in subsequent instructions in the programme, and defines the new part surface.

In ptp programming the subsequent motion commands may be either in absolute dimensions with respect to a defined origin or incremental distances from the present tool position. The statements used are GOTO/x,y,z and GODLTA/ Δx, Δy, Δz, respectively.

4.5.2.7 Rotating The Tool Axis

For 4 and 5 axis machining it is often desirable to rotate the tool axes. This can be easily done in APT by one of the following statements:

TLAXIS/vect i or TLAXIS/i, j,k

Where the tool axis is made parallel to vector i or to the unit vector given by the direction cosines i,j,k. Another statement TLAXIS/ NORMPS moves the tool axis perpendicular to the part surface. This can prove extremely useful in compound angle operations.

4.5.2.8 Additional Statements:

A further category of statements are available to control several machine tool functions that are similar to the miscellaneous functions described in Section 4.2.5. Some common examples are:

COOLNT ON	coolant on
COOLNT FLOOD	coolant flood
COOLNT MIST	coolant mist
COOLNT OF	coolant off
DELAY/n	a dwell block n secs long
END	end of programme - machine and control off
FEDRAT/n	feedrate n inches per minute
SPINDL/ n CLW	spindle clockwise at n rpm
SPINDL/ n CCLW	spindle anticlockwise at n rpm

4.5.2.9 Computational Capabilities:

The APT language also has system commands and library functions of angles, logs, etc., to perform arithmetic calculations that may be specified in the part programme. It is almost identical to the FORTRAN system commands. The computation of capabilities that are available are as follows:

+	add	ATANF	( )	arc tan
-	subtract	SQRTF	( )	square root
x	multiply	LOGF	( )	natural log
/	divide	EXPF	( )	exponential
**	exponentiate	ABSF	( )	absolute value
SINF ( )	sine	LNTHF	(V_1)	vector length
COSF ( )	cosine	DOTF	(V_1V_2)	dot product of vectors v_1 and v_2

4.5.2.10 LOOP and MACRO Statements:

APT has looping capabilities (c f. DO LOOPS IN FORTRAN). The first statement of a LOOP is LOOPST, and the last is LOOPND, there are certain laws governing the nesting of loops within loops, (which is again similar to FORTRAN). A simple loop statement is illustrated in the following example:

```
        LOOPST
        W = .125
10      X = (6.3/COSF (W)
        Z = W SQRT (W)
        GOTO/X, 0, -Z
        GODLTA/0, .375, 0
```

```
                  GODLTA/0, -.375, 0
                  W = W + .125
19                IF (1.0 - W) 20, 10, 10
20                LOOPND
```

Statement 19 means that if (1.0-W), is negative the programme will proceed to statement 20, if 0 is positive, the programme will proceed to statement 10. Thus it is apparent that this loop will "drill" 8 holes at the co-ordinates X, -Z which vary as shown, as the value of W increases from .125 in increments of .125 until W exceeds1, and then the programme proceeds to the next statement after statement 20.

It is often useful to define MACROS, which are groups of statements which can be recalled anywhere in the programme and different variable values inserted.

For example

```
MAC 1  =  MACRO/D
          GO DLTA/ 0, 0, D
          GO DLTA/ 0, 0, -D
          TERMAC
```

Anywhere in the programme the parts programmer can WRITE CALL/MAC 1, D = N, and those two statements in the MACRO will be performed with the value of D = N inserted. A MACRO may contain any valid APT statement and must end with a TERMAC statement.

4.5.2.11 Programming From Auxiliary Views:

To facilitate programming from machine drawings, some sections of the programme may be taken from different views, projections, etc., and the data may be programmed in different co-ordinate systems. In order to keep the cutter location data in the same co-ordinate system the programmer can order the computer to transform the auxiliary coordinates to the main co-ordinate system.

MI - MATRIX/matrix Definition of location of Auxiliary Origin

REFSYS/MI

) Geometric definition
) statements in auxl. view

REFSYS/NO MORE

All the geometric statements that appeared between the REFSYS/M1 and REFSYS/NO MORE statements are transformed by Matrix M1 to the main system.

The cutter centre line data may also be transformed using a TRACUT routine in a similar manner to the REFSYS routine above. In this case, however, tool motion statements are transformed (not geometrical statements) with respect to the M.T. origin.

4.5.3. THE BASIC STRUCTURE OF APT

4.5.3.1 Programme Sections:

APT consists of 3 sub-sections controlled by a main or executive programme.

Section 0, is the executive programme which retains control of the other sections.

Section 1, is the language translator. It transforms the geometric definitions into cannonical and calculates the arithmetic functions and outputs a PROTAPE or PROFILE. Control goes back to Section 0 which then inputs the PROTAPE to Section 2.

Section 2, is the arithmetic element known as ARLEM. This calculates the cutter path co-ordinates and outputs a CUTTER LOCATION TAPE (CL TAPE) which is then used as an input to Section 3.

Section 3, is the CL TAPE EDITOR. This also contains the COPY LOGIC for repeating PATTERNS and MARCOS defined in the programme. It performs the TRACUT transformation and translates the CL TAPE into suitable English for a cutter location listing and other output format for the processor.

4.5.3.2 Comparison with FORTRAN:

The APT language translator programme resembles that of FORTRAN in many ways. Some of the apparent differences are that there is no distinction between integers and real numbers in APT, and everything is calculated in single precision.

APT functions are really function classes with variable length argument lists. For example, LINE is a class of function which consists of $LINE_1$, $LINE_2$... etc., each has a different geometric construction which defines a line. The format of the argument list refers to a particular construction. A slash (/) is used to separate the word from the argument instead of parenthesis as in FORTRAN. The words CENTRE and RADIUS are known as permanent identifiers.

APT procedures do not have a value assigned to them. For example, GOFWD/L1, REFSYS/M1. In addition these usually have variable length argument lists.

All APT functions and procedures are written in FORTRAN, and are the equivalent of library functions. The translator must reduce the APT source programme into a proper sequence of requests for library routines compatible with FORTRAN. Computer storage must be allocated for variables and for data, as in FORTRAN. APT also follows the same hierarchy in arithmetic operators as in FORTRAN.

4.5.3.3 Method of Geometrical Representation:

APT uses a 3 dimensional cartesian co-ordinate system as a common base for all defined surfaces. Lines are represented by planes perpendicular to the X Y plane, and circles by right cylinders with their axes perpendicular to the X Y plane, to give them a 3-D interpretation.

All defined geometric shapes are reduced to cannonical forms, viz. A sphere is reduced to the x,y,z, co-ordinate of the centre point and the radius, A vector, to a unit vector and a scalar magnitude, a plane to a normal vector and its shortest distance to the origin. Similarly, there are cannonical forms for points, free vectors, circular cylinders, cones, generalized quadratic surfaces, ruled surfaces, transformation matricies etc. This assists calculation of cutter path co-ordinates and matrix transformations.

4.5.3.4 Tool Motion:

The APT system assumes only linear interpolation capability of the machine tool. Linear interpolation implies that movement along all independent axes occurs simultaneously, in some co-ordinated fashion to produce straight line motion between two points relative to the machine bed. In moving along a contour the path is approximated by a large number of straight line increments which are calculated in the programme. (In cases where the machine tool has circular interpolation and the cutter is directed along an arc of a circle, this section of the programme becomes redundant).

4.5.3.5 Tolerance Specifications:

The programme is so designed that it calculates the size of increments necessary to remain within the tolerances specified, or assumed, if not specified.

Take for example, the case of a circle, from the geometry of Fig. 4.13 it can be shown that the span of increments for a chordal approximation is equal to: $\Delta = 2\sqrt{(2R-t)t}$ where t is the tolerance, which if defined in the programme would be the INTOL/t statement. A tangential (or OUTOL/t) approximation shown in the

Chordal approximation to a circle radius R

$$= 2\sqrt{(2R-t)t}$$

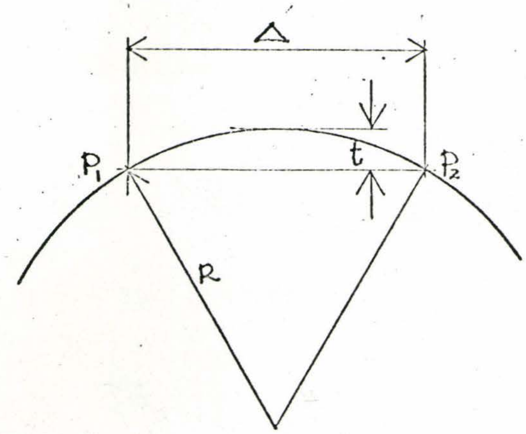


FIG. 4·13

Tangential approximation to a circle radius R

Span Shorter

$$= 2\sqrt{(2R'-t)t}$$

where $R' = R + t$

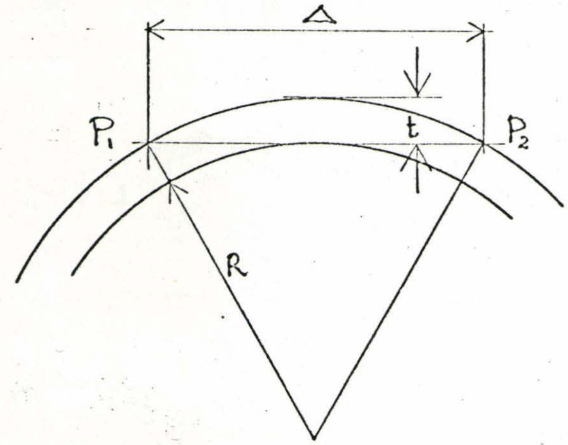


FIG. 4·14

Chordal approximation to circle radius R with cutter compensation

$$2\sqrt{(2R' - T)T}$$

where $R' = R + r$

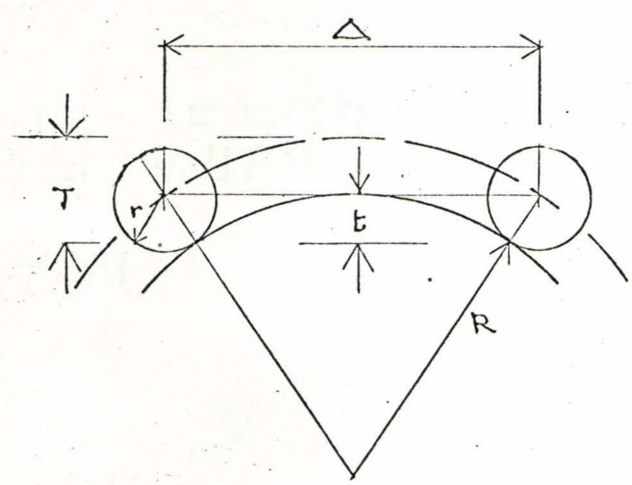


FIG. 4·15

A tool approaching a part and drive surface

Construction to get Vector V

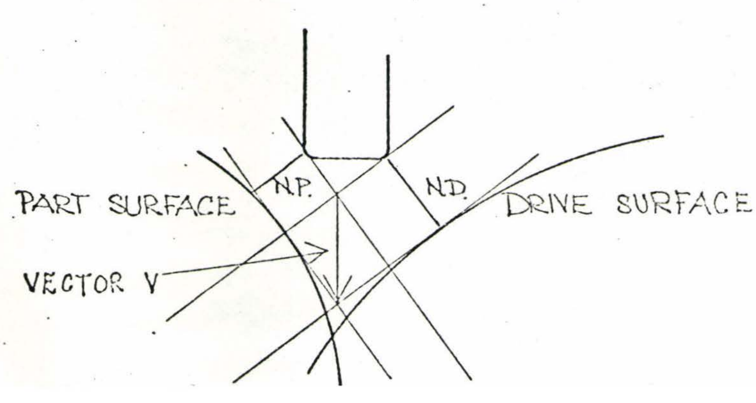


FIG. 4·16

Fig 4.14 reduces the span of the increments slightly. However, in the above cases the tool radius has been neglected so this too must be included in the calculations. In the following figure (4.15) a chordal approximation with a finite cutter radius is shown, however, there are two solutions depending on whether the tool is on the concave or convex side of the arc. This basic analysis is extended to other plane and 3-D curves. The span length is calculated from the minimum radius of curvature. This calculation is trivial in the case of simple plane curves, however, it becomes very complex in some 3-D shapes.

Another routine in the geometrical section is to control a cutter of a complex shape to move within tolerance of the controlling surfaces. It is first moved to a 'close' position, in the direction of the defined surfaces. The normals NP and ND to the surfaces and the parallel tangent planes are constructed as shown in the Fig. 4.16. When the tool is 'close' the vector, (v) of these tangent planes is calculated and added as a correction to the tool tip location. This process is iterated until all tolerances are satisfied.

4.5.3.6 Tool Compensation:

The CL tape gives the co-ordinates of the cutter path with the programmed cutter dimensions, as well as normals to the cutter path. This latter data can be processed by the MCU to compensate for any change in cutter dimensions from the programmed dimension. The amount of compensation is usually dialed in on the control unit. This is an important feature to enable the operator to use under or over size tools without preparing a new CL tape.

4.5.3.7 Additional Features:

An additional feature of this programme is the mechanism for rotation, translation and change of scale of cutter location co-ordinates. This capability is invaluable in programming parts of high symmetry and is known as the copy logic.

The error diagnosis is carried out at all levels of the language. The language translator usually finds errors in grammar or syntax of the programme. The geometrical section finds errors in geometric definitions, for example, a line defined parallel to a line and through a point on that line, or moving a cutter to a check surface that does not intersect the drive or part surfaces. The postprocessor also has diagnostic capabilities which are discussed in section 5.

4.6 ADAPT

4.6.1 Introduction:

This language was developed by IBM under contract to the U.S. Air Force. It has complete two dimensional capabilities (profiling) in the X and Y plane but only linear velocity control on the third axis. ADAPT belongs to the APT family of languages, utilizes similar words and syntax, but has a smaller vocabulary and is far less flexible than APT III. The programme is designed for small or medium size computers (e.g. IBM 1620 with 20K core) and is relatively popular in Canadian and American metal working industries that do not need the full APT capability (20% in survey [21]). Various major computer manufacturers have developed a version of ADAPT for their computers, as shown in the Appendix.1.

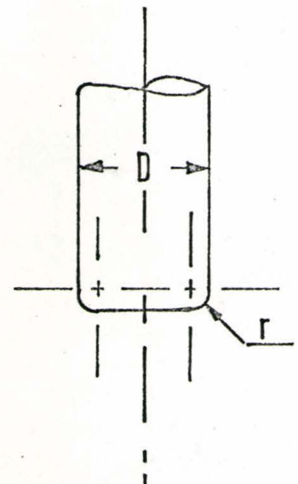
4.6.2 PROGRAMMING ADAPT

4.6.2.1 General:

The programming procedure is almost identical to APT, except ADAPT has fewer acceptable geometrical definitions, and has other limitations that restrict the flexibility and usage of the language (e.g. there are only 6 ways of defining a point and only 7 ways of defining a circle in ADAPT). In two dimensional, milling the plane, in which the cutter tip moves, is called the part surface which is analogous to APT. If no part surface is defined the X Y plane (Z=0) is assumed.

As in APT, before the first motion statement is given, the cutter dimensions must be defined, but the ADAPT language only provides for a flat bottomed cutter with rounded edges. Both the cutter diameter and the radius of the rounded edges are modifiers to the CUTTER/statement. If a ball cutter is used then the corner radius is equal to the cutter radius, and if a straight edge cutter is used then the corner radius is zero. The tool length is inserted in another statement viz TOOL NO/1001,3.500. The number 1001 is

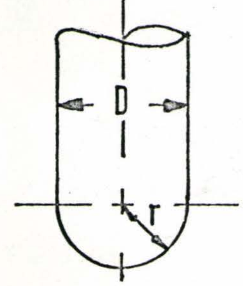
a) CUTTER/D,r



General cutter shape

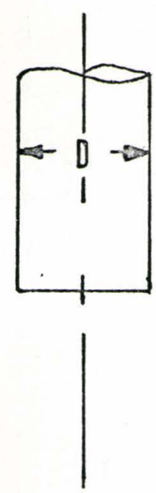
b) CUTTER/D,r

r = D/2



Ball cutter shape

c) CUTTER/D



Straight edge cutter shape

FIG. 4.17 A CUTTER DEFINITION IN ADAPT.

a number allotted to that particular tool. Each tool must have a 4 digit number, irrespective of whether the machine tool has a manual or an automatic tool change. The length of that tool is given as 3.5". Both the CUTTER and the TOOLNO statements are modal, they remain fixed in the control memory until the instruction appears again in the programme, with different values.

Almost all rules that apply to APT apply also to ADAPT. A FROM statement must be programmed, giving the initial starting position of the cutting tool. The part surface is defined with a PSIS/ statement, and may be any plane parallel or at an inclination to the X-Y plane. The feedrate instruction is given directly in inches per minute, and both the part surface and feedrate instructions are also modal. ADAPT also has the same cutter compensation routine as APT (normals to the cutter path on the CL tape).

4.6.2.2 Tolerance Specifications:

ADAPT approximates contours by small straight line increments. The tolerances are specified, using INTOL/ and OUTOL/ statements, however, the statements do not always mean the same as in APT. In ADAPT, INTOL applies to the inside curvature of the contour, and, not to the part, as in APT. Similarly OUTOL applies to the convex side of a contour. APT tolerance statements are acceptable in ADAPT. If both INTOL and OUTOL are of equal value. If unequal tolerances are desired the ADAPT programmer must continually re-define the tolerance statements, depending on which side (concave or convex), of the contour the tool is cutting (see Fig. 4.18).

