ADAPTIVE CONTROL FOR MACHINE TOOLS

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ABSTRACT

Adaptive Control (AC) of machine tools is a recent development in production engineering which aims at performing the cutting operation more efficiently. Uusally feeds and/or speeds are adaptively controlled in accordance with the data obtained by sensing process parameters such as tool tip temperature, cutting force, spindle torque, vibration, etc. By virtue of its ability to economize metal tutting process, AC can be expected to play a vital role in machine tool industry. AC systems applied to machining processes such as turning, milling, grinding are discussed in this report. The principle, types and advantages of AC systems are also described.

Keywords: Adaptive control, Machine Tools.

INTRODUCTION

Metal cutting process is an old manufacturing process but the least understood. When a cutting tool removes a chip from a work-piece, the actual effects which take place are complex and not easy to analyse. Repetitive experimental studies yield large amount of empirical data related to machinability of various materials. Cutter types, speeds, feeds and other process inputs are selected using these data. However, the values selected often depart from the optimum values and the reasons are [1, 2]: (1) Variation in metallurgical properties of workpiece materials, (2) Variation in cutter effectiveness due to dulling, (3) Unpredictable chatter effects on surface finish, and (4) Variations between hand-book data obtained under controlled laboratory anvironments and actual production environments. Because of these, the metal cutting process as being practiced now is relatively inefficient.

Adaptive control of the feed and speed values based upon online measurement of process performance offers a potential for significant improvement

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in process efficiency and economy [3–5]. Present production methods therefore suffer from utilization losses thereby reducing the effective application of cutting tools to a low fraction of their theoretical capacities. The utilization losses may be reduced by the use of computers for intensive production control and supervision. Cutting down the non-productive times would also help in reducing utilization losses. This requires that the system be relieved of the technological machining factors which were oriented so far in relation to worst case conditions, as otherwise performance of the machine-tool would be utilized only during individual periods of the machining time.

In the machining literature therefore, AC means a control system which measures process variables such as torque, temperature, vibration, etc., and uses thess measurements to adjust feed and/or speed in the operation. In other words AC influences the machining cycle in such a way that the cycle is optimised considering fully all those factors which affect it.

The various factors therefore must be matched to the pertinently prevailing machining conditions in such a manner that the performance of the machine-tool at any moment of the machining time is utilized at maximum efficiency.

AC enables sensing and automatically correcting for variations in metal cutting conditions. It is one of the most fascinating metal working acdvancements in recent years.

In this article, the principle, types, advantages and effictiveness of adaptive control systems are briefly discussed. Adaptive control schemes for turning, milling, drilling and grinding operations are also described.

ADVANTAGES

The main advantages [7, 8] of AC are:

(1) shortening of total cutting times or increase of tool life and protection of the machine-tool and workpiece during cut.

(2) shortening of idle time lost in cutting air.

(3) programme preparations done more quickly and with less effort in case of AC applied to NC machine tools.

AC increases tool life and metal removal rate in machining toughest alloys. They can be frequently used with HSS tools to do jobs that usually call for carbides and they often eliminate semi-finish cuts by removing more stock than usual in one operation. AC can be used on a whole range of machine-tools including drilling, milling, turning and grinding equipment.

AIMS AND NEEDS

The aim of AC is to control the variables like cutting speed and feed rate on a machine or a group of machines in such a way as to achieve some objectives like control of workpiece dimensions [9], surface finish, maximum output or minimum cost.

Machining Situations Warranting use of AC [10, 11] are:

(*a*) Variable geometry of cut, as is normally encountered in profile milling or contouring operations;

(*b*) Variable workpiece hardness owing to the presence of hard spots;

(*c*) Variable rigidity of the workpiece, giving rise to workpiece deflection;

(*d*) Tool wear; and

(*e*) Air-gaps during cutting.

TYPES

A simple block diagram of an adaptive control scheme for machine tools is shown in Fig. 1. There are two kinds of AC systems, *viz*., (1) Adaptive control constraint (ACC) and (2) Adaptive control optimisation (ACO)

ACC

Systems based on the idea that the machining proceeds within the given limits are called Adaptive Control Constraint systems. The behaviour of such a system in a cutting speed—feed rate field is shown in Fig. 2. A characteristic of ACC systems is that the working point which is provided by a pair of values (V_c, f) is at one of the limits in the steady state. The location of the limits in the $V_c - f$ field will be changed as the operating conditions change and if only feed can be varied the working point will change its location as shown in Fig. 2. The change in operating condition here is a change in depth of cut as given in Fig. 3.

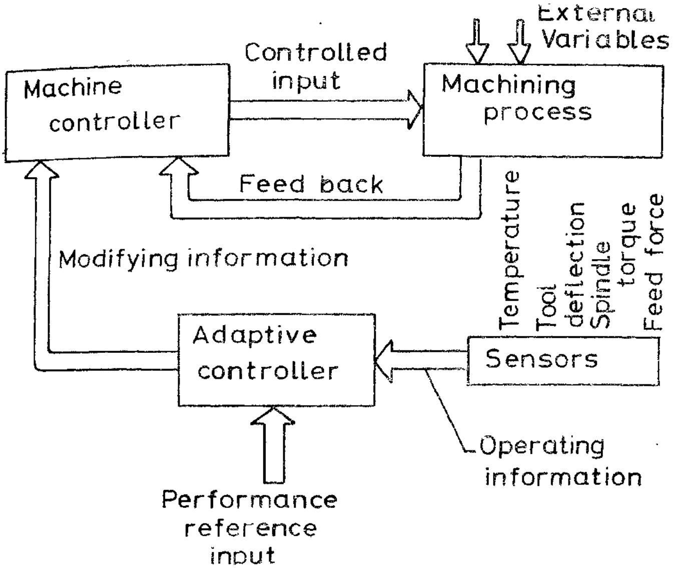

FIG. 1. Block diagram for a typical adaptive control system for a machine tool.