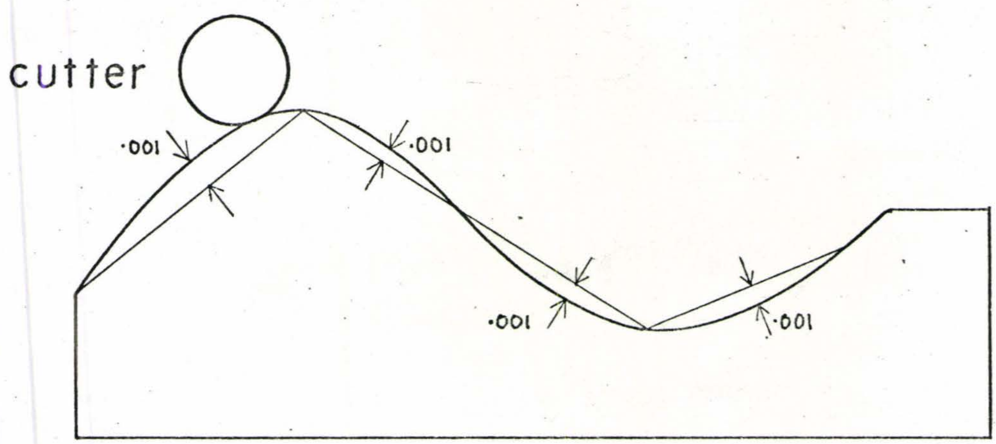
4.6.2.3 Pocket Milling:

The ADAPT pocket milling routine makes used of the computer to calculate the passes required to clear a pocket, however, the pocket may only have straight sides, less than five corners, and must be convex in shape (i.e. all inside corners are less than 180°). To surmount the latter two restrictions one pocket may be divided up into several imaginary pockets as illustrated in the Fig. 4.19.

4.6.2.4 Point To Point Programming Capabilities:

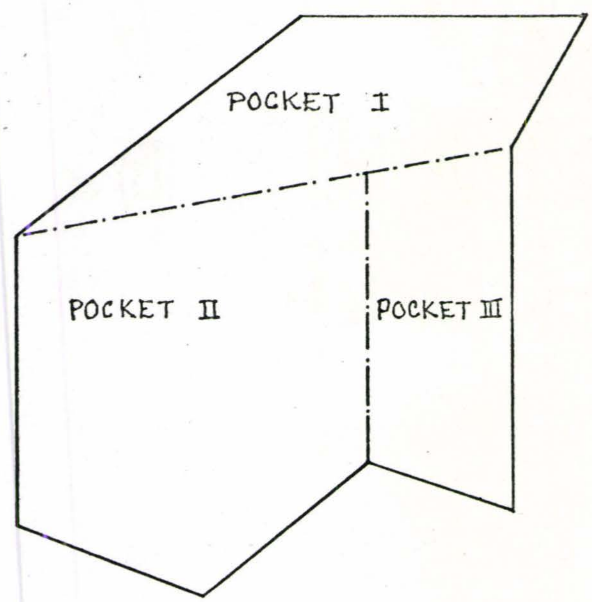
Although ADAPT is not very well suited for ptp programming, it can be used with some measure of success. The problem is that in ADAPT geometric and tool motion statements may not be mixed in a MACRO or COPY series of statements. For example, each hole on a bolt hole circle would have to be programmed individually. A method that is frequently used in ADAPT ptp programming is an INDEX - COPY routine.

The word INDEX, followed by an identifying number, starts a series of commands. This series terminates at a COPY statement, which has the same identifying number, a modifying word, and another number indicating how many times the series of commands should be repeated. The modifying word indicates whether to repeat exactly or



intol / ·001
applies to concave
edge of contour
not the part.

FIG. 4·18



This pocket could be divided into 3 imaginary pockets to satisfy ADAPT requirements.

FIG. 4·19

rotate or translate the commands each time they are copied. For example, drilling 12 holes in a straight line, inclined at 30° to the X axis, a distance of 1.72 inches apart, would be programmed

```
INDEX/500
FEDRAT/15
GODLTA/0,0,3
FEDRAT/50
GODLTA/0,0,-3
FEDRAT/200
GODLTA/2,1,0
COPY 500, SAME, 12.
```

It should be noted that after the 12th hole is completed, the tool still indexes a further 2 inches in X and 1 inch in Y, which can only be avoided by copying 11 holes and programming the 12th separately. The traverse rate of 200 ipm was not specified as a RAPID, because a GOTO command must always follow any RAPID feedrate programmed.

4.7 AUTOSPOT

AUTOSPOT was developed jointly by IBM and Kearny & Trecker in 1962. Basically, it is designed for 3 AXIS point to point operations. Although it can be programmed for limited 4th AXIS operations as well. It also has elementary profiling capability, however, if any milling instructions appear in the programme it requires an additional pass through the computer. This makes it a 3 pass system with milling operations, or a 2 pass system for only ptp machining. The language used is similar to AUTOMAP (an IBM subset of APT II with similar capability to ADAPT) and AUTOPROMT (used for 3 dimensional contouring).

For regular ptp operations, this language has various useful features. The programme compensates for cutter tip angles in drilling operations and also gives an additional break through allowance when required. Patterns of co-ordinates can be given a symbol and stored in memory for later use in the programme. Any number of holes on a bolt hole circle can be calculated by one instruction. Incremental programming can be used effectively to produce large numbers of equally spaced holes in a matrix formation. Patterns of holes can be inverted, translated or transformed to a mirror image equivalent. Programming can be done in polar co-ordinates if the geometry of the part makes it more convenient. There are several other useful ptp programming routines.

The milling capability is limited to three types of operations. The basic mill cycle operation is sequential programming of straight lines and arcs of circles. Geometrical shapes must be defined by co-ordinates of various points on the contour. A pocket mill cycle can be used to clear pockets to a specified depth, and similarly, a Face Mill cycle will mill a surface area to a given depth.

IBM have a new ADAPT-AUTOSPOT 360/system. This programme combines both languages together. It can be loaded on an IBM 360/30 with 32k memory core (see section 5.11).

4.8 2CL

4.8.1 General:

This language has been prepared by the National Engineering Laboratories (N.E.L.) in Glasgow, together with Ferranti Limited, under a contract from the British Ministry of Technology. This is intended to become the standard NC programming language in the U.K. It is based on the recommendations of a report prepared by a subcommittee studying NC programming [15] published in 1965. The language is for machine tools with two axis (X and Y) contouring control, and an independent 3rd axis (Z), with linear velocity control. Hence the name 2 contouring (C) and one linear (L) axis control. The language is compatible with APT and EXAPT, using a similar part programming vocabularly and modus operandi where possible, and has the same facility for cutter compensation.

To achieve a high degree of computer independence, the processor programme is written in FORTRAN IV and could be readily modified for any computer with an ASA FORTRAN IV compiler, and at least 12K core storage of at least 24 bit words. At present, four different computer manufacturers have been, or are, working on their versions of 2CL. The computers used are; Univac 1108; ICT 1900 series; English Electric KDF9 and Elliot 4100 series.

A general postprocessor has also been prepared, which is relatively computer independent, and can easily be modified for any particular machine tool and control unit combination. Most of the new APT postprocessors written in FORTRAN IV are relatively easily modified for use with 2CL.

N.E.L. are responsible for the language and keep it regularly updated. The language is available to British manufacturers free of charge.

2CL originally developed abbreviated words for several of the most popular vocabulary terminology, and these may be used as an alternative to the longer word. For example; in defining a circle C1 tangent to 3 previously defined lines L1, L2, L3, the programmer could write:

C1 = CIRCLE/ Y LARGE, L1, X LARGE, L2, Y SMALL, L3

or the terse alternative:

C1 = C/YL, L1, XL, L2, YS, L3.

Recently APT also introduced some abbreviated words for optional use. The arithmetic capability, the geometrical definitions, the drive part, and check surfaces and the motion statements are all much the same as APT. The INTOL and OUTOL dimensions refer to the inside and outside of the part surface, as in APT, not the concave and convex sides of the curve as in ADAPT. In the MACHIN/statement, defining the postprocessor, that should be used, the part programmer can indicate whether the machine tool has circular interpolation or not. If so, the computer will then avoid the unnecessary vector cut calculations, when the tool is directed around the arc of a circle; this cannot be done in APT.

Again, as in APT, this language has facility for defining a MACRO and a PATTERN. Point to point programming has good application on 2CL, better than ADAPT, which is roughly the IBM equivalent to 2CL in profiling capabilities.

4.8.2 Pocketing Routines:

An attractive feature found on 2CL, is its area clearnace capability. The computer can be instructed to calculate the cutter movement required to pocket mill any closed contour bounded by straight lines and arcs of circles, and which may contain other contours (also bounded by straight lines and arcs of circles) which are to be saved. The area will be cleared by straight line cuts parallel to a drive surface specified by the part programmer. The routine automatically provides a final cut around the specified contours, to remove any scallops generated. An additional finish cut around the contour may also be called for. With the same pocketing routine a negative finish cut may also be used to clear the surface of a metal block, leaving behind a defined contour island. This routine has several other applications and is a useful additional capability to have available.

4.9 EXAPT

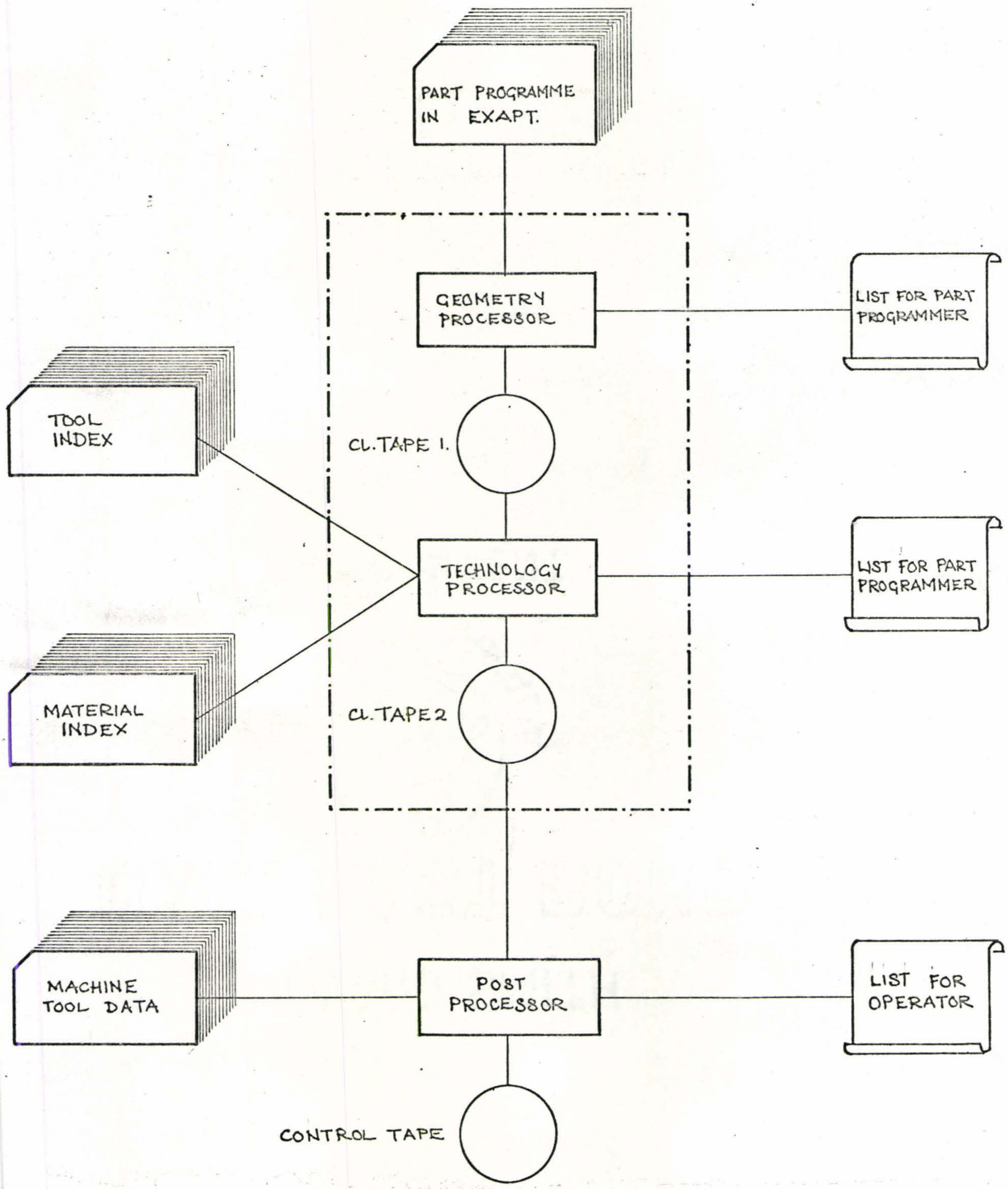
4.9.1 General:

Several German University Institutions, with the support of a few European computer control and machine tool manufacturers, made a study of NC programming languages about three years ago. They found that APT was the most suitable to meet the requirements of European industry, however, certain deficiencies were observed. Namely, APT had no facility to utilize the computer for solving technological parameters of the various machining operations. Consequently, it was decided that a new family of languages, compatible within APT, should be written to fulfil these requirements. EXAPT 1 is for three Axis point to point programming and simple line milling operations. This has already been completed and is in use. EXAPT 2 is for turning operations. It deals with programming lathes with straight path or contour control. EXAPT 3 is for 2 axis profiling with linear velocity control on the 3rd Axis and will be used mainly for milling machine tools. The latter two are still in the development stage, and it will be some time before they are made available. A generalized block diagram of the principal processing stages of the EXAPT language is shown in Fig. 4. 20.

4.9.2 EXAPT 1

4.9.2.1 General:

The structure of EXAPT 1 is much the same as the APT family of languages, and may be considered as another subset. The



A GENERALIZED BLOCK DIAGRAM OF THE PRINCIPLE PROCESSING STAGES IN EXAPT.

FIG. 4·19

CL tape conforms to an APT format. The processor can be loaded in computers which have an ASA FORTRAN IV compiler with a minimum of 16 K core storage.

The type of geometrical definitions that occur in ptp programming are easily expressed in EXAPT 1 and an analogy may be drawn to the geometrical definitions available in Autospot (and APT). The language has adequate capabilities of inversion, mirror image, patterns, etc.

4.9.2.2 Tool and Material Indicies:

All tools suitable for NC machining are filed on a card index. Each is given a number by the individual user. This is entered on the index card, together with the tool dimensions, (length, diameter, angle), and several other code numbers that identify the type of machining operation the tool is used for (drilling, turning, or milling), the geometric shape of the tool, the material from which it is made, and the type of tool holders required. These cards form the tool index and are loaded into the computer memory. Further, a material index is also compiled from the individual manufacturers previous machining experience . Materials with similar machinability properties may be classed together in the card index. The data required for each material, and each type of machining operation, include; whether a coolant is required; the cutter material; the type of tool (coded); the angle of the tool tip; the cutting speed, and a feed factor. All this data is also stored in the computer memory.

In the parts programme, the workpiece material must be programmed, before any machining instructions are given, and other parameters concerning the initial surface finish may also be included.

4.9.2.3 Machining Operations:

A particular machining operation may now be defined and given a symbol, for example:

MACH 1 = DRILL/ SO, DIAMT, d DEPTH, t TOOL, e (or e,f) FEED, s, SPEED V, SPIRET g, NOREV

The underlined modifiers must be given in every case. The remaining ones may be omitted, if so, they will be calculated by the computer (SO is single operation, SPIRET is an instruction for a feed spindle return motion).

Alternatively, a work cycle, as opposed to a single operation, may be defined, where only the last operation is specified, e.g. tapping. All the necessary premachining and machining sequences and the tool selections are automatically generated, and the cutting parameters are calculated by the computers. Only certain modifiers are then permissable in the machining statement, which is similar to the one above, without the first parameter SO. These work cycles, or single operations, may be called up later on in the programme by the following statements, for example,

WORK/MACH 1

GO TO/PT 1

This instruction will perform the machining operation defined by MACH 1 at PT 1. The language provides for the following kinds of operations:

Centre Drilling	Drilling
Centre Boring	Centre Sinking
Reaming	Milling
Tapping	

4.9.3 EXAPT II

EXAPT II follows a similar pattern, and is used for turning operations, however, in this case it is necessary to define the geometry of the unmachined workpiece as well as the final geometry of the machined part. The computer will then calculate the required number of cuts, and the cutting parameters, to machine the material from the original workpiece to the desired proportions.

4.9.4 EXAPT III

EXAPT III is still in preliminary stages, but basically it will be an upgraded version of EXAPT I, to include a milling capability similar to that to 2CL and ADAPT.

4.10 ADDITIONAL LANGUAGES

Split is a 5 axes machine orientated continuous path programme, written by Sundstrand Machine Company specifically for a particular series of milling machines they manufacture. This programme requires only one pass through a computer, as the post processor functions are included in the processing stage. The vocabulary is relatively small, about 70 words are used. The Split programme has been written for most of the major NC controls and various Sunstrand Machine tools. There are language compilers for the IBM 7090, 1620 and 650, although the languages on the smaller computers are limited, several other computers may also be used, and may be substantially smaller than the minimum size computer for APT III. The Sundstrand Machine Company have also prepared APT postprocessors for their machine tools.

An extremely powerful ptp language has been developed by Westinghouse, who manufacture N/C controls. The current version is Camp IV and has 4 and 5 axis capability. It can be considered another APT subset. (Although Camp I and Camp II were not) and may be run on computers that take a FORTRAN IV compiler.

SNAP is a simple 2 axis ptp language, developed for Brown and Sharps' "Turn - E - Tape" drills. It was designed for the IBM 1401 data processing system, but has been run on several other computers as well.

There are at least a hundred other computer languages for NC machines, and it would be impossible, and purposeless, to list them all. The major languages which are currently used in industry have been dealt with.

Another interesting approach to programming 2 or 3 axis ptp machines for relatively straight forward components has been developed by Digital Equipment (and probably several other computer manufacturers as well). This is a total system the hardware consists of a small G.P. digital computer (PDP - 8/S) connected to an electric printer with a paper tape reader and paper tape punch. This is purchased together with the language and the postprocessor software package. This system of ptp programming, in conversational mode with the computer, has been found extremely effective in several NC installations.

5.0 POSTPROCESSORS

5.1 Introduction:

5.1.1 General:

The postprocessor programme serves to translate the generalized cutter location data, into a machine tool control tape compatible with a particular control system, on a particular machine. Formerly postprocessors were written in a cumbersome computer dependent language. Each particular machine tool and control combination required a new postprocessor, the preparation of which was both uneconomical and time consuming. In addition a parts programmer would have to become familiar with each particular postprocessor.

Present trends are to write the postprocessor in a computer independent language; FORTRAN IV is commonly used. This saves time in writing the postprocessor and any changes, extensions, or modifications to include another NCMT can be easily carried out. The advantages gained, however, are at the expense of computer efficiency. The possible computing time that could be saved by running a programme written in machine language is negligible on large computers, and today special postprocessor for machine tools are rarely written unless there is some other incentive. For example, a postprocessor, written in assembly language, requires far less memory core than one written in FORTRAN IV. The AUTOSPOT-ADAPT language can run on an IBM 360/30 computer with 32K, however, the AUTOSPOT-ADAPT postprocessor for several machine tools has to be written in assembly language, to fit into 32K memory storage. The same postprocessor, written in FORTRAN IV requires 64K memory core.

There are many postprocessors presently available for various languages, controls and machine tools. IITRI, who are controlling APT, have established a set of APT postprocessor standards (1963) which are issued as a guide to postprocessor authors as a means to establish some uniformity in the APT system.

5.1.2 Modern Postprocessor Structure:

Currently postprocessors have a modular structure as shown in the Fig. 5.1. They are generally not orientated towards individual machine tools, but are composed of a library of elements in each module. Each machine tool will require different combinations of these elements for postprocessing the CL tape, suitable for their control unit. The common control element serves to co-ordinate various sections of the postprocessor programme. This type of arrangement, again emphasises the facility to change and add to the existing programme library, to include new machines, and to keep pace with the expanding technology.

5.2 AN APT POSTPROCESSOR

5.2.1 General:

In the APT system the particular postprocessor is specified in the first operational statement of the parts programme. It defines the type of control unit and the servo lag characteristics of the machine tool. In addition, it arranges the axis nomenclature to suit the item manufactured and indicates whether circular interpolation is available or not.

The input element (Fig. 5.1) reads the data, performs some minor diagnostics and sorts it into various prescribed storage areas in a coded form.

5.2.2 The Motion Element:

The motion element has a further two sections which, together, deal with all motion commands, and maintain the diagnostic process. The section dealing with geometry, transforms the co-ordinates of the generalized cutter location tape to correspond with the datum of the particular machine. The co-ordinates may now

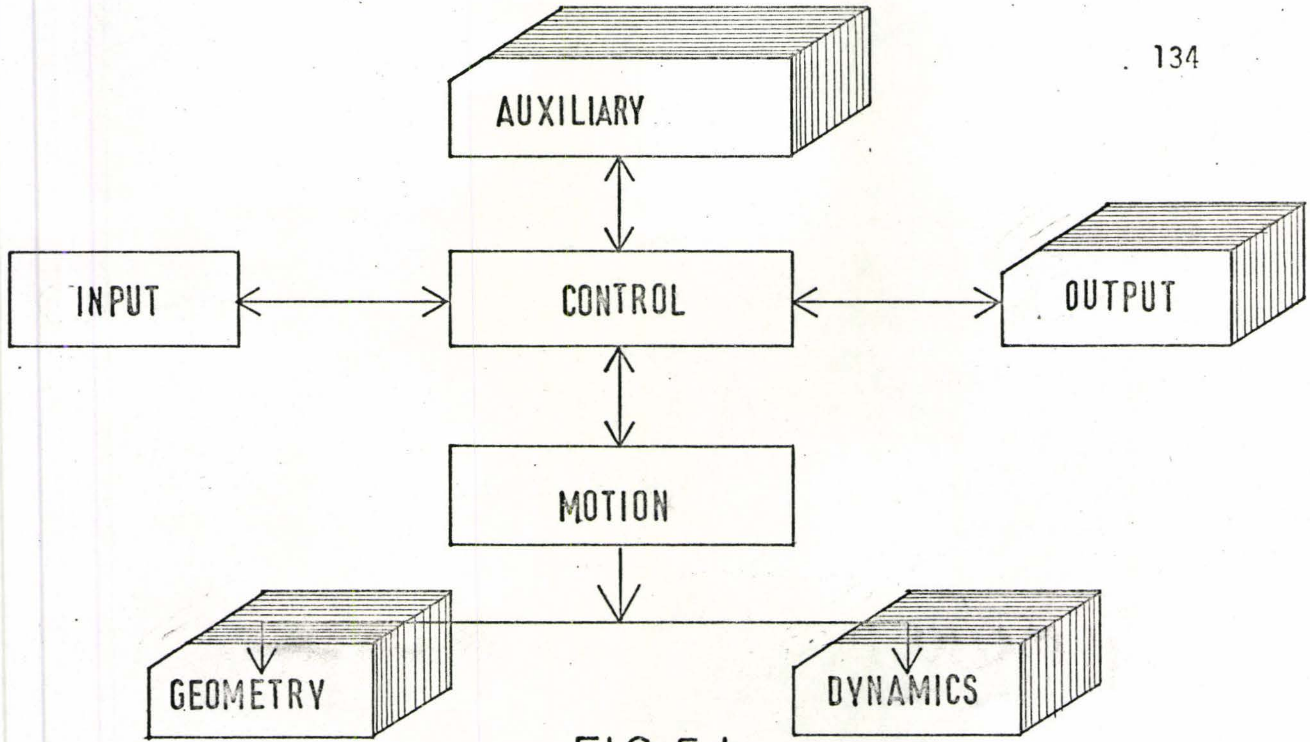


FIG.5·1

Structure of a Modular Post-Processor

Helical Vector Control

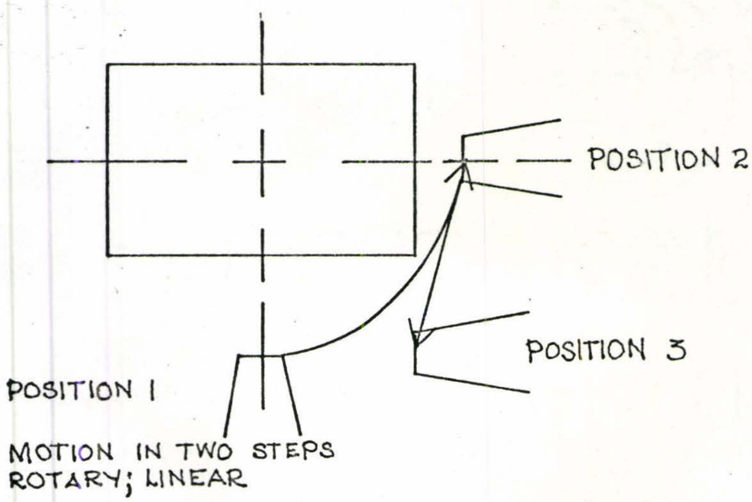


FIG. 5·2a

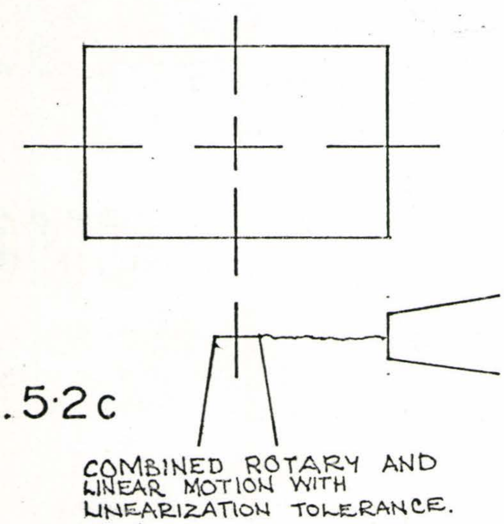


FIG.5·2c

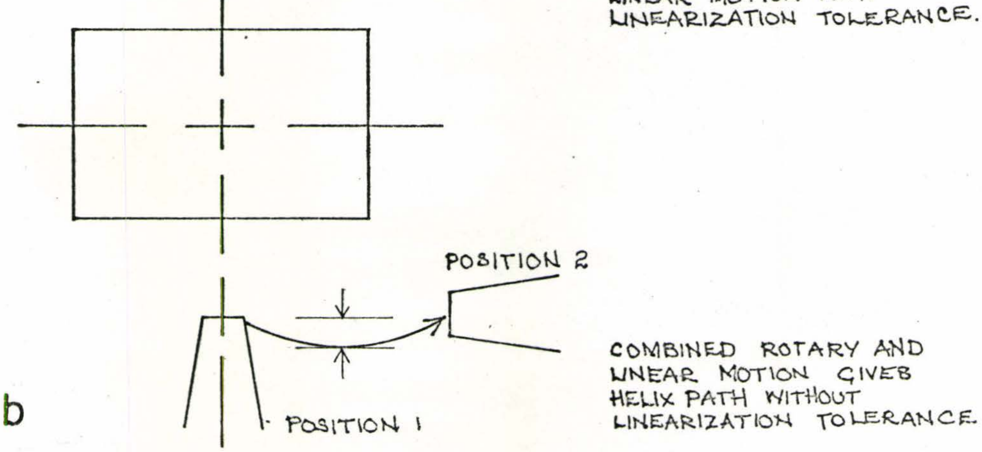


FIG. 5·2b

be expressed in absolute, or incremental form, on the tape, depending on the control system used. This section can rotate and translate a particular pattern defined by a set of co-ordinates to any location on the work table. It also can perform inversion and mirror image representation of data. All these calculations have to be carried out with great accuracy to ensure there is no error accumulation or round off which would alter the tool path from the one programmed.

5.2.3 Linearization:

Postprocessors for 4 and 5 axis NCMT are complex and include several additional features. For example: all rotary or combined linear and rotary (helical) motions of the cutting tool may be tested for deviation from a linear programmed path. The linearization can be kept within a certain tolerance defined in the programme (e.g. APT statement LINTOL/.001) if no such statement is programmed the motion is done at a rapid traverse rate and not linearized (Fig.5.2b). This can best be explained by the following example from an APT postprocessor. The following 3 diagrams indicate the tool motion; (5.2a) with a rotary command first, and then a linear command; (5.2b) with combined rotary and linear motion without a linearization tolerance specified and, finally (5.2c) one with combined rotary and linear motion and a defined linearization tolerance. The linearization routine calculates additional points along the cutter tool path to keep it within the tolerance defined.

5.2.4 <u>The Dynamics Element:</u>

The other section concerned with cutter motion is called "dynamics" in Fig. 5.1. In this section the dynamic characteristics of the machine tool are stored in memory. In cases of positional machine tools, this part of the postprocessor is relatively straightforward, however, this is not true for a continuous path machine tool. The postprocessor serves to edit the programmer's instructions of cutter velocity (and acceleration) to within the capability of the machine. For example, in programming, the cutter velocity can be changed instantaneously, however, the acceleration and response times of the machine tool's servo drives are finite. This element in the postprocessor issues instructions that the machine tool can follow, and that are compatible with the type of machine control unit used. For example, with a Bendix cpp control the feedrate is coded either as a feedrate number* or as a inverse time feedrate number** on the punched control tape.

---

* Feedrate number (FRN)

$$FRN = \frac{24574 \times 2^n \times |\text{ vector feedrate}|}{60 \times |\text{ vector length}| \times \text{ basic pulse weight}}$$

n is a positive integer representing the number of digits in binary equivalent of the largest axis integer in that block, and basic pulse weight is either .0002 ins. or .0001 ins.

** Inverse time number (ITN)

$$ITN = \frac{10 \times |\text{vector feedrate}|}{|\text{vector length }| \times \text{ basic pulse weight}}$$

The postprocessor will calculate, by the appropriate formula, the one indicated by the sign of the first argument following the postprocessor name in the MACHIN/statement. The Bendix system controls feedrate adequately, but has no control over acceleration and deceleration. Consequently, whenever the cutter has to move in rapid traverse, (it may be instructed to do so in the parts programme, or on executing a 'cycle' command that calls for rapid traverse) preparatory functions of acceleration and deceleration are punched into the tape. The postprocessor calculates, from data (usually empirical), stored in the memory, the distance the machine tool requires to decelerate from rapid traverse to the next programmed feedrate. It then checks whether the remaining distance to be moved in that block is sufficient to accelerate from its present velocity to rapid traverse. If this distance is too small it will change directly to the new feedrate, otherwise it punches 3 separate command blocks on the tape, an acceleration block, a deceleration block and a correction block (see Fig. 5.4). This is illustrated in the following example using APT and a continuous path Bendix control. The feedrate is given as an inverse time feedrate number.

INPUT programmed in APT

RAPID

GODLTA/13.972, 10.479,0

OUTPUT AFTER PROCESSED AND POSTPROCESSED

G08	X 11364	Y 9533	F 1247	Acceleration block
G09	X 2605	Y 1944	F 3240	Deceleration block
	X 3	Y 2	F 33282	Correction block

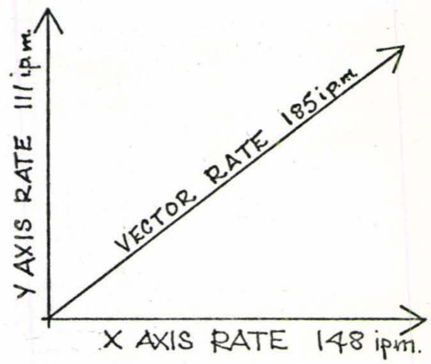
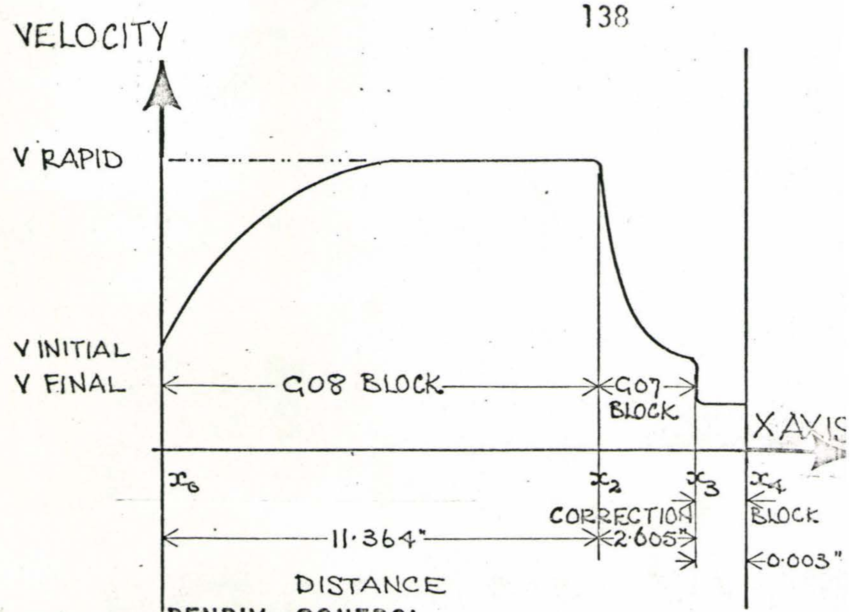


FIG.5·3



BENDIX CONTROL
FIG. 5·4

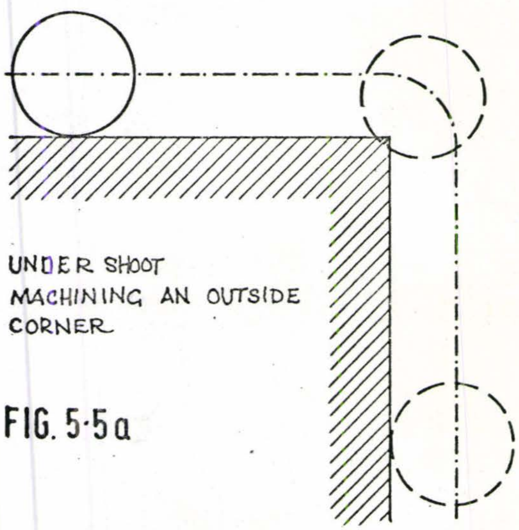


FIG. 5·5a

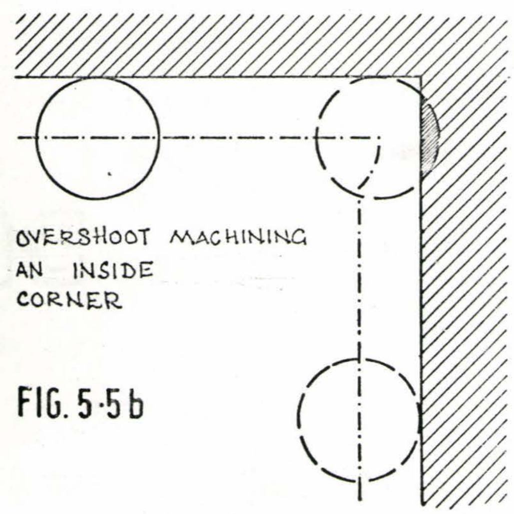


FIG. 5·5b

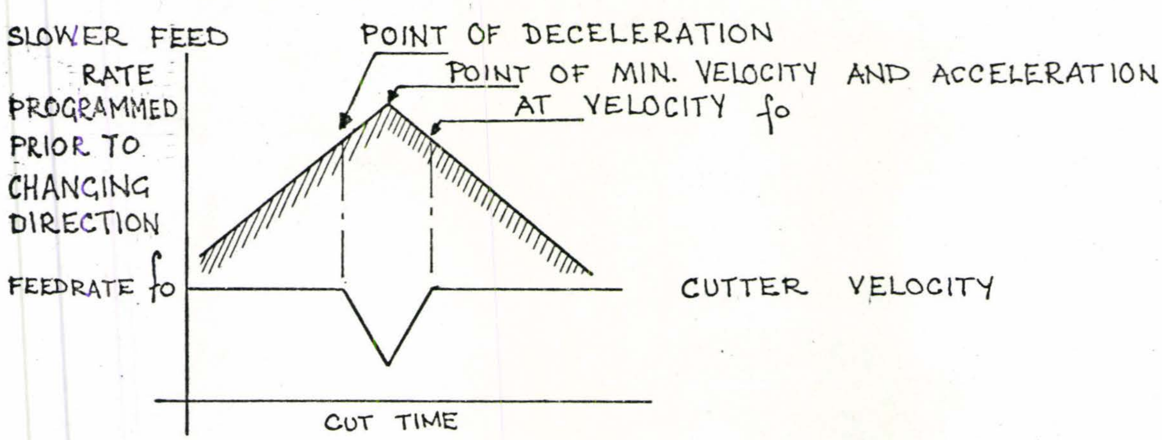


FIG.5·6

It can be seen that the total movement in the X and Y directions are 13.972 and 10.479 respectively, by adding the coordinates in each block (1 unit is 1 thousandth of an inch). The feedrate vectors for the first two blocks are 185 ipm (see Fig 5.3) and 1.2 ipm for the last one.