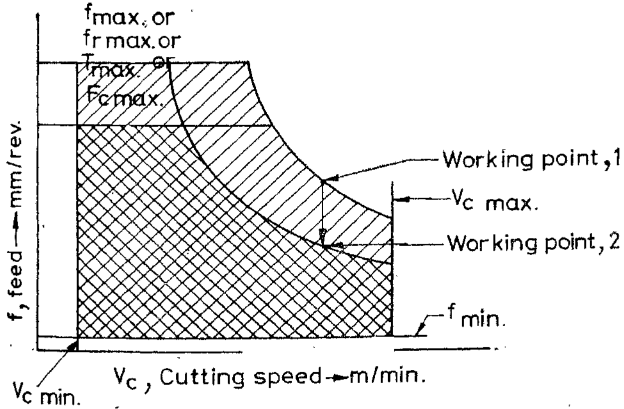

FIG. 2. ACC System, constraints in $V-f$ field.

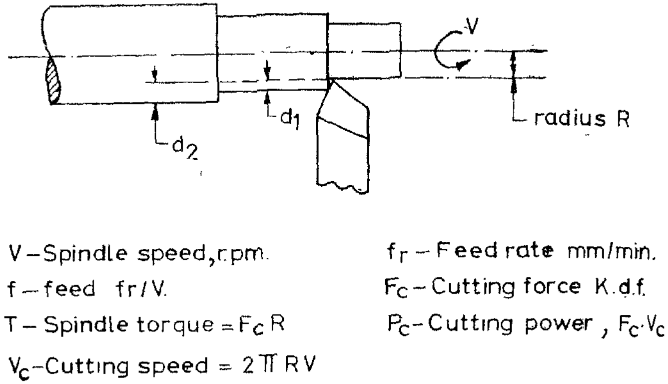

FIG. 3. Depth of cut change as a change in operating conditions.

ACO

Equipment in which the control is based on an optimized performance index has been given the name of ACO. The functioning of such a system for a change in depth of cut is shown in Fig. 4. Here the performance index chosen is minimum cost and equicost lines are shown in the figure. Cost lines and constraints for operation condition I are shown by continuous lines and those for II by broken lines. The operating point is changed as shown in Fig. 4 such that during both the conditions the operation is performed at minimum cost. The system is employing a hill climbing method for selecting the working point at which the selected performance index is at its best. As before, the limits provided by the cutting tool and machine-tool must be maintained. Figure. 5 gives a typical block diagram of the internal strudture of an ACO system.

ACC systems have been almost the only ones developed and suitable for unrestricted operation. The development of ACO systems depends heavily on the problem of tool wear determination and on the problem of finding suitable substitute solutions.

STATE OF ART

During the past years attempts were made to employ the temperature at the cutting edge as a suitable characteristic. But, there has been considerable

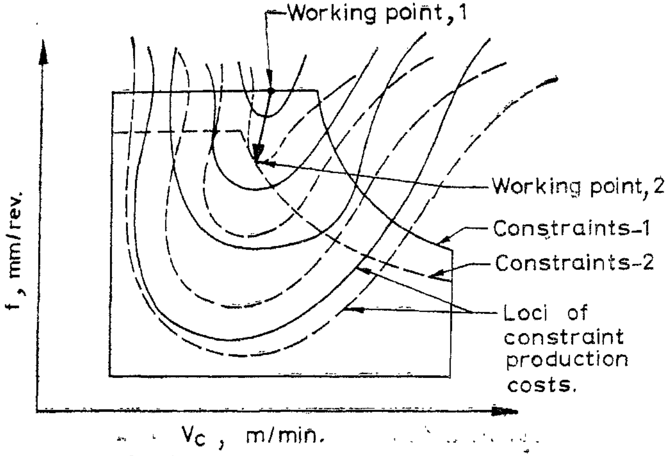

FIG. 4. ACO: Optimization criterion, production costs.

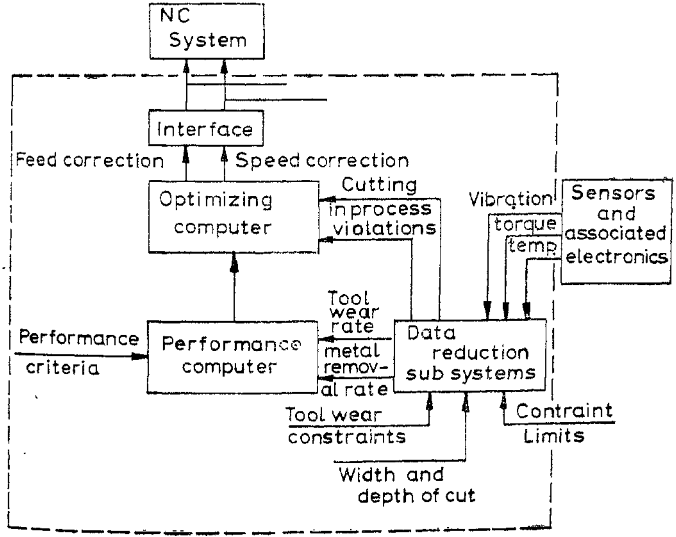

FIG. 5 Typical internal structure of adaptive controller and data reduction block

evidence that temperature by itself provides insufficient information and that the required measuring techniques are hard to handle. Therefore, many present systems restrict themselves to the measuring of motor load, torque and cutting force characteristics which can be measured with less effort. The problem of sensing the process variables under cutting conditions, however has not been satisfactorily solved so far [12] and AC will achieve its greatest importance when the sensor problems are completely solved and some standardisation is reached.

According to the correcting variables AC systems can be divided into two groups, (*a*) in which feed and depth of cut are adjusted, and (*b*) in which only feed is adjusted. Using the spindle speed as the correcting variable only few systems have been developed. These foregoing facts are presented in Tables I, II and III for turning, milling and grinding [1] systems respectively.

Lathes and milling machines claim the majority among the machines for which AC has been employed. However, few drilling and grinding machines have also come out with AC. These AC systems vary [6] from one another in several aspects such as operating principles, degree of complexity, cost and advantages claimed.