A similar problem can occur even when a RAPID rate is not demanded, but a large change in feed velocity is programmed, in this case, (Bendix control) a feedrate step function is employed. The step's rate and distance,is a function of the servo lag and minimum block interpolation time, which is stored in the memory of the postprocessor. Thus the postprocessor calculates whether the time required to generate the command pulses to the servo, (block interpolation time), is less than the time required to reach the new feedrate programmed in that block (dependent on servo lag). If the block interpolation time were less, several separate blocks of instructions are prepared by the postprocessor, increasing the feedrate in steps, until the programmed feedrate is reached. A machine tool with a low servo lag will have to take smaller velocity steps than one with a high servo lag.

5.2.5 Overshoot and Undershoot:

In continuous path machining, the overshoot or undershoot of the machine tool, directed to a specified location, must be within the machine tolerances defined in the programme. See Fig. 5.5. Again the servo lag characteristics which can be expressed as, a steady state positional error, determine the appropriate instruction to keep the cutter path within the tolerances. For example, if the direction of cutter motion is changed sharply (say 90° or more), an additional instruction block may be necessary to decrease the feedrate before the point, at which the cutter direction is changed. This is to ensure that the overshoot is within the tolerance specified (Fig. 5.5b). The postprocessor actually simulates the tool motion and will compute an additional instruction block if it is necessary, (a high lag servo will have a faster approach velocity than a low lag servo). Similarly a dwell or delay block (only a feedrate command) may be necessary to allow the servo to recover its steady state positional error and to ensure no undershoot error in the cutter path (Fig. 5.5a). Each programmed feedrate is tested for overshoot or undershoot relative to the next cutter velocity vector instruction.

5.2.6 Other Control Systems:

This type of feedrate control does not apply to all systems, the Cimtrol and General Electric controls do not require acceleration and deceleration instruction blocks, this function is incorporated in the machine control unit. The absolute feedrate is punched directly into the control tape and, when the machine tool is instructed to change from one feedrate to another, it does so with linear acceleration without any additional commands from the tape.

The postprocessor however, will calculate whether the servo acceleration, needed to satisfy the programmed feedrate, can be reached within the distance programmed in each information block and, if not, a lower feedrate will be used. This postprocessor handles cutter overshoot and undershoot in a similar manner to the Bendix postprocessor described previously (see Fig. 5.6).

5.2.7 The Auxiliary Element:

The auxiliary element of the postprocessor deals with the preparatory and miscellaneous functions (see Tables 4.1 and 4.2 for lists of EIA standard preparatory, and miscellaneous functions) as they appear in the programme. Whenever a recognisable word (in language vocabulary) is read by the postprocessor, the corresponding coded instruction is punched in tape. These may be divided into motion and non-motion instructions. The non-motion functions are represented by the letter M and two digits. For example, a few common miscellaneous (EIA standards) functions are:-

M13	Spindle clockwise and coolant on
M09	Coolant off
M03	Spindle clockwise
M01	Optional stop

There is provision for unassigned miscellaneous codes to be tailored to the requirements of the individual machine tool user. The preparatory functions, on the other hand, assist the machine control unit to perform the next instruction. For example, clockwise circular interpolation is indicated by G02 or, acceleration and deceleration commands (which have already been discussed) are indicated by G08 and G09 respectively.

In addition there are instructions, for including the cutter compensation settings on the machine tool dials; for a cutter moving forward on the left or on the right of a contour; and ones for ignoring the cutter compensation settings altogether. Included in this list of preparatory functions are 'canned cycle' routines. These are used in manual programming and have been discussed more fully elsewhere in this thesis. This section also has some memory storage space where patterns or marcos, can be retained. They may be repeated, rotated, inversed (mirror image), at any other location on the part, as specified in the part programme. On reading instructions for drilling or tapping, and other similar type operations where the tool follows a certain sequence of operations, the appropriate G codes are punched on the control tape.

5.2.8 Tapes and Output Listings:

Today, the majority of control units use a 1" wide 8 channel punched tape input, coded in accordance with EIA standards. The tape may be made from paper, nylon, laminar paper and nylon, or even aluminum. Several machine tools use magnetic tape prepared directly by the computers as an input medium to the MCU. It has greater storage, and can be read faster, however, most North American manufacturers of NCMT claim the advantages are marginal for the additional cost involved. It cannot be produced or modified by hand as a punched tape and cannot be read by inspection which is extremely useful in debugging a programming error or MT breakdown.

In addition to the tape output, other print-outs can be called for, for example, a print-out of the cutter location tape assists the MT operator to verify the first tape of a component, a cutting tool listing is also usually prepared. There are postprocessor subroutines available that calculate the total machining time and tape length for each individual programme.

SECTION C

Computer Aided Design and Optimisation of a Hydrostatic Thrust Bearing for NCMT Manufacture

Section C illustrates a practical application of integrating computerized design techniques with NCMT manufacture. The geometrical proportions of an annular, multi-recess, hydrostatic thrust bearing are optimised for a minimum power loss using Dickinson's Random Strategy. By changing the values of the design parameters and the constraint variables, in the programme, solutions for various design applications are readily obtained. The optimised dimensions are then used as input data to a generalized APT programme to generate a NC tape for the bearing manufacture. This eliminates the preparation, of working drawings and the part programming, of each successive bearing design, from the manufacturing cycle.

6.1 INTRODUCTION

6.1.1 Frequently the manufacturing cycle is considered as three discrete activities; initial design; technical preparation and industrial manufacture. However, the productivity increases usually associated with NCMT manufacture result largely from improvements in the latter stage; often the two former stages congest, and prevent any further overall productivity gains. Computer controlled manufacturing systems (e.g. Mollins System 24 [6]), and several other recent advances, in manufacturing technology, are effectively widening this gap between the stages.

In the past, most attempts at a solution were to improve the balance between the stages, by accelerating the slowest steps in the existing cycle. For example; working drawings, which formerly were manually prepared, may now be produced by computer controlled NC draughting machines. Computer optimisation techniques are also frequently used to obtain a better and faster design solution, yet few of these methods are sufficiently integrated with each other to streamline the whole cycle for efficient manufacture.

In a number of cases a more integrated approach to manufacture is practicable and can eliminate some inefficiencies of the present system. This concept is best illustrated in NCMT manufacture of certain component types.

6.1.2 Criteria For Using an 'Integrated Manufacturing Cycle':

Many families of mechanical components used in several different engineering applications, have identically similar geometrical layouts; however, the actual component dimensions vary with the design criteria of each specific application. Typical examples of these families are; various types of bearings; (journal, thrust, roller) piping flanges, tools, extrusion dies, and may even include assemblies of geometrically similar components such as; couplings; clutches; mechanisims (Geneva) etc.

Several of these families are extremely well suited to NCMT manufacture and the usual criteria for economical utilization of NCMT are valid. (They require many, or fairly complex machining operations on several conventional MT: high tooling and fixture costs would be incurred using conventional MT; close tolerance machining is necessary; conventional inspection costs and scrap losses represent a high proportion of total manufacturing costs; the batch sizes are relatively small).

In these cases, without much additional effort, a generalized NC programme can be written for a particular family of components, instead of a programme for just one particular component. The generalized NC programme would comprise of a main programme deck where all variable geometrical dimensions would be assigned a symbolic name, and a data deck with the numerical values of these variables.

In certain cases the geometrical design of the components readily lends itself to computer optimisation techniques, and by combining a design optimisation programme, with a generalized NC computer programme, the component design and manufacture is integrated into almost a continuous process.

However, generally it is preferable to have two independent programmes, and an intermediatory stage between them allows the design engineer to exercise some discretion as to the practicability of the computer solution, and to round off dimensions to standard sizes (e.g. bit diameters etc.). The optimisation programme should also be very flexible so that the design variables, the constraints and the objective function can easily be altered, and solutions obtained for numerous other design applications.

6.1.3 Choice of an Illustrative Example:

An externally pressurised oil bearing was chosen as an illustrative example of an 'integrated' approach to design and manufacture; it satisfies all the criteria described in the previous section. It is a multi-recess, annular thrust bearing, it has a high load bearing capacity, very low friction at all speeds, and can be designed for high static stiffnesses. The applications are numerous and range from; large turbine generators, machine tools, radar antennas, to precision dynamometers and gyroscope gimbal bearings; however, these bearings are not standard "off the shelf" items, and the bearing for each application is usually individually designed and manufactured.

The bearing assembly consists of the bearing thrust plate, mounted in a suitable housing which has means to collect and recirculate the lubricating oil through the bearing. Bearing thrust plates, within a given range of inner and outer radii, can be mounted in similar housings. The geometrical dimensions of the thrust plate, however, should be optimised according to the design criteria of each application. These criteria are for example; the axial load; the shaft speed; the thrust plate inner radius; and they may also include several constraints on the solution, such as: the maximum supply pressure, the maximum oil flow, the maximum outer thrust plate radius, the minimum bearing stiffness etc.

The optimisation of the bearing geometry can only be done satisfactorily by computer, as there is no deterministic solution; consequently either an iterative, 'cut and try', method, or a probablistic approach has to be used.

The thrust plate is also well suited to NCMT manufacture, even though it does not require many complicated machining operations, it is awkward to manufacture on conventional machine tools, and has high geometrical symmetry which simplifies the NC programme considerably.

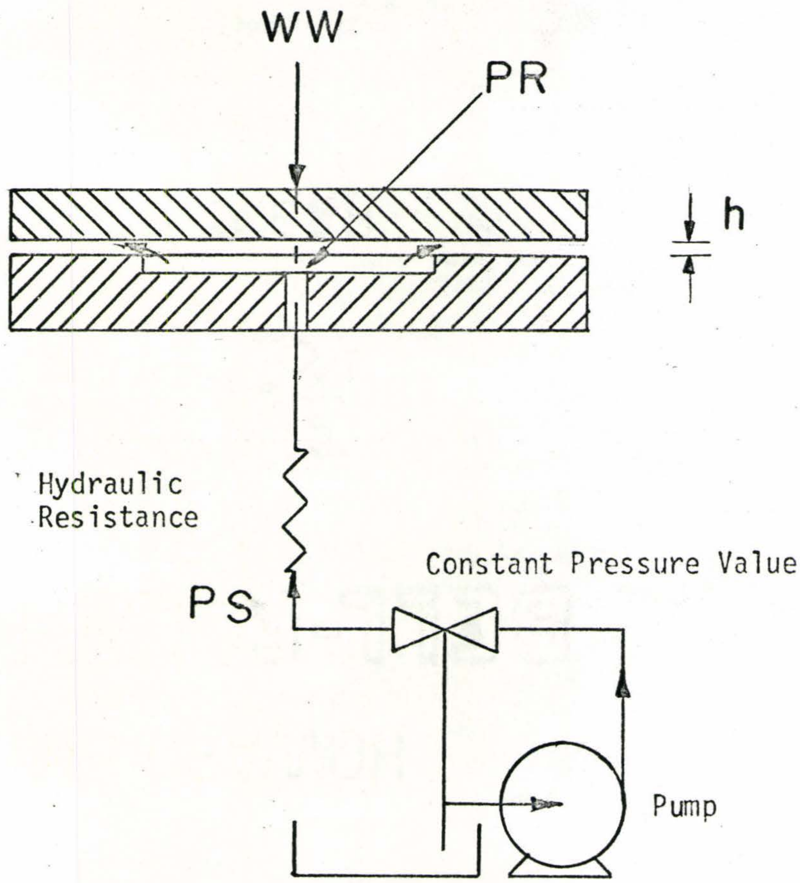
The author contends that this is a valid, practical, design problem in industrial manufacture. The method used, not only illustrates the concept of an "Integrated Manufacturing Cycle", but is a workable and feasible solution. The same ends could be achieved in various ways, and the techniques used are only limited by the imagination and ability of the designer.

6.2 THE HYDROSTATIC THRUST BEARING

6.2.1 General Operating Principles:

A schematic of a single recess hydrostatic bearing is shown in Fig. 6.1. Oil is supplied under pressure through a hydraulic resistance to the thrust plate recess. As the recess oil pressure increases, it becomes sufficient to support the axial load, acting on the upper disc, (the runner) and the oil begins to flow through the bearing. The recess oil pressure drops as the flow through the bearing increases and eventually, steady state conditions are reached, when the recess pressure is just sufficient to support the load on an oil film of finite thickness. The film thickness is usually small compared to other geometrical dimensions of the bearing.

The hydraulic resistance controls the oil flow to the bearing, it is known as a compensating element, and has an appreciable effect on the bearing performance. Generally either a capillary tube, an orifice, or a constant flow valve is used for flow compensation. The flow through the two former compensating elements is dependent on the supply and recess pressures, their geometrical dimensions and the physical properties of the fluid. Further analysis of the bearing and the types of compensation yield optimum pressure ratios (recess/supply) for constant stiffness, and for constant film



A SCHEMATIC SINGLE RECESS HYDROSTATIC THRUST BEARING

FIG 6·1

thickness, to maximize bearing stiffness. Generally, it is found that orifice compensated, externally pressurised bearings, are slightly stiffer than capillary compensated types (3). However, in the case of orifice compensation, the optimum pressure ratio is only an optimum for a given viscosity and supply pressure. This is not the case for capillary compensated bearings (4), the optimum pressure ratio is independent of viscosity and oil temperature. The design calculations are for capillary compensated bearings. The constant flow type compensation is generally superior to either orifice or capillary tube compensation, but is also far more expensive.

In many cases the stub end of the shaft cannot be used as the thrust runner, and an annular, shaft-collar, type bearing is preferable. The bearing is often broken up into six equal recesses with interconnecting drain grooves, which permits the bearing to resist some shaft misalignment. Since any misalignment will cause unequal film thicknesses between opposite pads, which in turn cause unequal recess pressures and oil flows from the higher pressure recesses to the lower ones, creating a restoring couple, opposing the forces causing the misalignment. Figure 6.2 is a generalized drawing of the proposed hydrostatic thrust plate design, dimensioned in terms of the symbolic code used in the NC programme (see section 6.4)

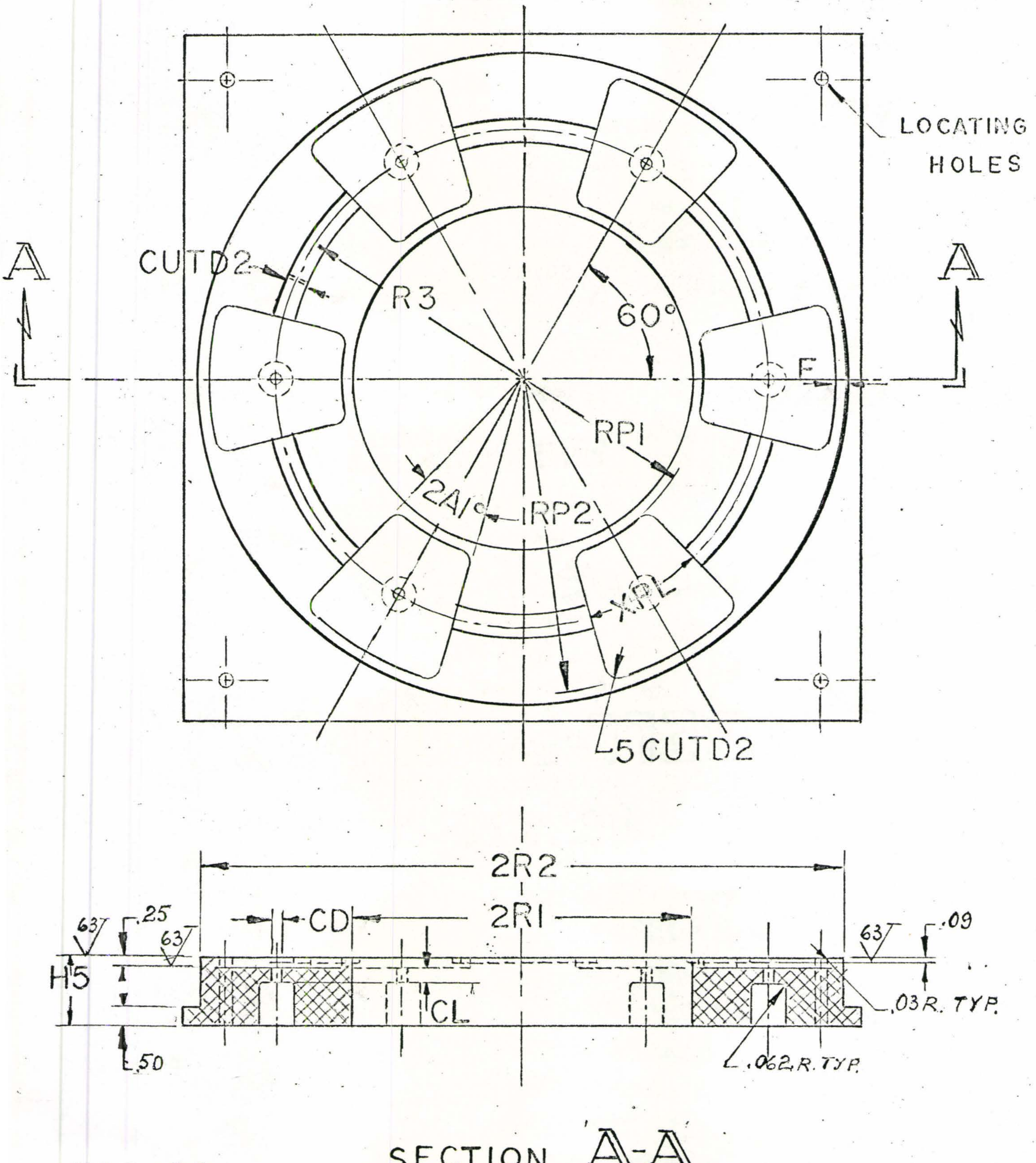


FIG. 6.2

THE THRUST PLATE OF

A HYDROSTATIC BEARING

6.3 THE OPTIMISATION PROGRAMME

6.3.1 Dickinson's Random Strategy:

Dickinson's Strategy is one of the more sophisticated Monte Carlo optimisation techniques. Since it is a probabalistic method, it can easily handle non-linear design equations; equality and inequality constraints, however, the solutions found are usually only good approximations of the absolute optima [5].

In the programme the dependent design variables are given specific values, (according to the design criteria), and a feasible range of values is defined for each independent design variable. Values for each independent variable, within the ranges specified, are selected at random and are substituted into the design equations. Provided none of the design constraints are violated, a feasible solution of the objective function is obtained. The programme calculates a given number of feasible solutions, sorts them and retains a smaller number of the 'best' solutions(of the objective function). The number of solutions evaluated and the number retained, depend on the number of independent variables and the desired accuracy of the optimisation. Dickinson proposed [5] that with 6 independent variables, the best 10, of 40 solutions should be retained for a satisfactory optimum. Although the solution can usually be improved in choosing larger numbers. The random values of the independent variables used to generate the 'best' solutions which were retained in memory, are then examined, and the highest and the lowest values of each independent variable becomes the new limit points for that variable. This process is iterated until the ranges of each independent variable have converged to within a defined percentage of their initial ranges, and this defines the optimum solution.

6.3.2. Optimising the Thrust Bearing:
(A print out of the programme appears in Appendix II)

6.3.2.1 The Dependent Design Variables:

These parameters vary with each design application. They included: -

the axial load (WW lbs.)
the shaft speed (RPM rpm)
the inner thrust plate radius (RI ins.)
the thrust plate thickness (H ins.)
the lubricating fluid density (DENSTY lbs/ins.^{3})
the pump motor efficiency (EFF)

Only an approximation for the lubricating fluid density is required, generally a value of .03 lbs./in^3 for oil is quite adequate (only used in calculation of Reynold's Number to ensure laminar flow). The thrust plate thickness depends on several factors; the plate mountings and supports in the bearing housing; the axial load; the shaft radius; the type of material selected; and the amount of plate deflection that can be tolerated. The design engineer is expected to decide the plate thickness. The variable T is the number of capillary tubes supplying oil to each recess, and must be a whole number. T is initially set at one; and from the solution obtained the design engineer can decide whether to run the programme again with a higher value of T, or not. This is discussed further on in Sections 6.3.2.4 and 6.3.3.

These variables are the control variables of the optimisation programme. They are:-

The number of randomly chosen independent variables in the programme	(N)
The maximum number of iterations to reach an optimum	(NMAX)
The number of solutions evaluated each iteration	(NUMR)
The number of 'best' solutions retained in the programme	(NRET)
The percentage range convergence that define the optimum	(S)

In this case there are seven random variables (N=7). Since a high speed computer was used* there was very little increase in computing time by selecting large values of NUMR and NRET to obtain more accurate results, so 100 and 10 were used respectively. (The effect of using a large NUMR is to decrease the standard deviation of different optimum solutions, with different starting values, which actually increases the probability of a 'solution' closer to the absolute optimum). A value of S = .05 was considered adequate.

6.3.2.3 <u>The Random Independent Variables</u>:

As mentioned earlier, seven independent variables were selected. They are shown on the following tables where I is the variable subscript (from 1 to 7); A(I) the lower bound; B(I) the upper bound, and W(J,I) the normalized random number for the Jth

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* CDC 6400

solution of the Ith variable given by the equation:

$$W(J,I) = A(I) + R(I) \times (B(I) - A(I))$$

Where R(I) is the Ith random number generated such that $0 \leq R(I) < 1.000$

Subscript	Lower Bound	Upper Bound	Design Equation
I	A(I)	B(I)	
1	1.25	3.00	R2 = W(J,1) x R1 Outer Radius = W(J,1) x Inner Radius
2	.25	1.00	PL = W(J,2) x R3 Pocket Mean Circumfrential Length = W(J,2) x Mean Radius
3	.5	.99	BB = W(J,3) x (R2 - R1) Pocket Radial Length = W(J,3) x (Outer-Inner Radii)
4	1.0×10^{-6}	3.5×10^{-6}	VS = W(J,4) Viscosity = W(J,4)
5	0.1	0.9	PS = PR/W(J,5) Supply Pressure = Recess Pressure/ W(J,5)
6	0.00	1.00	CL = 20 x CD + W(J,6) x (H-.5-20 x CD) Capillary Length = 20 x Capil. Diam. + W(J,6) x (Bearing Thickness -.5 -20 x Capil. Diam.)
7	0.05	$\frac{H-.5}{20}$	CD = W(J,7) Capillary Diameter = W(J,7)

where: lengths are in inches
viscosity in reyns, slugs/ins sec
pressures in psi

The limit points of the first three variables are apparent from the geometrical layout of the bearing. The upper bound of the viscosity random variable is dependent on the operating oil temperature. The heat generated in the bearing by the friction and pumping power losses, should also be considered as well as the initial oil temperature and the heat dissipation properties of the bearing housing. The supply pressure must always be larger than the recess pressure and the limit points shown are for that general case. However, in the Appendix III it is shown that for maximum bearing stiffness an optimum pressure ratio exists. For a constant maximum stiffness the ratio (supply/recess) equals 2/3 and in such an application both the limit points of that variable are set equal to 2/3.

The last two random variables are for the capillary tube design. Their dimensions are constrained as follows:-

The capillary tube should be at least .05 inches in diameter, as dirt may block smaller tubes and would cause catastrophic failure of the bearing.

The capillary tube length must be at least twenty times the tube diameter.

The maximum tube length is; the bearing thickness (H) - the pocket depth (.25);- an allowance to connect the oil supply to the bearing (.25),(i.e.(H - .5) ins.).

These constraints are always satisfied by setting the limits of the capillary diameter (CD) equal to .05" and $\frac{H-.5}{20}$ and the range of the capillary length random variable,(W(J,6)),to between 0 and 1 where the capillary length (CL) is given by equation:

$$CL = 20 \times CD + W(J,6) \times (H - .5 - 20 \times CD)$$

6.3.2.4 Subroutine RANOS:

A standard library function, FRANDN, is used to generate N (i.e. 7) random numbers between .000000 and .999999. Each random number is first normalized within the range of a particular random variable W(J,1) and then they are substituted into the design equations which have been derived in the Appendix III. As the calculations are done, the constraints are checked and if violated a new set of random numbers is requested. In this programme only the essential constraints are included, they are:-

The ratio of recess area to pad area should be within .25 and .75
The film thickness should be within .001 and .01 ins.
The capillary flow should be laminar, (i.e. Reynolds Number is less than 2000).

However, other constraints limiting the maximum supply pressure, the oil flow, etc., can easily be added to this subroutine. The three constraints given have been found necessary in practical design applications (2).

In cases of large bearings supporting heavy axial loads, the constraint that the capillary flow should be laminar is often limiting, however, improved solutions are possible by increasing the number of capillary tubes to each recess (i.e. the parameter T). This factor should be left to the discretion of the design engineer and is limited by the circumferential pocket length. The design engineer may run this programme several times with various values of T, until satisfied with the solution. If a large amount of heat is generated in friction, the flow may also be increased, to reduce the rise in oil temperature.

6.3.2.5 Subroutine OBJFN:

The power losses of the bearing, as derived in the Appendix III may be divided into friction losses and pumping losses. The bearing may either be optimised for a minimum total power loss, or for a minimum friction loss. The index II, an input variable, set equal to zero indicates the former objective function and set equal to one, the latter. Further constraints could be added to the programme in this subroutine. Such as limiting the maximum oil temperature, however, this will depend on the initial oil temperature, the heat transfer characteristics of the bearing housing and the ambient operating temperatures.

6.3.3 THE SOLUTION

The optimisation routine appears to be working adequately; there is only a relatively small range of optimum solutions using different starting numbers (M) for the random number library function.

Example 1 is the design of a thrust bearing for a large steam turbine, with a maximum thrust of 70,000 lbs., at a speed of 3600 rpm. The fixed dimensions of the thrust plate are; the inner radius 6.5 ins. and the thickness 4 ins. An oil density of .03 lbs/in^3 and a pump efficiency of .8 were approximated. The bearing is optimised for minimum total power loss.

A trial solution was run through the computer, using only one capillary inlet for each recess (T = 1). This gave an optimum of power loss of 122.6 H.P., however, 120.2 H.P. were friction losses and the flow was only 18.4 ins^3/sec. (Table 6.1) Thus it was obvious that by increasing the oil flow to the bearing the film thickness would increase and the friction losses decrease, besides with 120.2 H.P. converted to heat energy a higher oil flow rate is necessary to reduce the operating oil temperature. Trial solutions with 4 and 5 capillary tubes were attempted (see tables 6.2 and 6.3). The former solution gives the minimum total powerloss and was used for the generalized NC programme. A comparison of design solutions for a tapered land and a tilting pad thrust bearings, operating under similar load conditions is given in the table below based on calculations given in [1].

EXAMPLE 1 OF AN OPTIMISED HYDROSTATIC THRUST BEARING

HYDROSTATIC BEARING SPECIFICATIONS

LOAD	70000
SPEED	3600
VISCOSITY	.00000275
SUPPLY PRESSURE	689.68
OIL FLOW	18.3837
POWER LOSS	122.56802
FRICTION LOSS	120.168

GEOMETRICAL DIMENSIONS

FILM THICKNESS	.00135
INNER RADIUS	6.500
OUTER RADIUS	9.286
RADIAL POCKET LENGTH	2.268
POCKET LENGTH ALONG MEAN RADIUS	7.061
BEARING THICKNESS	4.000
CAPILLARY LENGTH	2.946
CAPILLARY DIAMETER	.0552
NO CAPILLARIES PER POCKET	1

TABLE 6.1

EXAMPLE 1 OF AN OPTIMISED HYDROSTATIC THRUST BEARING

HYDROSTATIC BEARING SPECIFICATIONS

LOAD	70000
SPEED	3600
VISCOSITY	.00000224
SUPPLY PRESSURE	518.82
OIL FLOW	61.5051
POWER LOSS	81.26791
FRICTION LOSS	75.227

GEOMETRICAL DIMENSIONS

FILM THICKNESS	.00202
INNER RADIUS	6.500
OUTER RADIUS	9.894
RADIAL POCKET LENGTH	2.832
POCKET LENGTH ALONG MEAN RADIUS	7.714
BEARING THICKNESS	4.000
CAPILLARY LENGTH	3.169
CAPILLARY DIAMETER	.0567
NO CAPILLARIES PER POCKET	4

TABLE 6.2

EXAMPLE 1 OF AN OPTIMISED HYDROSTATIC THRUST BEARING

HYDROSTATIC BEARING SPECIFICATIONS

LOAD	70000
SPEED	3600
VISCOSITY	.00000259
SUPPLY PRESSURE	695.12
OIL FLOW	86.8905
POWER LOSS	85.01209
FRICTION LOSS	73.578

GEOMETRICAL DIMENSIONS

FILM THICKNESS	.00223
INNER RADIUS	6.500
OUTER RADIUS	9.275
RADIAL POCKET LENGTH	2.266
POCKET LENGTH ALONG MEAN RADIUS	6.783
BEARING THICKNESS	4.000
CAPILLARY LENGTH	3.069
CAPILLARY DIAMETER	.0556
NO CAPILLARIES PER POCKET	5

TABLE 6.3

EXAMPLE 1 OF AN OPTIMISED HYDROSTATIC THRUST BEARING

HYDROSTATIC BEARING SPECIFICATIONS

LOAD	35000
SPEED	5000
VISCOSITY	.00000262
SUPPLY PRESSURE	332.29
OIL FLOW	60.5941
POWER LOSS	62.55283
FRICTION LOSS	58.741

GEOMETRICAL DIMENSIONS

FILM THICKNESS	.00249
INNER RADIUS	4.000
OUTER RADIUS	7.731
RADIAL POCKET LENGTH	3.332
POCKET LENGTH ALONG MEAN RADIUS	5.158
BEARING THICKNESS	3.000
CAPILLARY LENGTH	2.209
CAPILLARY DIAMETER	.0636
NO CAPILLARIES PER POCKET	3

TABLE 6.4

EXAMPLE 1 OF AN OPTIMISED HYDROSTATIC THRUST BEARING

HYDROSTATIC BEARING SPECIFICATIONS

LOAD	10000
SPEED	2000
VISCOSITY	.00000257
SUPPLY PRESSURE	252.82
OIL FLOW	22.7491
POWER LOSS	2.70766
FRICTION LOSS	1.619

GEOMETRICAL DIMENSIONS

FILM THICKNESS	.00202
INNER RADIUS	2.500
OUTER RADIUS	4.738
RADIAL POCKET LENGTH	1.933
POCKET LENGTH ALONG MEAN RADIUS	3.287
BEARING THICKNESS	2.000
CAPILLARY LENGTH	1.366
CAPILLARY DIAMETER	.0535
NO CAPILLARIES PER POCKET	2

TABLE 6.5

Type of Bearing	Hydrostatic	Tilting Pad	Tapered Land
Load lbs	70,000	70,000	70,000
Speed rpm	3,600	3,600	3,600
Inner Radius ins	6.5	6.5	6.5
Outer Radius ins	9.89	15	15
Operating Viscosity reyn x 10^{-6}	2.24	2.65	2.65
Minimum Film Thickness ins	.0020	.0016	.0015
Friction Power Loss	75.2	86	76
Oil Flow ins^3/sec	61.5	92.4	60.5
Film Temperature Rise °F	57	44	58

The film temperature used can be calculated from the equation

$$\Delta \text{ temp} = \frac{42.4 \times \text{Friction Horse Power Loss}}{C_p \times Q/3.85}$$

Where C_p is the specific heat of oil assumed 3.5. Q is the flow in ins^3/sec.

Table 6.4 and 6.5 are optimised solutions of two other bearing designs obtained by changing the values of the dependent variables in this programme.

6.4 MANUFACTURING THE BEARING

6.4.1 Preliminary Preparation:

An initially square work piece, with sides equal or slightly larger than the outer diameter of the thrust plate, can be conveniently mounted on the MT worktable by a locating bolt in each of the four corners. The bolts should be spaced an adequate distance from the edges and an integer number of half inches apart, to fit most slotted NCMT work-tables. Both the thickness of the thrust plate and the type of material used should be left to the discretion of the design engineer.

The bearing thickness (H5) is an input parameter to the generalized NC programme. The bottom of the set up face, must be milled level, and this could also be done on an NC machining centre, so that both the locating bolt holes, and the oil supply holes (to each pocket) could be drilled while the work-piece is set up on the MT worktable. A generalized programme could also be written for these operations. If this were done, it would be helpful in setting up the other work-piece face accurately, to drill an additional hole, through the work-piece centre. The work-piece is then mounted on a scrap metal plate of uniform thickness (say 1 inch) to protect the worktable from tool damage.

6.4.2 Tool Selection and Cutting Specifications:

The actual machining parameters and choice of cutting tools must be decided upon by the production engineer. In this specific example, the generalized NC programme is written in APT and all the technological cutting specifications must be defined in the programme (cf. EXAPT III will be able to calculate milling, cutting specifications, as explained in Section 4.9.4). All the machining operations in the programme are performed with two end mills.

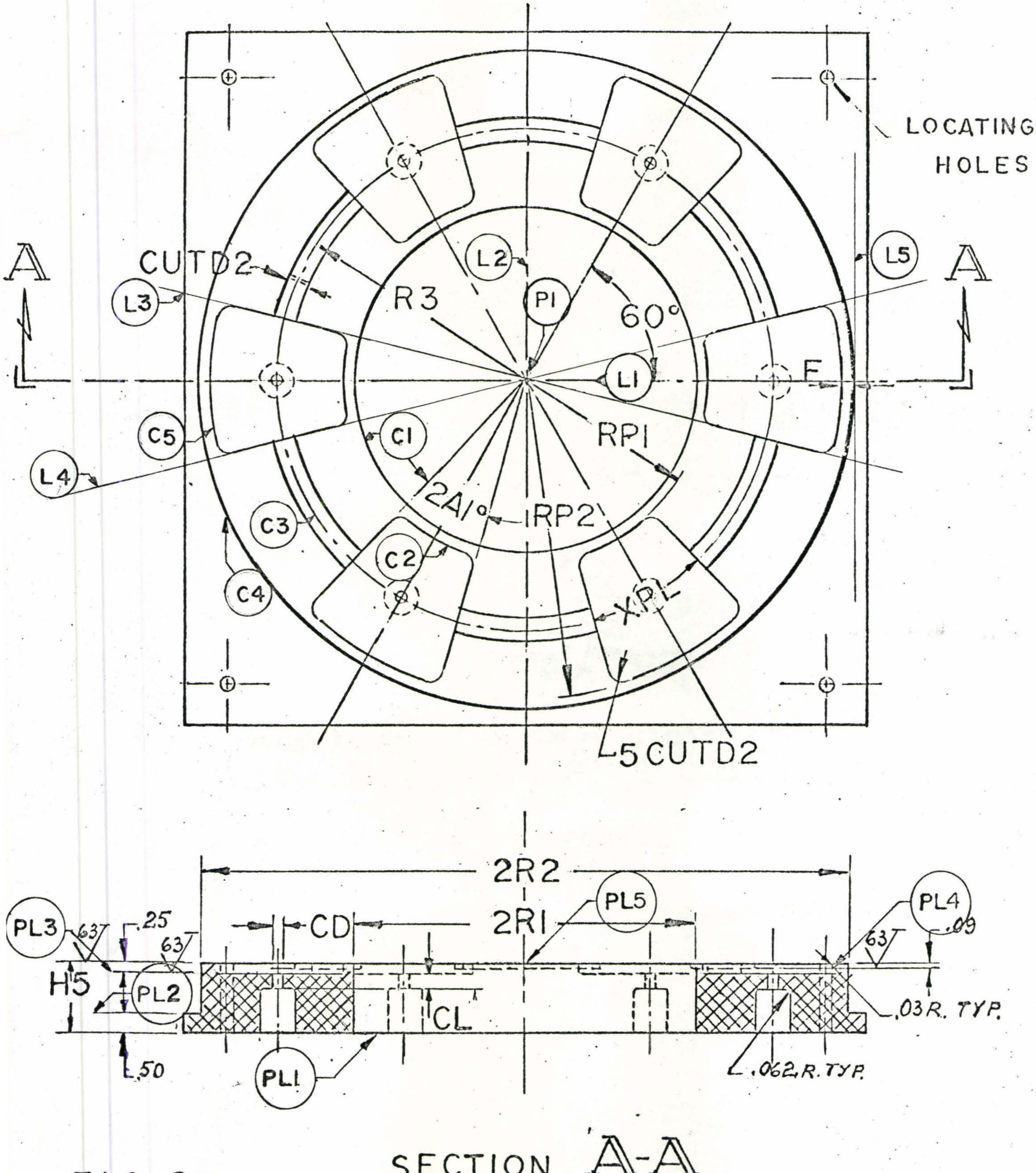


FIG. 6·4

THE THRUST PLATE OF

A HYDROSTATIC BEARING

The first tool is used to face mill the annular ring, mill out the six pockets; and cut both inner and outer diameters of the thrust plate. The second tool is generally less than half the diameter of the first, and it finish cuts the pockets reducing the pocket corner radii and also cuts the interconnecting oil groove between all the pockets.