EFFECTIVENESS

AC systems present a wide range of different design solutions and hence there arises the necessity for reliable methods of assessments of the effects introduced by the given system. The comparison of achievements with expenditure should help in selecting the most economical AC system for the cutting process involved [6].

A reliable way of assessing the effectiveness is by comparative tests. Laboratory tests must be carried out by cutting with predetermined disturbances, because disturbances before everything else justify the introduction of AC. The chosen form of disturbances must be relevant to the character of a main disturbance which can be anticipated under workshop conditions.

The effectiveness of an AC system [6, 13, 14] was assessed at Warsaw Technical University, by keeping the cutting temperature constant during cutting (turning) by means of changes in cutting speed. As predetermined distrubances, jump changes in depth of cut and the hardness of workpiece material were chosen as shown in Fig. 6 (*a*). Tool wear (the width of nose wear land) was measured scope. The increase in tool life by using constant cutting temperature control was obtained as given in Fig. 6 (*b*).

TABLE I

AC systems for turning

System	Measured quantity	Correcting variable	ACC ACO	Aim
ACEMA (GDR)	F_c, P_m	f_r, d	ACC	Maximum utilization cut dissection
AEG—Pittier (GFR)	P_m	f_r	ACC	Maximum utilization
AEG–VDFI (GFR)	F_c	f_r	ACC	Maximum utilization
AEG–VDF II	T	f_r, d	ACC	Maximum utilization cut dissection
Bath University (Great Britain)	Y_c	V	ACC	Constant temperature of the cutting edge
Bendix dynapath system 4 (USA)	F_c, I_m, K_m	f	ACC	Maximum utilisation
ACC to frost smith (Great Britain)	T, Y_c	V, f	ACC	Maximum utilisation forecasting the wear rate
General Electric (USA)	I_m, P_m	V_c (or) f_r	ACC	Maximum utilization
ACC to Groszman and Hemming (Great Britain)	T	V, f	ACC	Maximum utilisation
ACC to Korytin and Shaparer (USSR)	Y_c	V_c	ACO	Maximum metal removal rate
University of Pisa (Italy)	Y_c, P_m	V	ACC	Constant temperature of the cutting edge
Royal Aircraft Establishment	Y_c, F_c	V, f	ACC	Maximum utilisation constant temperature of the cutting edge
Siemens—Gildemaster (GFR)	T	f_r, d	ACC	Maximum utilisation cut dissection
ACC to Takeyama	$W = f(F_c)$	V_c	ACO	Optimal tool life minimum cost
University of Wisconsin (USA)	Y_c	V	ACC	Constant temperature of the cutting edge

d., depth of cut; I_m, motor current; T., spindle torque; f., feed; P_m., motor load, W., tool wear; f_r., feed rate; V_c., cutting speed; Y_c, temporary of cutting edge; F., cutting force; V., spindle speed; K_m., Temporary of the motor

TABLE II

AC systems for milling and boring

System	Measured quantity	Correcting variable	ACC / ACO	Aim
ACC to Beadle and Bolinger (USA)	T	V, f_r	ACC	Constant metal removal rate
Bendix (USA) . .	T, L, Y_c, F_c	F, f	ACC	Maximum metal removal rate
Bendix (U.S.A.)	T, L, Y_c	V, f_r	ACO	Minimum cost
Boeing (U.S.A.)	D	f_r	ACC	Maximum utilisation
Cincinnati Acramizer (U.S.A.)	T, P_m, N	V, f_r	ACC	Minimum cost
Hungarian Academy of Sciences (Hungary)	T	f_r	ACC	do.
Makino milling machine company (Japan)	T	V, f_r	ACC	do.
SAPCONS (U.S.S.R.)	Geometry of work	Path of tool	ACC	Improved accuracy
ACC to Vul'fson (U.S.S.R.)	F_c	f_r	ACC	Maximum utilisation

TABLE III

AC systems for grinding

System	Measured quantity	Correcting variable	ACC / ACO	Aim
Cornegie—Mellon University (U.S.A.)	W_{gw}	f_r	ACO	Minimum of coat
University of Delft	W_{gw}	f_r	ACO	do.
ACC to R—Hahn (U.S.A.)	Defln. of the spindle	f_r	ACC	Improved accuracy
Toyoda Machine Works (Japan)	F_{gw}	f_r	ACC	Maximum utilisation

D., gap between machine frame and tool holder; F_{gw}., grinding wheel pressure; W_{gw}., wear rate of grinding wheel; L., vibration; N., Deflection of the spindle.

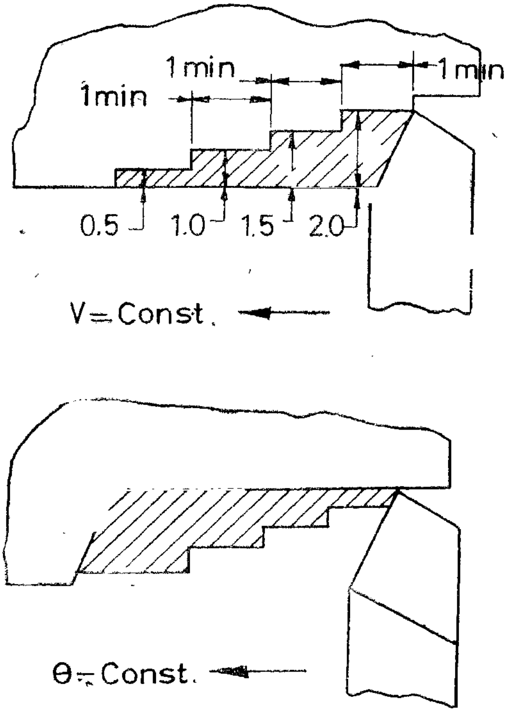

FIG. 6*a*. Test workpiece for both adaptive and non-adaptive processes.

ADAPTIVE CONTROL SYSTEMS FOR LATHES

In conventional programming, all data such as speeds, feeds and traverse ust always take into consideration the extreme values occurring within workpiece batch.

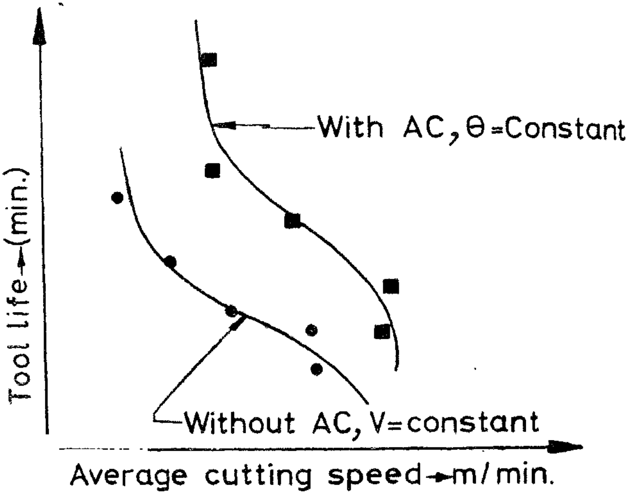

FIG. 6 *b*. Increased tool life due to AC.

Referring to Fig. 7 *a* it can be seen that in order to make sure that the tool does not traverse on any of the workpieces within a batch into the blank

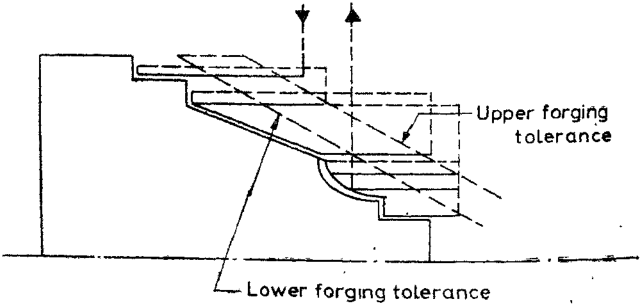

FIG. 7 *c*. Tool travel in a typical lathe operation.

at rapid traverse rate, the change over from rapid to working feed has to occur at a coordinate point outside the maximum blank tolerance.

As a result, the tool has to cover a greater or lesser idle traverse after changing over to working feed and cuts air on most of the workpieces in a batch, the time required for this is irretrievably lost. Similar conditions with respect to speed and feed rates on workpieces with varying hardnesses or in the case of tool wear [8, 15, 16].

An adaptive control system overcomes the above mentioned idle traverse in the following way.

The tool moves from the starting point towards the workpiece at rapid traverse rate. As soon as the tool point touches the workpiece, a torque build up occurs, which is measured by a highly sensitive measuring device in the turning spindle. The increase in torque is used to stop the rapid traverse instantaneously. A timer element in the control system maintains the stop—to allow the tool to cut itself free—until the workpiece has completed at least one revolution at the lowest programmable speed. Subsequently, the tool is moved in the $-Z$ direction with the smallest programmable speed so that the torque can be increased.

The torque now continues upto the programmed maximum permissible torque. When this value is reached the feed is stopped in the *minus* Z direction and changed to *plus* Z direction.

There are two limits, $\dot{Z}_{max}$ and $\dot{Z}_{min}$ within which the feed rate Z is automatically controlled in relation to the measured torque. When the adaption system reaches anyone of these limits there is either a reduction in depth of cut in the case of reaching $\dot{Z}_{min}$ or a depth of cut increase in the case of reaching $\dot{Z}_{max}$.

Typical variations in feed and depth of cut in producing a part has been given in Fig. 7 *b*. The description of the method so far highlights the potential advantages of simplified programming and the saving of ideal time.

ACC System for a Turret Lathe

In principle, the equipment consists of a cutting power control loop and a control loop for the spindle speed. Feed rate is the correcting variable. Spindle speed is corrected/adjusted such that cutting speed is held constant.

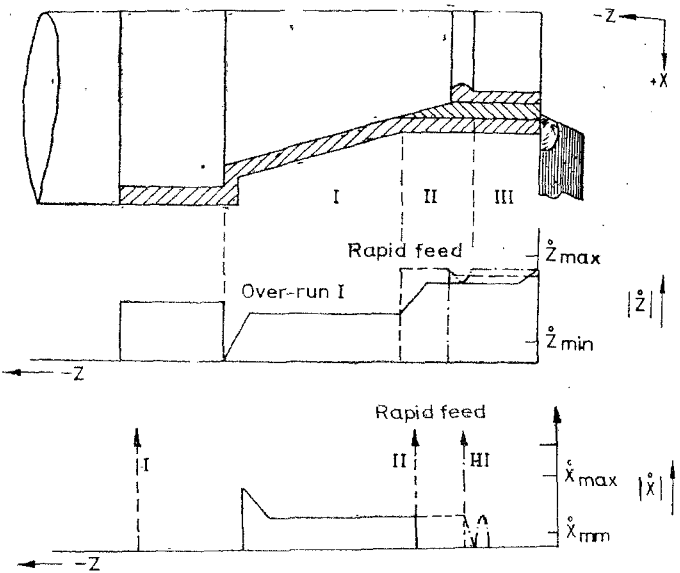

FIG. 7 *b*. Distribution of cuts on workpieces with varying machining allowance.

The setting values are fed analogously into the system. For each turret position, a cutting force F_c and a cutting speed V_c can be fed first. F_c depends on the load capacity of the tool., and V_c on the expected tool life. In addition a maximum feed $f_{\max}$ can be programmed for each turret position.

The restricted command power (cutting) is compared with the actual value and taken to a power controller at the output of which the command signal for the feed rate appears. This signal can be limited in turn in relation to the present maximum feed. To establish the actual cutting power, the no-load power of the main drive is measured during the non-cutting process, stored and deducted from the measured motor output.

DIRECT FEEDBACK TYPE OF AC FOR CENTRE LATHES

This form of AC could provide a practical method of varying machining speeds and feeds, by the changing cutting conditions giving a direct feedback of cutting performance. The control of thrust force gives improved metal removal rate and tool protection in conditions of work hardness and geometry.