The annular ring is face milled by three concentric cuts equally spaced along the radial breadth of the work-piece. Thus the cutting tool diameter should be equal, or greater than, .90 (outer bearing radius - inner bearing radius)/3 where the factor .90 is to compensate for the end mill edge radius. This tool should also be long enough to cut the full height of the work-piece.

The second cutting tool diameter determines the breadth of the oil groove which is approximately one half or a third of the 1st tool diameter.

6.4.3 Input Data and Geometrical Definitions for the Generalized APT Programme:

* A typescript of the programme is given in Appendix IV.

The generalized APT programme was written for a 3 AXIS cpc milling machine. The tool lengths are preset, and the tools are changed manually. A special setup tool is used to position the work-piece accurately on the worktable. The length of this set up tool plus an additional length for clearance is the required

* This was written for a Marwin Maximill with a Bendix Control (3 Axis cpc).

value of E0 in the programme. An arbitrary convenient tool change height is estimated at approximately twice the set up tool length and this is the value of TLCH. For the bearing given in Example 1 the set up tool used was 7.5 ins. long, and consequently E0 and TLCH were set equal to 8.0 and 15.5 respectively. The diameters of the other two tools are expressed as CUTD1 and CUTD2 (the 1st and 2nd tool resepctively).

In machining a component, it is often convenient to programme a larger or smaller tool diameter than the nominal size. Consequently CUTDD1 is equated to the 1st tool diameter plus .060 ins., and CUTD1D to 90 percent of the 1st tool diameter. Most industries using preset tooling attempt to standardize the preset lengths wherever possible. The parameters E1 and E2 are the preset lengths of tools 1 and 2 respectively. The preset length is the length from the tool tip to a certain point in the shank of the tool holder, as illustrated in Fig. 6.3. To keep all tool changes at a convenient height (TLCH) and lengths EE1 and EE2 are calculated as follows:

EE1 = TLCH - E1 and EE2 = TLCH - E2

(cf. the programmed dimensions in APT are always with reference to the tool tip, Section 4.5.2.5)

Assuming the bearing of Example 1 is made of aluminum, or any similar free cutting metal, (e.g. brass), a range of feedrates

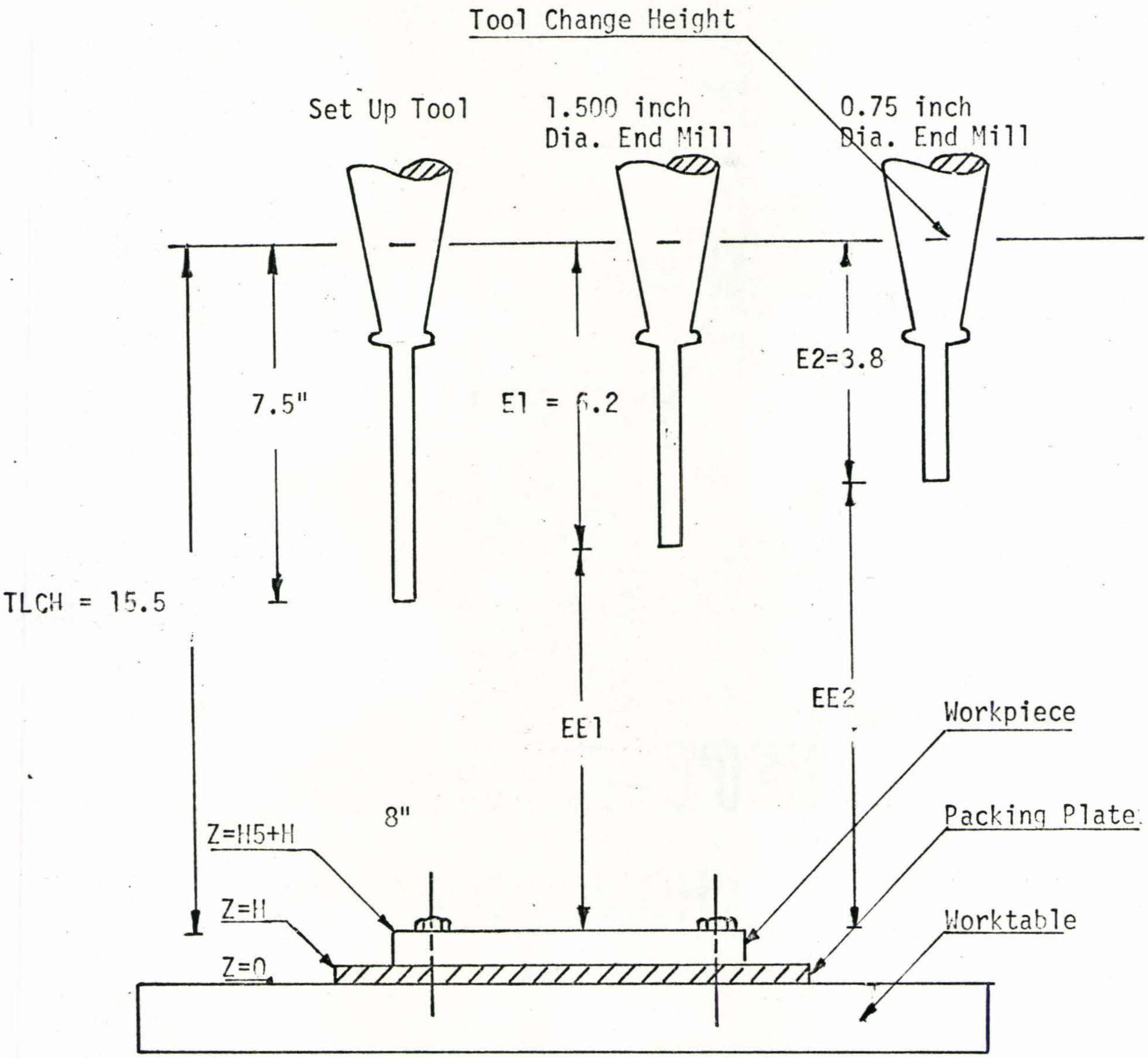


FIG. 6.3

THE TOOLS AND TOOL CHANGING POSITION FOR THE MANUFACTURE OF BEARING #1 from 20 to 35 ipm in increments of 5 ipm and a fast feedrate of 60 ipm are appropriate. Thus FED 1 = 20, FED 2 = 25, FED 3 = 30, FED 4 = 35, FED 5 = 60, are other input parameters to the NC programme.

The parameter REVOL 1 and REVOL 2 and are the number of concentric tool rotations about the inner and outer diameters, respectively, to cut the depth of the bearing. This is explained in greater detail in describing the CIRMAC routine (section 6.4).

The bearing geometry input data; inner radius, R1; outer radius, R2; land width, F; and pocket circumferential length, XPL; are obtained from the optimisation programme, and are rounded off where necessary. Symbols are assigned to several arithmetical calculations which are needed in the rest of the programme.

Most of the geometrical definition statements have been covered in Section 4.5.2.2 and the symbolic names of the lines, circles and planes are shown pictorially in Fig. 6.4. The matrix M1 is defined to raise the plane of the Z co-ordinate axis to coincide with the bottom plane of work piece.

6.4.4 TOOL MOTION STATEMENTS

The sequence of machining operations are as follows:-

(i) The set up tool in the spindle is brought down to the work piece and the accuracy of the set up locations are checked. The 1st tool

(1.500" diameter) is loaded in the spindle at the calculated tool changing height (EEI). The delay statements are necessary to allow for the acceleration and deceleration of the spindle motor.

(ii) The annular ring is face milled in three concentric circles with the workpiece moving counter clockwise, (the standard end mill is a right hand cutter) so that the cutting tool is feed milling. A cutter diameter, ninety percent of the nominal diameter, is programmed to allow some overlap between cuts, and compensates for the end mill edge radius. The tool is instructed to move around; the inner edge of circle C4; right on circle C3 and on the outer edge of the circle C1. This operation is repeated twice, the first time the surface is milled down to within .010 ins. of the defined height H5, and the second time the remaining .010 ins. is removed (see Fig. 6.4.)

(iii) The pocketing routine is programmed for the extreme left pocket in Fig. 6.4 and these instructions are then repeated 5 times, rotating the X and Y co-ordinates through 60° each time. The tool begins in the upper left hand corner, moves down C5, along L4, up C2, along L3, and down C3. The programmed cutter diameter is .060 ins. larger than nominal size, which will leave an additional .030 ins. that will be removed by the finishing cut. Only the cut up C2 is in the same direction as the feed, but is permissable as the tool is cutting metal on both sides of it (i.e. the tool is not climb milling)

(iv) The CIRMAC routine has been developed in private industry*. The routine computes points on a circle or helix, from any starting point, and instructs the cutter to move with a series of GODLTA commands in x,y and z directions. The first statement is:-

CIRMAC = MACRO/RD,DLT = 0,ANGL = 0, TLCON = 1, NO. REV = 1

The arguments:-

RD = Radius of the circle (or helix) minus cutter radius

DLT = Total amount of Z travel (positive up and negative down). The DLT or plunge motion is divided evenly among all X and Y motions (i.e. the Z increment is constant).

ANGL = The angle with respect to the positive X axis the cut should begin (i.e. the angle between the vector 1,0,0 and the vector from the circle centre to the cutter centre).

TLCON = Tool condition. If set equal to 1, TLLFT, or counter clockwise around radius RD, if set equal to -1 TLRGT or clockwise around radius RD.

NO. REV = Number of revolutions to reach plunge depth DLT , it may be any positive integer or decimal.

In calling CIRMAC, RD and DLT , must always be defined, however, if the other arguments are the same as the ones assigned, in the 1st card of the CIRMAC macro they may be omitted.

---

* Used with permission of Douglas Aircraft Canada.

This subroutine allows circular holes and helices to be milled with an end mill without an initial start up hole. It is used to machine the inner and outer diameters of the thrust plate. The former is programmed .25 ins. deeper than the bearing thickness, to attain a good finish, and the latter is programmed to a depth half an inch less than the bearing thickness, so that the work piece remains rigidly attached to its locating bolts and the worktable. The normal cutter diameter is programmed for the inner diameter (i.e. RD = X 3 = R1 -.5 CUTD1) as it is a finishing cut, but a larger cutter diameter (i.e. RD = X 4 = R2 -.5 CUTDD1) is programmed for the outer diameter

(v) A finishing cut slightly higher than the previous cut depth (.002") is then programmed for the outer diameter, using the nominal cutter size. When the tool has completed one full revolution (about the outer diameter), it is then instructed to move a further distance (1.1 x CUTD 1) along a line tangential to the circle, (L5) so that there is a good surface finish at the initial starting point of that cut.

(vi) The spindle is directed to the 2nd tool changing position and the 2nd tool is loaded, a finishing cut is again programmed, for the extreme left pocket, commanding the tool round the boundary of the pocket, using the nominal cutter diameter and this is again 'copied' 5 times, rotating the X-Y co-ordinates through 60° each time.

(vii) The last machining operation is cutting the oil groove between the pockets. The tool is instructed to go counterclockwise around circle C3 at the defined depth of the oil groove (.01 ins. from the upper thrust plate surface).

(viii) Once again the tool is commanded back to the tool change position, then the tape is rewound back to statement N/000, AUTO and the machine is ready to manufacture the next thrust plate.

6.4.5 ADDITIONAL MACHINING

The thrust plate still requires several finishing operations. The machined face probably will not be smooth enough and should be ground or hand finished; as a good NCMT milled surface is only about 60 x 10^{-6} ins. and a surface finish of at least 1/40 of the film thickness is recommended (2). The capillary holes would probably be drilled manually as the bit diameters are of the order of .050 to .100 inches.

Finally, a bandsaw could be used to remove the material remaining on the outer thrust plate diameter (only 1/2 inch thick).

SECTION D

Discussion And Conclusions Of This Study On NCMT

7. DISCUSSION AND CONCLUSIONS

7.1 General:

Over the last several years NCMT which formerly were only found in specialized aerospace industries, have become widely accepted in many types of industrial manufacture. In fact, during this last decade NCMT, which represented less than 4% of the total value of machine tools sold by U.S. manufacturers, increased to over 20% by 1966, and is anticipated to exceed 75% by 1975 [1].

7.2 Section A:

The need for research and development in NCMT design is apparent. At present analytical models have been used successfully for design synthesis of NCMT structures and feed drive systems. [Section A 16,17]. These however, are often limited by unsufficient knowledge of the physical parameters of the system, such as; damping factors; flexibilities of bolted joints, non linearities of hydraulic valves, causes of machine tool chatter and many other troublesome phenomena. The use of self optimising dampers to minimize resonant amplitudes in the machine tool structure is another recently developed technique that warrants further investigation.

Apart from these, the more fundamental problems in metal cutting such as machining hard metals; improving machineability of these alloys; tool wear and tool life prediction; will have to be solved to keep pace with the additional capabilities of the next

[1] Stanford Research Institute - Report on NCMT

generation of NCMT.

7.3 Section B:

In the short history of NCMT a good deal of effort has been spent in devising means of communication between man and machine, however, these are still far from adequate. Many different approaches were attempted, and each has merit in certain applications, however, as yet there is no 'best' system available.

At present many industries, which manufacture relatively simple components, find manual programming satisfactory and the most economical means of part programming. In a recent survey of U.S. manufacturers [Section B,21] 68% of the participating industries replied they were using manual programming techniques and would continue to do so in the forseeable future.

At the present expansion rate of the computer 'population' in North America, it seems obvious that in the future, computer time will become less expensive, and computer availability will increase. In addition, the recent development of time sharing computer terminals, give the smaller industries access to large computing installations. Both these factors together will stimulate an even greater application of computer aided programming languages in various industries.

The advantages of computer aided NC programming are apparent when the part geometry is complex or has high symmetry. Often computer assistance is absolutely necessary for part programming certain complex components. At present there are numerous NC computer languages available, which vary widely in many respects. In spite of the confusion caused by having so many NC computer languages it does not appear feasible to standardize on one particular language. A possible solution is to concentrate on a family of languages with different levels of complexity, which have upward compatibility with each other. The AUTOSPOT-ADAPT-APT family has relative upward compatibility however, further research should be directed towards this objective.

Several research laboratories are attempting to combine computerized design using a cathoderay tube and light pen, on line to a GP computer as input/output media. They have made some progress, but this system will not be suitable for industrial applications for several years.

7.4 Section C:

Current industrial trends show increasing computer utilization in design. Numerous computer optimisation techniques are easily adapted to mechanical component design. The example of the optimisation programme and the generalized NC programme given in this section shows, that the concept of integrated manufacture is feasible, and it appears to be economically attractive for manufacture of certain component types. The generalized NC programme was written in APT and this programme also demonstrates a deficiency of the APT language. APT does not have the facility, to calculate the technical cutting parameters, nor to select the necessary cutting tools, that is availabe in EXAPT. Writing a generalized NC programme in EXAPT would generally make this system of integrated manufacture even more practicable, as the engineer would not have to select the cutting tool, nor calculate the cutting parameters.

The most recent major inovation in NCMT design is adaptive control. The machine tool has closed loop feedback control that optimise the cutting parameters with respect to cost or production rate. Consequently, in an 'integrated manufacturing' cycle,the designer would then only have to specify the cutting tools for the machining operation, and the M.T. control would operate at the 'optimum' feed and speed to satisfy the surface finish requirements.