Control of Average Cutting Edge Temperature Using Tool/Work Thermo E.M.F.

Tool work thermo e.m.f. has been used to measure the average temperature of the cutting edge. This method suffers from a number of disadvantages because of the variability produced both by tools and workpieces of nominally the same type [19].

Variation of thermo e.m.f. with cutting speed is as shown in Fig. 8. The reduction of slope with cutting speed indicates the reduction of tool forces and attainment of plastic chip deformation. Tool temperature control enables a repeatable cutting process cycle to be maintained in these conditions so that a definite number of parts can be produced before a cutting

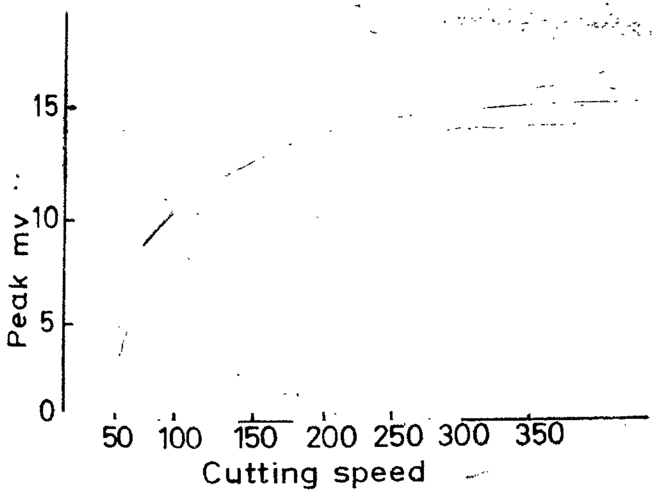

FIG. 8. Variation of therma e.m.f. with cutting speed.

edge change is necessary. Typical variations of cutting speed and wear land during a constant temperature control are shown in Fig. 9.

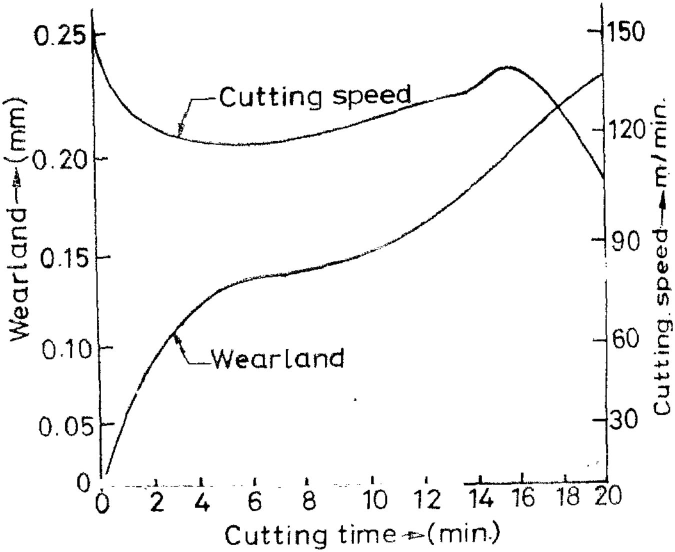

FIG. 9. Turing results using cutting temperature control.

The use of this system, when facing, increases metal removal rate by about 30% as a result of the fact that control of temperature results in an approximate control of cutting speed. Thus the spindle speed increases automatically as the tool approaches centre and there is the additional benefit of improved surface finish which would make it useful in profiling work. Figure. 10 gives the block diagram of a typical temperature control system for a lathe.

Control of Thrust Force

Thrust force can be more conveniently measured by measuring the deflection of the nose of the conventional insert too holder. Semi-conductor strain gauges can be used for the purpose. Alternatively, a piezo-resistive

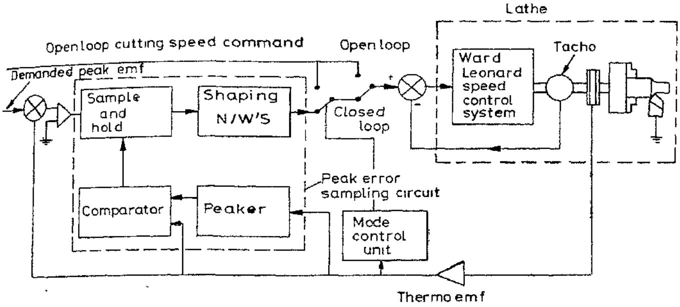

FIG. 10. Lathe cutting temperature control system.

beam transducer situated at the near of the tool holder, away from the heat producing area, is quite successful in practice and its drift properties are good enough to allow dry cutting [19].

The object of force control is to set the demanded force to within the limits imposed by the machine power and rigidity so that the highest metal removal rates can be maintained in the presence of varying work geometry and hardness, while providing automatic protection of the cutting edge. Typical variations in cutting speed, spindle speed and feed rate are shown in Fig. 11, when both the temperature and force control are employed together.

ADAPTIVE CONTROL FOR MILLING MACHINE

In order that the cutting process in a milling machine is performed economically, the tool life should be maintained at a constant value T_e which is given by the following expression [10].

$$(1) - T_e = \left(\frac{1}{n} - 1\right)\left(T_c + \frac{60R}{c}\right),$$

R — tool depreciation and regrind cost;

t_c — time to change a worn tool (min.)

c — hourly cost of labour, overhead and burden rate and n is given by Taylor's equation.

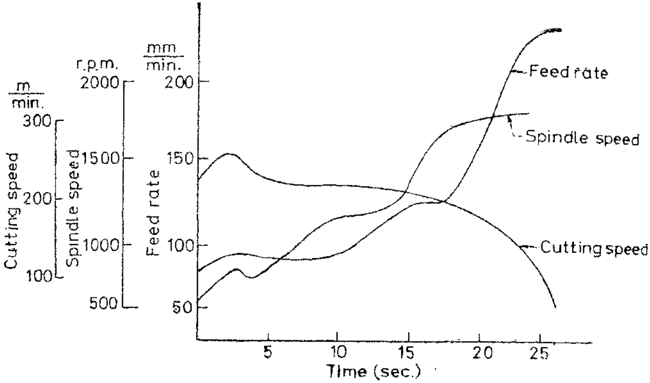

FIG. 11. Facing with temperature and force control

$$VT^n = C$$

V-cutting speed

T-Tool life

C-constant.

In fact, C is not a constant. It depends on so many process variables. Only if the value for 'C' is kept constant the expres ion for T_e is valid. Hence it is necessary to determine these variables and establish what changes in cutting speed are necessary to adapt to them so that expression (1) will always be satisfied.

Five important variables are:

(1) width of cut
(2) depth of cut
(3) tool wear
(4) workpieces hardness
(5) stiffness between tool and workpiece.

Also it is necessary to find out process parameters which can be sensed in process and whose response to the above variables is of the same order and magnitude as their respective influence on cutting speed for constant tool life.

Through metal cutting research, the Physical Research Department of the Cincinnati Milling Machine company has discovered a feedback parameter composed of cutter torque and deflection sensor measurements, whose relative response to the above variables is of the same order and magnitude as their respective influence on cutting speed for constant tool life. With the help of this feedback parameter, they have constructed an adaptive controller for a 3-axis numerically controlled milling machine. The controller is integral with the N.C. system. The A/C — N/C control loop is shown in Fig. 12. Cutter deflection sensed at the spindle nose and cutter torque sensed in the spindle are continuously sensed by the electrical sensors. Sensor signals are received by the adaptive controller which computes the feedback quantity and determines the optimum speed and table rate. There are also constraints such as maximum deflection and *hp* capacity of the motor which are also taken care of in the controller. It has been reported that adaptive control produces parts of desired quality at production rates which are unachievable using constant speed and feed for the same cutter and cutting conditions.

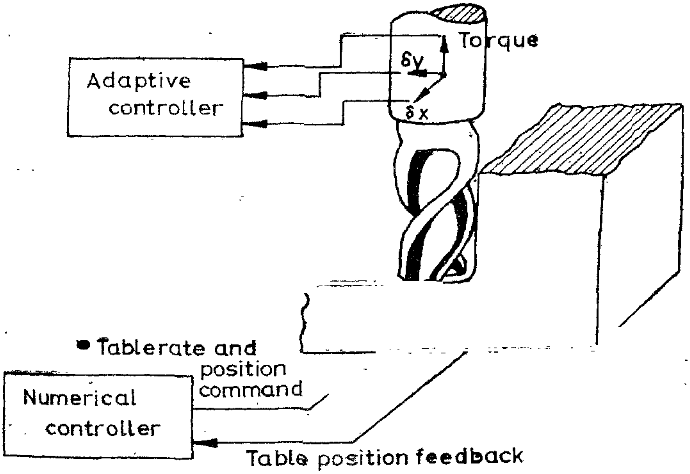

FIG. 12. Adaptive controlled NC loop.

Expression for economic tool life:

$$\text{Cost/part} = \frac{c}{60}(t_h + t_p + t_m)\left(1 + \frac{t_c + \frac{60R}{t_c}}{T}\right)$$

c –hourly cost of labour

t_c –time to change worn tool (min)

R –Tool depreciation and regrind cost

t_m –machining time (min)

T –tool life (min)

t_p –time spent in positioning tool and workpiece

t_h –time spent in loading and unloading the workpiece.

Making use of Taylor's Tool Life equation and differentiating the appropriate term in the expression for cost/part, we get,

$$T_e = \left(\frac{1}{n} - 1\right)\left(t_c + \frac{60R}{t_c}\right)$$

which is known as economic tool life [10, 20, 21]. If the resulting tool life is below T_e too much non-productive time is lost in changing the tool. If the resulting tool life is greater than T_e the production time is too long.

FEEDS AND SPEEDS FOR MILLING PROCESS

For any metal cutting operation, the cost/inch of cutter travel is related to the spindle speed and feed by the curves given in Fig. 13.

In general, highest production rate and lowest cost is obtained by operating at maximum feed of 0·01″[11]. But it is not always possible to operate at this point. For many roughing cuts there are either spindle torque (h.p.) constraint or cutter deflection constraint, that impose limitations on the obtainable feeds. These constraints change the optimum cutting conditions as shown in Figs. 14 and 15. Torque also imposes similar constraints in the speed-feed field.

In any case, true optimum speed and feed is obtained by operating at the lowest point of the maximum feed curve or at the lowest point along a constraint boundary, whichever is highest.

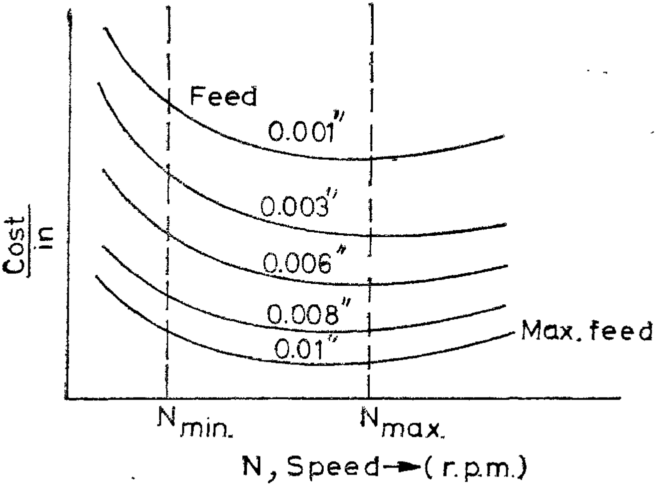

FIG. 13. Cost as a function of feed and speed.