APPENDIX I

A LIST OF VARIOUS NUMERICAL CONTROL COMPUTER LANGUAGES

1. POINT TO POINT COMPUTER AIDED NUMERICAL CONTROL LANGUAGES

Processor	No. Controlled Axes	Computer	Postprocessors	Remarks
Autoprops	2 axis ptp	IBM 1401	None	Pratt & Whitney
Autospot I & & III	3 axis ptp limited 4th axis	IBM 1620	Many available	
Autospot 360	3 axis ptp	IBM 360/30 (32K)	Many available	
Camp I	3 axis ptp	LGP-30	Limited	Developed by Westinghouse
Camp II	2-5 axis ptp	IBM 7094,7090	Many available	
Camp III	2-5 axis ptp	Fortran IV compiler	Many available	
Pronto	3 axis ptp	IBM 704, IBM 7090 G.E. 225	Many available	Developed by General Electric
Snap	2 axis ptp	IBM 1401		Brown & Sharp
Snap II	2 axis ptp	IBM 360/30		
Quickpoint	3 axis ptp	DDP Sigma 8	Several available	Digital equipment
Exapt I	3 axis ptp		Several available	c/o N.E.L. in England

2. CONTINUOUS PATH COMPUTER AIDED NUMERICAL CONTROL LANGUAGES

Processor	No. Controlled Axes	Computers	Postprocessors	Remarks
Action I & II	2 axis cpp	IBM 1620, IBM 360/40		
Adapt	2 axis cpp 3 axis ptp	GE, 200,400,600 GE-PAC 4800	Many available	U.S.A.F. Contract
Adapt (time sharing)	2 axis cpp 3 axis ptp	GE - 600		
Adapt 360	2 axis cpp 3 axis ptp	IBM 360/30 (64K)	Many available	
Adapt/Autospot	2 axis cpp 3 axis ptp	IBM 360/30 (64K)	Many available	
Adapt - RX	2 axis cpp 3 axis ptp	SDS 900 Honeywell 200		By L. R. Reeves
APT III	5 axis cpp	IBM 7090 Univac 1107/8 CDC 3600/6600 G.E. 600 Philco 2000	Many available	Administered by IITRI for APT long range programme
APT 360	5 axis cpp	IBM 360/40 (256K)	Many available	IBM APT
APT-RX	5 axis cpp	Univac 1107/8	Many available	By L.R. Reeves
APT IV	5 axis cpp	IBM 360,RCA Spectra 70 ICT 1900 Eng.Elec Syst.4 Fujitsu Facom 230	Not yet available	IITRI
Automap	2 axis cpp 3 axis ptp	IBM 1620	Some available	IBM
Autoprompt	5 axis cpp	IBM 7090	Many available	IBM

3. CONTINUOUS PATH COMPUTER AIDED NUMERICAL CONTROL LANGUAGES (CONT'D)

Processor	No. Controlled Axes	Computers	Postprocessors	Remarks
Compact	3 axis cpp	SDS 940	Few available	Time sharing
Exapt II	3 axis cpp (turning)		Not yet released to public	
Exapt III	2 axis cpp (milling) 3 axis ptp			
Remapt II	2 axis cpp 3 axis ptp	G.E. 600 series	Many available ecent	Time sharing
Split	5 axis cpp	IBM 7090, 1620 IBM 360/30 (64K) IBM 650 (limited)	No postprocessor	For use with sunstrand machines only
2CL	2 axis cpp 3 axis ptp	Univac 1108 I.C.T. 1900 series Elliott 4100 series English Electric KDF9	Many available	Developed by N.E.L.

APPENDIX II

The Optimisation Programme

```
C       LIST OF SYMBOLS USED FOR HYDROSTATIC BEARING OPTIMISATION
C
C       AF              LOAD COEFFICIENT
C       AP              PAD AREA
C       AR              RECESS AREA
C       BAR             RECESS TO PAD AREA RATIO
C       BB              RECESS LENGTH IN RADIAL DIRECTION
C       CD              CAPILLARY DIAMETER
C       CK              CAPILLARY COEFFICIENT
C       CL              CAPILLARY LENGTH
C       DENSTY          OIL DENSITY
C       EFF             PUMP MOTOR EFFICIENCY
C       F               LAND WIDTH IN RADIAL DIRECTION
C       FT              FILM THICKNESS
C       H               BEARING THICKNESS
C       HPF             FRICTION HORSE POWER LOSS
C       HPP             PUMP HORSE POWER LOSS
C       NOP             PART NUMBER
C       PL              RECESS LENGTH ALONG MEAN CIRCUMFRENCE
C       PS              SUPPLY PRESSURE
C       PR              RECESS PRESSURE
C       QF              FLOW COEFFICIENT
C       Q               TOTAL FLOW
C       REY             REYNOLDS NUMBER FOR CAPILLARY FLOW
C       RPM             SHAFT SPEED
C       R1              INNER RADIUS
C       R2              OUTER RADIUS
C       R3              MEAN RADIUS
C       T               NUMBER OF CAPILLARY TUBES PER RECESS
C       VS              OIL VISCOSITY
C       WW              AXIAL LOAD
C       X               PAD LENGTH IN RADIAL DIRECTION
C       Y               PAD LENGTH ALONG MEAN CIRCUMFRENCE
C
C
C       II              OBJECTIVE FUNCTION INDEX
C
C       II = 0          OBJECTIVE FUNCTION U =HPP+HPF
C       II = 1          OBJECTIVE FUNCTION U =HPF
C
C       LIST OF SYMBOLS USED FOR DICKINSONS RANDOM STRATEGY
C
C
C       A(I)            LOWER LIMITS OF RANDOM VARIABLES
C       B(I)            UPPER LIMITS OF RANDOM VARIABLES
C       FRANDN(R,N,M)LIBRARY FUNCTION RANDOM NUMBER GENERATOR
C       N               NUMBER OF RANDOM VARIABLES
C       NCYCLE          COUNTER FOR NUMBER OF CYCLES
C       NMAX            MAXIMUM NUMBER OF CYCLES FOR CONVERGENCE
C       NRET            NUMBER OF BEST SOLUTIONS RETAINED EACH CYCLE
C       NUMR            NUMBER OF RANDOM SOLUTIONS EVALUATED EACH CYCLE
C       R(I)            RANDOM NUMBER
C       S               PERCENTAGE RANGE CONVERGENCE DEFINING TEST(I)
C       TEST(I)         DISIRED MINIMUM RANGE DEFINING FINAL OPTIMUM SOLUTION
C       U               VALUE OF THE OBJECTIVE FUNCTION
C       UTEMP           TEMPORARY VARIABLE FOR SORTING
C       UXTRA           VALUE OF U FOR NUMR MORE SOLUTIONS
C       W(I,J)          NORMALISED RANDOM VARIABLE
C       XTEMP           TEMPORARY VARIABLE FOR SORTING
```

```
C     DICKENSONS RANDOM STRATEGY TO OPTMISE A HYDROSTATIC THRUST BEARIN
C
      DIMENSION TEST(9),XTEMP(9),X(26,9)
      DIMENSION R(9),W(26,9),A(9),B(9)
      DIMENSION HPF(26),HPP(26),U(26)
      READ(5,1)WW,RPM,R1,H,DENSTY,T,EFF
      READ(5,2)(A(I),B(I),I=1,6)
      READ(5,7)N,NMAX,NUMR,NRET,II,NOP,S
      A(7)=.05
      B(7)=(H-.5)/20.
      M=159
      K=0
C     GENERATE VALUES FOR TEST(I)
      DO 22 I=1,N
      TEST(I)=S*(B(I)-A(I))
 22   CONTINUE
      NCYCLE =1
      WRITE(6,8) N,NMAX,NUMR,NRET,II
      WRITE(6,3)NCYCLE,(A(I),I=1,N),(B(I),I=1,N)
C     CALCULATING NRET FEASIBLE SOLUTIONS
      J=1
 99         CALL RANOS(K,N,M,W,A,B,R1,R2,R3,Y,BB,PL,B1R,WW,
     1                PR,PS,VS,FT,Q,CD,DENSTY,F,J,H,T,CL)
            CALL OBJFN (R1,F,R2,HPF,VS,RPM,FT,Y,PL,
     1                 R3,HPP,PS,Q,EFF,U,II,J)
      DO 102 I=1,N
 102  X(J,I)=W(J,I)
      J=J+1
      IF(J.LE.NRET)GO TO 99
C     PUT LARGEST U(J) AT U(1)
      DO 10 J=2,NRET
      IF(U(J).LE.U(1))GO TO 10
      UTEMP=U(J)
      U(J)=U(1)
      U(1)=UTEMP
C     IDENTIFY X(J,I) WITH NEW U(1)
      DO11 I=1,N
      XTEMP(I)=X(J,I)
      X(J,I)=X(1,I)
 11   X(1,I)=XTEMP(I)
 10   CONTINUE
      WRITE(6,105)U(1)
C     GENERATE NUMR MORE POINTS. IF ANY POINT HAS U(J).LT. U(1)
C     REPLACE U(1) BY U(J).  W(16,I) IS A TEMPOARY LOCATION
 59   K=0
 60   J=NRET+1
            CALL RANOS(K,N,M,W,A,B,R1,R2,R3,Y,BB,PL,B1R,WW,
     1                PR,PS,VS,FT,Q,CD,DENSTY,F,J,H,T,CL)
      K=K+1
            CALL OBJFN (R1,F,R2,HPF,VS,RPM,FT,Y,PL,
     1                 R3,HPP,PS,Q,EFF,U,II,J)
      JJ=J
      IF(U(JJ).GE.U(1)) GO TO 60
      U(1)=U(JJ)
      DO 14 I=1,N
 14   X(1,I)=W(JJ,I)
C     PUT NEW LARGEST U(J) AT U(1)
      DO 30 J=2,NRET
      IF(U(J).LE.U(1))GO TO 30
```

```
      UTEMP=U(J)
      U(J)=U(1)
      U(1)=UTEMP
      DO31 I=1,N
      XTEMP(I)=X(J,I)
      X(J,I)=X(1,I)
 31   X(1,I)=XTEMP(I)
 30   CONTINUE
      IF (K.LE.NUMR) GO TO 60
C     SELECT NEW A(I) AND B(I)
 111  WRITE(6,105)U(1)
 110  DO 15 I=1,N
      A(I)=X(1,I)
      B(I)=X(1,I)
      DO 16 J=2,NRET
      IF(X(J,I).GT.A(I)) GO TO 17
      A(I)=X(J,I)
      GO TO 16
 17   IF(X(J,I).LT.B(I)) GO TO 16
      B(I)=X(J,I)
 16   CONTINUE
 15   CONTINUE
C     TESTING NEW LIMIT POINTS FOR OPTIMUM SOLUTION
      DO 18 I=1,N
      IF(B(I)-A(I).GT.TEST(I)) GO TO 62
 18   CONTINUE
      GO TO 61
 62   NCYCLE=NCYCLE+1
      WRITE(6,3)NCYCLE,(A(I),I=1,N),(B(I),I=1,N)
      IF(NCYCLE.EQ.NMAX) GO TO 100
      GO TO 59
C     SELECT SMALLEST U(J)
 61   UXTRA=U(1)
      DO 19 J=2,NRET
      IF(U(J).GT.UXTRA) GO TO 19
      UXTRA=U(J)
        DO 51 I=1,N
      XTEMP(I)=X(J,I)
      W(2,I)=XTEMP(I)
 51   CONTINUE
 19   CONTINUE
      K=1
      J=2
            CALL RANOS(K,N,M,W,A,B,R1,R2,R3,Y,BB,PL,B1R,WW,
     1                 PR,PS,VS,FT,Q,CD,DENSTY,F,J,H,T,CL)
            CALL OBJFN (R1,F,R2,HPF,VS,RPM,FT,Y,PL,
     1                  R3,HPP,PS,Q,EFF,U,II,J)
      WRITE(6,4)
      WRITE(6,3)NCYCLE,(A(I),I=1,N),(B(I),I=1,N)
      WRITE(6,5)UXTRA
      WRITE(6,138)
      WRITE(6,106)NOP
      WRITE(6,107)WW,RPM,VS,PS,Q,U(2),HPF(2)
      WRITE(6,150)FT,R1,R2,BB,PL,H,CL,CD,T
      STOP
 100  WRITE(6,6)NMAX
      STOP
 1    FORMAT(7F10.5)
```

```
 2     FORMAT(2F10.5)
 3     FORMAT(1X,15HNO. OF CYCLES= ,I3,/,1X,12HLOWER LIMITS,7(4X,F13.9),/
      1,1X,12HUPPER LIMITS,7(4X,F13.9),//)
 4     FORMAT(//,1X,17HPROCESS CONVERGED,//)
 5     FORMAT(10X,23HMINIMUM HORSEPOWER LOSS,7X,F12.6)
 6     FORMAT(1X,33HPROCESS FAILED TO CONVERGE AFTER ,I3,2X,6HCYCLES)
 7     FORMAT(6I5,F5.0)
 8     FORMAT(10X,5I10,//)
 104   FORMAT(4(5X,F12.5)//)
 105   FORMAT(10X,24HSMALLEST HORSEPOWER LOSS,6X,F12.5,///, )
 106   FORMAT(///,10X,8HEXAMPLE ,I1,1X,42HOF AN OPTIMISED HYDROSTATIC THR
      1UST BEARING,//)
 107   FORMAT(//,25X,34HHYDROSTATIC BEARING SPECIFICATIONS,////,10X,
      14HLOAD,26X,F12.0,//,10X,5HSPEED,25X,F12.0,//,10X,9HVISCOSITY,21X,
      2  F12.8,//,10X,15HSUPPLY PRESSURE,15X,F12.2,//10X,8HOIL FLOW,22X,
      3 F12.4,//,10X,10HPOWER LOSS,20X,F12.5,//,10X,13HFRICTION LOSS,
      4   17X,F12.3,//)
 138   FORMAT(1H1)
 150   FORMAT(//,25X,22HGEOMETRICAL DIMENSIONS,////,10X,14HFILM THICKNESS
      1 ,16X,F12.5,//,10X,12HINNER RADIUS,18X,F12.3,//,10X,
      2 12HOUTER RADIUS,18X,F12.3,//,10X,20HRADIAL POCKET LENGTH,
      3 10X,F12.3,//,10X,31HPOCKET LENGTH ALONG MEAN RADIUS,F11.3,//,
      4  10X,17HBEARING THICKNESS,13X,F12.3,//,10X,16HCAPILLARY LENGTH,
      5  14X,F12.3,//,10X,18HCAPILLARY DIAMETER,12X,F12.4,//,
      6  10X,25HNO CAPILLARIES PER POCKET,5X,F12.0,//)
       END
$IBFTC  RANOS
       SUBROUTINE RANOS(K,N,M,W,A,B,R1,R2,R3,Y,BB,PL,BAR,WW,
      1                PR,PS,VS,FT,Q,CD,DENSTY,F,J,H,T,CL)
C
C      SELECTION AND SUBSTITUTION OF RANDOM VARIABLES IN DESIGN EQUATIONS
C
       DIMENSION R(9),W(26,9),A(9),B(9)
       IF(K.EQ.1)GO TO 11
C      RANDOM NUMBER LIBRARY FUNCTION
 9     CALLFRANDN(R,N,M)
       M=0
       DO 10 I=1,N
 10    W(J,I)=A(I)+R(I)*(B(I)-A(I))
 11    R2=W(J,1)*R1
       R3=.5*(R2+R1)
       X=R2-R1
       Y=3.142*R3/3.
       AP=X*Y
       AB=6.*AP
       PL=W(J,2)*R3
       BB=W(J,3)*X
       F=.5*(X-BB)
       AR=BB*PL
       BAR=AR/AP
       IF(BAR.GT..75) GO TO 9
       IF(BAR.LT..25) GO TO 9
       AF=(1.+BAR+SQRT(BAR))/3.
       QF=((X+BB)/(Y-PL)+(Y+PL)/(X-BB))/AF
       PR=WW/(AB*AF)
       VS=W(J,4)
       PS=PR/W(J,5)
       CD=W(J,7)
```

```
      CL=20.*CD+W(J,6)*(H-.5-20.*CD)
      CK=3.142*(CD)**4/(128.*CL)
      FT=(6.*T*CK/(QF*AF)*(PS-PR)/PR)**.33
      IF(FT.GT..01) GO TO 9
      IF(FT.LT..001) GO TO 9
      Q=QF*WW*FT**3/(AB*VS)
      REY=4.*DENSTY*Q/(6.*T*3.142*VS*386.*CD)
C     CHECK THAT CAPILLARY FLOW IS LAMINAR
      IF(REY.GT.2000.) GO TO 9
      RETURN
      END
$IBFTC  OBJFN
      SUBROUTINE OBJFN (R1,F,R2,HPF,VS,RPM,FT,Y,PL,
     1                  R3,HPP,PS,Q,EFF,U,II,J)
C
C     OBJECTIVE FUNCTION
C
      DIMENSION HPF(26),HPP(26),U(26)
      RR=(R1+F)**4
      RRR=(R2-F)**4
      HPF(J)=(VS*RPM**2*1.E-6)/FT*(2.61*(RR-R1**4+R2**4-RRR)
     1 +3.32*(Y-PL)*((R2-F)**3-(R1+F)**3))
      HPP(J)=(PS*Q/3.85)/(1715.*EFF)
      U(J)=HPF(J)
      IF(II.EQ.1) GO TO 10
      U(J)=U(J)+HPP(J)
 10   RETURN
      END
'        6400 END RECORD
 70000.   3600.     6.5       4.0       .03       1.0       .80
  1.25       3.0
  .25          1.0
 .50          .999
 .000001      .0000035
 0.1          0.9
 0.00         1.0
    7   25  100   10     0    1   .05
'        6400 END FILE
```

APPENDIX III

Analysis Of A Capillary Compensated Hydrostatic Thrust Bearing

NOMENCLATURE

af	Load Coefficient
AB	Total Bearing Area
AP	Pad Area
AR	Recess Area
AS	Sill Area
b	Width of Flow
BAR	Bearing Area Ratio AR/AP
BB	Pocket Length in Radial Direction
CD	Capillary Tube Diameter
CL	Capillary Tube Length
CQ	Capillary Tube Flow
DENSTY	Lubricating Fluid Density
EFF	Pump and Motor Efficiency
F	Land Width in Radial Direction 1/2 (X - PL)
F_s	Viscous Friction Force
h	Film Thickness
HPF	Horsepower Friction Losses
HPP	Horsepower Pump Losses
i	No.of Recesses
kc	Capillary Tube Coefficient
e	Length of Flow
N	Bearing Speed
P	Pressure Ratio PR/PS
PL	Pocket Length Along Mean Circumference
PR	Recess Pressure
PS	Supply Pressure
gf	Flow Coefficient
Q	Total Flow
Re	Reynolds Number
R1	Inner Radius of Bearing Thrust Plate

R2	Outer Radius of Bearing Thrust Plate
R3	Mean Radius of Bearing Thrust Plate
T	Number of Capillary Tubes per Recess
V	Bearing Tangential Velocity at Radius from Centre
WW	Axial Load
X	Pad Length in Radial Direction (R2-R1)
Y	Pad length Along Mean Circumference ($\frac{2\pi}{i}$ R3)
δ	Depth of Recess
μ	Lubricating Fluid Viscosity (reyn i.e. slug/ins.sec.)