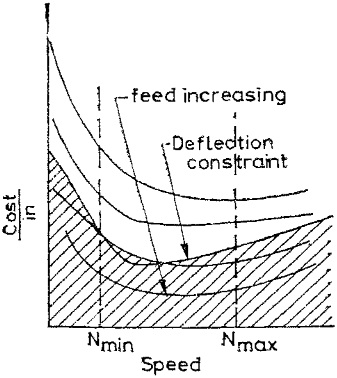

FIG. 14. Cutter deflection constraint brings down max feed allowable.

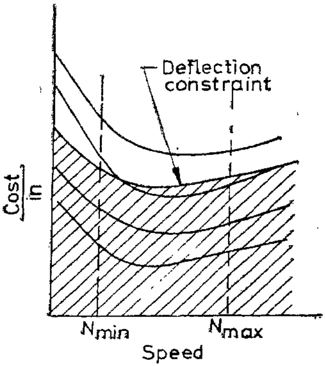

FIG. 15. Tighter deflection constraints for finish cuts.

Vertical dashed lines in the foregoing figures represent minimum and maximum cutting speeds. N_{min} is that which is prescribed for worn cutter, and highest depths and widths of cut to be encountered. Maximum speed, N_{max}, is that which is productive for sharp cutters and lowest depths and widths of cut to be encountered for the particular tool-workpiece materials. As one goes from a roughing operation to a finish operation or as cost factors change the economic tool life to a lower value both N_{min} and N_{max} are set to higher values. In any case, as stock variation, hardness variation, stiffness variation or tool wear occur, adaptive control varies the speed, between N_{min} and N_{max} so that maximum production rate and minimum production cost result. Hence the adaptive control is to be employed to define a control region of speed and feed and to establish the optimum speeds and feeds to match cutting conditions as they occur.

ADAPTIVE CONTROL SYSTEM FOR A DRILLING MACHINE

A system based on torque control is one of the successful systems employed for drilling operations. Based on the information obtained from the cutting edge of the tool, the director of the system makes corrections in the operation, by changing the torque-speed characteristics of the drive motor. This type of system can be easily retrofitted to a standard machine tool. Here, in this method either torque or the resultant tool force is sensed [7, 22] As the tool wears out, torque increases. Change in torque may also due to other variables in the material. In short, sensing of the change in torque is used as a signal that controls the effect of direct physical and indirect material variables. Feed rate, depth of cut and diameter are direct variables and hardness, strength, work hardenability and cutting temperature are some material variables. The effect of changes in all of the variables is summed up by a change in torque at the cutting edge as the tool wears out. By adopting an adaptive torque control the wear rate of the tool is controlled by input to the director and corrective action is taken within the director circuitry. This system of torque control can be applied to any machine tool such as drilling, milling and turning machines. But application of this system to drilling is somewhat different in the sense that here both speed and feed are controlled. When feed, speed and depth of hole are controlled, difficult operations such as drilling intersecting holes and deep holes are greatly simplified. Drill cycling at preset torque, rapid travel during drill approach and cycling, electrical depth sensing and other auxiliary functions can be incorporated in the system. This adaptive system using torque sensing can be applied to drilling machines of all capacities.

A/C FOR BELT GRINDING PROCESS

Due to few systematic or quantitative investigations on belt grinding, a process equally important as ordinary grinding, it has been improperly assessed or inadequately applied. Especially the deterioration characteristics are to be known thoroughly for economic and efficient use of the process. This is one of the most prospective areas [23] for adaptive control application.

In fact, the grindability during machining depends on two parameters, *viz.*, belt speed and contact pressure, whereas the former is not altered in an ordinary machine. From Fig. 16 it is clearly seen that higher the contact pressure, lower the cost is and obviously the highest pressure resulting in minimum cost. The belt grining process is not as simple as that. Instead of maintaining contact pressure constant, a gradual variation of it is extremely effective from an economical view point. As shown in Fig. 19 cumulative stock removal rate increases more for a particular mode of contact pressure variation than that of a constant contact pressure process. Thus cumulative stock removal is a function of mode of pressure variation. There exists an optimum mode of pressure variation. The function of the adaptive control system is to continuously monitor the contact pressure so that the machining process is economised.

A/C FOR NUMERICALLY CONTROLLED MACHINE TOOLS

Adaptive control generally indicates an elaborate means of optimizing efficiency of N/C machine tools when cutting difficult workpieces. Such

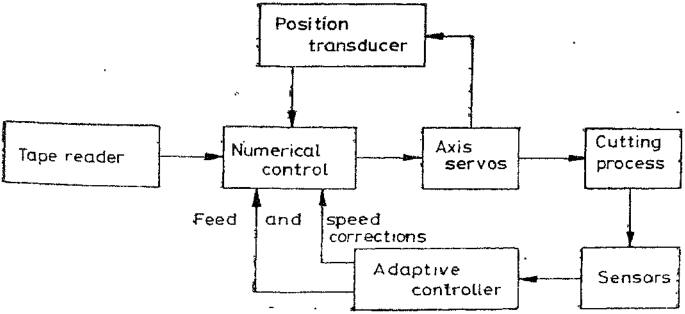

FIG. 16. Adaptive control applied to a NC system.

systems, though yet only just making their debut, certainly have a big future ahead in this field. But there is also a lot of other highly practical self-adaptive setups totally outside N/C area. They are being used either to optimize machining conditions or to reduce cost motion on drilling and grinding machines or to maintain dimensional tolerances.

Though A/C is not confined in its application to N/C machine-tools, it is undoubtedly N/Cs inherent suitability for initiating remedial action on the basis of in process measurements of machining parameters that has given the development of adaptive systems [24, 25] of most push.

Many of the new tough alloys have proved it difficult if not impossible to machine by conventional N/C without severe tool loss and/or damage to the workpiece. Adaptive control system coupled to N/C will adapt to the varying operating condition and optimizes the whole machining process. In an A/C system applied to a numerical controlled milling machine the sensed variables are (1) average tool tip temperature, (2) spindle torque, (3) tool vibration.

An adaptive controller processes the data obtained from the sensors to obtain a measure of the actual cutting performance. The performance measurement consists of two parts. (1) A calculation of the instantaneous productivity, (2) a determination of whether various machining parameters are within acceptable limits. The latter condition assures that the parts meet desired specifications, minimizes the possibility of tool breakage or part damage and assures a reasonable tool life.

The adaptive controller also contains circuits which provide feed and speed correction commands to the N/C system. These commands improve productivity without exceeding any of the constraint limits. The commands are obtained by optimization logic circuits, whose outputs provide gradual trial and error modifications of feed and speed values in the proper directions of tool/workpiece movement.

The use of A/C requires minor modifications in the basic system. In particular the system must be capable of accepting the feed and speed correction commands from the adaptive controller. This requires the addition of logic circuits which can accept the commands and enter then into N/C system. It may also require the addition of automatic feed rate and spindle speed controls.

Adaptive control is applied to a N/C system by adding another feedback loop, using sensors coupled as closely as possible to the cutting process.

Simple block diagram of an A/C system for a N/C machine is shown in the Fig. 18 and Figs. 19 and 20 show the variations in process parameters in both a conventional and adaptively controlled machines.

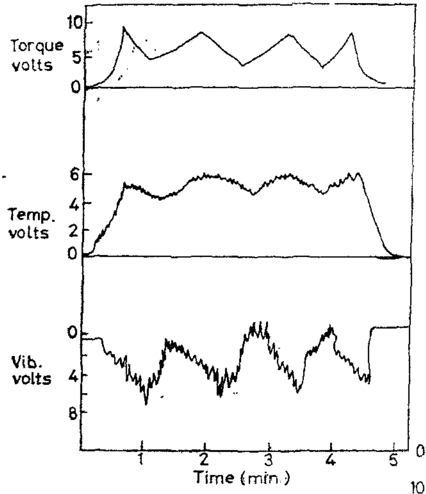

FIG.17.

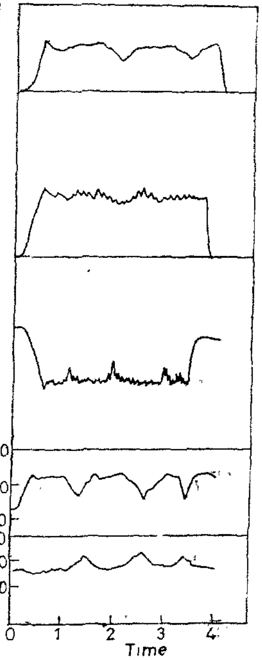

FIG.18.

Fig. 17. Non-adaptive variable depths of cut machining constant speed and feed.

Fig. 18. Adaptive machining variations in speed and feed rate (Torque, Temporary and vibrations are all kept more or less constant).

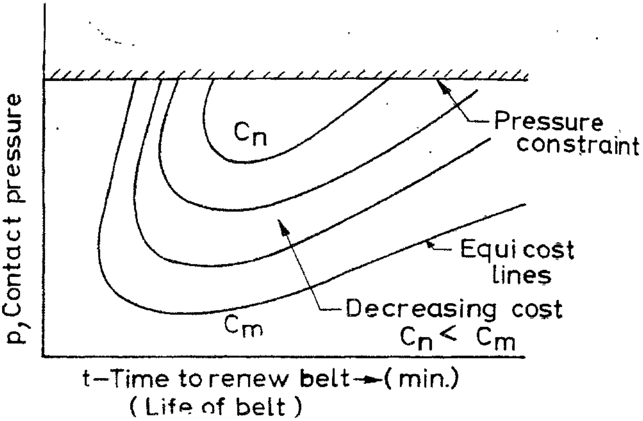

FIG. 19. Variation of cost in a pressure-life of belt field.

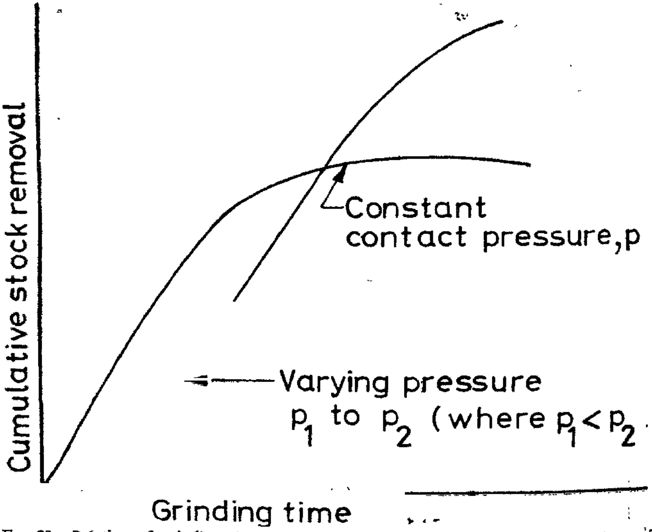

FIG. 20. Relation of grinding time and cumulative stock removal for two models of pressure application.

CONCLUSION

Adaptive control applied to machine-tool enables making speed and/or feed corrections during a process on the basis of the information obtained through sensed variables such as tool tip temperature, vibrations or cutting force so that the overall process economics or efficiency is improved. Since AC is a feedback control system with the principal aim of doing the metal cutting process more efficiently it can be applied to any machine-tool. However, application of this type of control to a numerically controlled machine is much easier than retrofitting it to a conventional machine.

Adaptive control systems for lathes, drilling machines, milling machines and other machines both conventional and numerically controlled have been developed in many countries. Adaptive control applied to NC microboring process [26] has enabled taking very minute cuts in predrilled workpieces without breakage. Adaptive control can also be advantageously applied to fields other than machine-tool industry. For instance, an analog computer can be effectively used for adaptive-predictive control of a fast chemical reaction in a batch reactor [28].

Still extensive research is going on in some of the problem areas in this field. For example, typical sensors to be used in production environment are yet to be evolved [12, 27]. The advantages obtained by using AC to any machine-tool are so large that there is a great scope ahead for this relatively new area of development pertaining to production engineering.

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