APPENDIX III

ANALYSIS OF A MULTIRECESS HYDROSTATIC THRUST BEARING FOR INCOMPRESSIBLE FLOW AND WITH CAPILLARY TUBE COMPENSATION

1. The Load Coefficient af

By definition let $WW = af \times AB \times PR$ (1)

Now assuming a pressure distribution over each recess is a frustrum pyramid as shown in Fig. 1 (viz. a linear pressure drop across the land widths)

From the geometry: AP and AR are the frustrum pyramid areas (Base and Upper Respectively) thus for one recess:

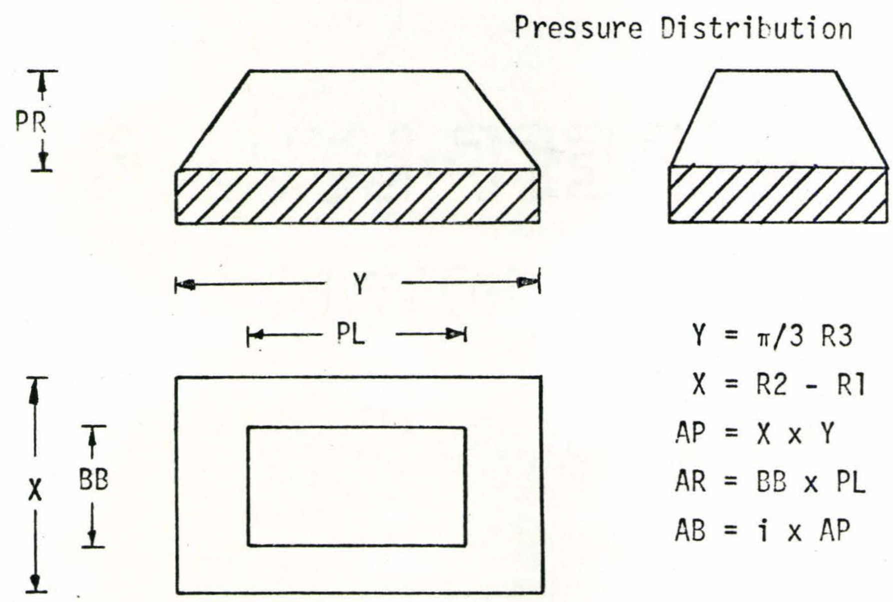
$$WW/i = 1/3\ (AP + AR + \sqrt{AR \times AP}) \times PR$$

The Bearing Area Ratio, $Bar = AR/AP$

Therefore $WW/i = 1/3AP\ (1 + BAR + \sqrt{BAR})\ PR$

Now $AB = i \times AP$

Each Recess is Approximated by a Rectangular Pad of Equal Area



$Y = \pi/3\ R3$

$X = R2 - R1$

$AP = X \times Y$

$AR = BB \times PL$

$AB = i \times AP$

FIG. 1

A Linear Pressure Drop Across The Land Widths and The Corners is Assumed. i.e. Pressure Distribution is a Frustrum Pyramid

$$WW = i \times AP \times PR \times 1/3(1 + BAR + \sqrt{BAR}) = af \times AB \times PR$$

Therefore $af = 1/3\ (1 + BAR + \sqrt{BAR})$ (2)

2. Flow Coefficient qf

By definition let $Qf \times (\frac{WW}{AB}) \times \frac{h^3}{\mu}$ (3)

Incompressible flow through a narrow slot is given as

$$Q = \frac{\Delta P \times b \times h^3}{12 \times \mu \times \ell}$$

Approximating each recess by a rectangular one of equal area

$$Q = i \times \frac{PR \times h^3}{12 \times \mu} \left(\frac{X + BB}{\frac{1}{2}(Y - PL)} + \frac{Y + PL}{\frac{1}{2}(X - B)}\right)$$

Substituting equation (1) and equating to equation (3)

$$Q = (\frac{WW}{AB}) \times \frac{h^3}{\mu} \times (\frac{X+BB}{Y-PL} + \frac{Y+PL}{X-BB})/af = (\frac{WW}{AB}) \times \frac{h^3}{\mu} \times qf$$

Hence $qf = \frac{i}{6} (\frac{X+BB}{Y-PL} + \frac{Y+PL}{X-BB})/af$ (4)

3. Flow Through a Capillary Tube

Laminar flow of viscous in compressible fluid through a capillary tube (with length > 20 x diameter) is given by:

$$Q_c = \frac{\pi \times (CD)^4 \times (PS-PR)}{128 \times \mu \times CL}$$

Let the capillary coefficient $kc = \frac{\pi \times (CD)^4}{128 \times CL}$ (5)

Then $Q_c = kc \times \frac{PS-PR}{\mu}$ (6)

However to ensure the flow is laminar

$$Re = \frac{4 \times DENSTY \times Qc}{\pi \times CD \times \mu} < 2000 \qquad (7)$$

Note the units of DENSTY are $lbs.sec^2/in^4$

4. Equating flow through the bearings and total flow through the capillary tubes equations (3) and (6) x i.

$$(qf \times (\frac{WW}{AB}) \times \frac{h^3}{\mu}) = Txixkc\ \frac{PS-PR}{\mu}$$

$$h = (\frac{Txixkc}{qfxaf} \times \frac{PS-PR}{PR})^{1/3} \qquad (8)$$

5. Bearing Stiffness: $\frac{\partial WW}{\partial W}$

In most applications of thrust bearings it is desirable to design the bearing for maximum axial stiffness. The bearing stiffness is dependent on the film thickness and the pressure ratio between the recess and the supply.

Rewriting equation (8) and substituting equation (1)

$$h^3 = [\frac{Txixkc \times PS}{qfxaf} \times \frac{afAB}{WW} - \frac{ixkc}{qfxaf}]$$

Thus $WW = \frac{TxixkcxPSxABxaf}{h^3xqfxaf + ixkc}$

for a given bearing h is the only variable quantity and bearing stiffness is given by

$$\frac{\partial(WW)}{\partial h}$$

Hence differentiating, multiplying by h/h and substituting for h^3 from equation (8) the stiffness becomes:-

$$\frac{\partial(WW)}{\partial h} = \frac{-3 \times WW \times (1 - PR/PS)}{h}$$

The negative sign shows the stiffness decreases as h increases and may be neglected

Now maximum stiffenss when $\frac{\partial^2 (WW)}{\partial h^2} = 0$

However $$\frac{\partial (WW)}{\partial h} = \frac{3 \times WW \times (1 - PR/PS)}{\left(\frac{T x i_x kc}{qf\bar{x}af} \quad \frac{PS - PR}{PR}\right)^{1/3}}$$

For a constant stiffness and since for a given bearing only PR is a variable quantity defining P = PR/PS

Then $\frac{\partial (WW)}{h}$ is a maximum when $\frac{\partial (P^{4/3} \ (1-P)^{2/3})}{\partial P} = 0$

$$\text{i.e. } P = 2/3 \qquad (9)$$

6. Friction Horsepower Loss

$$F_s = \mu \times AS \times \frac{V}{h} + \mu AR \ \frac{V}{h+\delta}$$

Since δ is usually 50 to 100 times the size of h, the second term is neglected.

Friction Power Loss (HPF) = Fs x V

The velocity at any radius r: $= \frac{2\pi Nr}{60}$

Hence

$$HPF = \frac{\mu}{h} \left(\frac{2\pi N}{60}\right)^2 \frac{2\pi}{6600} \left[\int_{R1}^{R1+F} r^3 \, dr + \int_{R_{2-F}}^{R_2} r^3 \, dr\right]$$

$$+ \frac{\mu}{h} \left(\frac{2\pi N}{60}\right)^2 \frac{i}{6600} \times \frac{(Y-L)}{1} \int_{R1+F}^{R2-F} r^2 \, dr$$

$$HPF = 2.61 \times 10^{-6} \times \frac{\mu x N^2}{h} \times \left((R1+F)^4 - R1^4 + R2^4 - (R2-F)^4\right)$$

$$+ .554 \times 10^{-6} \times \frac{i \times \mu N^2}{h} \times \left(\frac{Y-L}{1}\right) \left((R2-F)^3 - (R1+F)^3\right) \qquad (10)$$

7. Pump Horsepower Loss

$$HPP = \frac{PS \times Q/3.85}{1715. \times EFF.} \quad (11)$$

APPENDIX IV

The Generalized APT Programme

```
PARTNO-HYDROSTATIC BEARING
$$ INSERT STANDARD SYN DECK
SYN/AA,ATANGL,CA,CANON,CT,CENTER,C,CIRCLE,CY,CYLNDR,D,DELAY,FR,
SYN/FEDRAT,GB,GOBACK,GD,GODLTA,GF,GOFWD,GL,GOLFT,GR,GORGT,GT,
SYN/GOTO,IP,INDIRP,IV,INDIRV,I,INTOF,LG,LARGE,LC,LCONIC,L,
SYN/LINE,MX,MATRIX,NM,NOMORE,O,OBTAIN,PA,PARLEL,PE,PERPTO
SYN/PL,PLANE,P,POINT,PR,PRINT,R,RADIUS,SM,SMALL,S,STOP,T,TANTO
SYN/TH,THICK,TA,TLAXIS,N,TMARK,TR,TRACUT,V,VECTOR,XL,XLARGE,XS,
SYN/XSMALL,YL,YLARGE,YS,YSMALL,ZL,ZLARGE,ZS,ZSMALL
MACHIN/BENDAC,31501
CLPRNT/OPTION
$ $ $ INPUT TO APT PROGRAM FOR A HYDROSTATIC BEARING
$ $ $ TOOL SPECIFICATIONS AND CUTTING FEEDS
CUTD1 =1.500                    $$    1ST TOOL DIAM
CUTD2 =0.75                     $$    2ND TOOL DIAM
TLCH  =15.5                     $$    ARBITRARY TOOL CHANGE HEIGHT
E0    =8.                       $$    SET UP TOOL HEIGHT + .5 INS
E1    =6.2                      $$    PRESET LENGTH OF 1ST TOOL
E2    =3.8                      $$    PRESET LENGTH OF 2ND TOOL
FED1  =20.                      $$    FEEDRATE
FED2  =25.                      $$    FEEDRATE
FED3  =30.                      $$    FEEDRATE
FED4  =35.                      $$    FEEDRATE
FED5  =60.                      $$    FEEDRATE
REVOL1=6.                       $$    PARAMETER FOR CIRMAC ROUTINE
REVOL2=REVOL-1.                 $$    PARAMETER FOR CIRMAC ROUTINE
CUTDD1=CUTD1+.060               $$    1ST TOOL DIAM +.060
CUTD1D=.90*CUTD1                $$    .9* DIAM 1ST TOOL
EE1   =TLCH-E1
EE2   =TLCH-E2
$ $ $ GEOMETRICAL DIMENSIONS SEE MASTER DRAWING
H     =1.                       $$    HEIGHT OF PACKING PLATE
H5    =4.                       $$    HEIGHT OF BEARING
R1    =6.5                      $$    INNER RADIUS
R2    =9.875                    $$    OUTER RADIUS
XPL   =7.7                      $$    POCKET LENGTH ALONG R3
BB    =2.83                     $$    POCKET RADIAL LENGTH
F     =.5(R2-R1-BB)             $$    LAND WIDTH
R3    =.5*(R1+R2)               $$    MEAN RADIUS
A1    =XPL*180./(R3*3.142*2.)$$       POCKET ANGLE
H6    =H5/REVOL                 $$    HEIGHT OF PLANE 6
H3    =H5-.25                   $$    DEPTH OF POCKET = .25
H4    =H5-.09                   $$    DEPTH OF OIL GROOVE=.09
RP2   =R2-F                     $$    OUTER POCKET RADIUS
RP1   =R1+F                     $$    INNER POCKET RADIUS
$ $ $ ADDITIONAL CALCULATIONS FOR THE PROGRAM
X1    =(R2-.55*CUTD1)
X2    =(RP2-.55*CUTD1)
X3    =(R1-.5*CUTD1)
X4    =(R2+.5*CUTD1)
X5    =1.1*CUTD1
Z1    =H5+H
Z2    =H5-.5
Z3    =H5+.25
Z4    =H5+.1
$ $ $ APT GEOMETRICAL DEFINITIONS
SETPT =P/0,0,0
P1    =P/0,0,0
L1    =L/0,0,0,1,0,0
```

```
L2      =L/P1,PE,L1
L3      =L/P1,AA,-A1,L1
L4      =L/P1,AA, A1,L1
L5      =L/PA,L2,XL,R2
PL1     =PL/0,0,1,0
PL2     =PL/PA,PL1,ZL,.50
PL3     =PL/PA,PL1,ZL,H3
PL4     =PL/PA,PL1,ZL,H4
PL5     =PL/PA,PL1,ZL,H5
PL6     =PL/PA,PL5,ZS,H6
PL7     =PL/PA,PL2,ZL,.002
PL8     =PL/PA,PL3,ZL,.002
PL9     =PL/PA,PL5,ZL,.01
C1      =C/CT,P1,R,R1
C2      =C/CT,P1,R,RP1
C3      =C/CT,P1,R,R3
C4      =C/CT,P1,R,R2
C5      =C/CT,P1,R,RP2
P2      =P/XS,I,(L/PA,L3,YS,CUTDD1),(C/CT,P1,R,X2),Z4
TC0     =P/0,0,E0
TC1     =P/0,0,EE1
TC2     =P/0,0,EE2
M1      =MXTRANSL,0,0,-H
N/000,AUTO
N/000
STOP
D/2.5
FROM/SETPT,60
GD/E0
GT/TC0
TOOLNO/0001,E1
D/1.0
N/01
STOP
D/2.5
FROM/TC1
TR/M1
CUTTER/CUTD1D
GT/-X1,0,EE1
FR/FED4
INDEX/1
GT/-X1,0,Z3
GO/TO,C4,PL9,ON,L1
TLLFT,GL/C4,ON,2,I,L1
TLON,GL/ON,L1,ON,C3
GR/ON,C3,ON,2,I,L1
GL/ON,L1,TO,C1
TLRGT,GR/TO,C1,ON,2,I,L1
GD/Z3,FED5
FD/FED2
COPY/1,TRANSL,0,0,-.01,1
CUTTER/CUTDD1
INDEX/2
GT/P2,FED5
FD/FED3
GO/L3,PL3,C5
IV/0,-1,0
```

```
TLLFT,GF/C5,TO,L4
GL/L4,TO,C2
GL/C2,TO,L3
GL/L3,ON,C3
TLON,GL/ON,C3,TO,L4
GD/.5,FED5
COPY/2,XYROT,60,5
CUTTER/CUTD1
GT,X3,0,Z4
$$ INSERT CIRMAC DECK
CIRMAC=MACRO/RD,DLT=0,ANGL=0,TLCON=1,NO.REV=1
COSALP=(RD-.004)/RD       $$ .004=CROWN TOLERANCE
ALPHA=(ABSF(ALPH=2*TLCON*(ATANF((SQRTF(1-COSALP**2))/COSALP))))
DUMMYP=POINT/CANON,(THA=ANGL),(J=1),(NO.CUT=360*NO.REV/ALPHA)
CIRM01)THA=THA+ALPH
GODLTA/(RD*(COSF(THA)-(COSF(THA-ALPH)))),(RD*(SINF(THA)          $
       -(SINF(THA-ALPH)))),(DLT/NO.CUT)
IF((J=J+1)-NO.CUT)CIRM01,CIRM02,CIRM02
CIRM02)GODLTA/(RD*(COSF(ANGL+ALPH*NO.CUT)-(COSF(THA)))),          $
        (RD*(SINF(ANGL+ALPH*NO.CUT)-(SINF(THA)))),(DLT*           $
        (NO.CUT-(J-1)/NO.CUT)
PHE=ANGL+ALPH*NO.CUT
PRINT/2,(LINE/CANON,NO.CUT,ALPH,THA,PHE)
TERMAC
FR/FED3
CALL/CIRMAC,RD=X3,DLT=-Z3,NO.REV=REVOL1
GD/Z1,FED5
GT/X4,0,Z4
FR/FED3
CALL/CIRMAC,RD=X4,DLT=-Z2,NO.REV=REVOL2
GD/.80,0,.002,FED5
CUTTER/CUTD1
FR/FED3
GO/C4,PL7,ON,L1
TLRGT,GR/C4,ON,2,I,L1
GO/TO,L5,PL7,ON,L1
TLRGT,GF/L5,TO,(L/PA,L1,YL,X5)
GD/H5,FED5
GT/TC1
TOOLNO/0002,E2
D/1.0
N/02
STOP
D/2.5
END        $$ TOOL CHG TO .75 DIA END MILL F=3.8
FROM/TC2,100
TR/M1
CUTTER/CUTD2
GT/-R3,-1.0,EE2
INDEX/3
GT/-R3,-1.0,Z4
FR/FED1
GO/C5,PL8,L1
TLLFT,GL/C5,TO,L4
GL/L4,TO,C2
GL/C2,TO,L3
GL/L3,TO,C5
GL/C5,TO,L4
```

```
GD/.498,60
COPY/3,XYROT,60,5
GT/-R3,0,H5
FR/FED2
GO/ON,C3,PL4,ON,L1
IV/0,-1,0
TLON,GF/C3,PAST,2,I,L1          $$ MILL .75 GROOVE
GD/.5,60
TR/NM
GT/TC2
STOP
D/2.5
END

                                   CD TOT   0186
```

APPENDIX V

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