ACTIVE SUPPRESSION OF MACHINE TOOL CHATTER

by

A.B.Dunckley

This thesis is submitted for the degree of Doctor of Philosophy in the Faculty of Applied Science , University of Newcastle-upon-Tyne.

August 1978.

DISTORTED PAGES IN ORIGINAL

BEST COPY

AVAILABLE

Variable print quality

PREFACE

The work described in this thesis was undertaken in the Department of Mechanical Engineering at the University of Newcastle-upon-Tyne during the period October 1973 to September 1976.

All figures and plates are included at the end of the chapter in which they are first referred to, and are prefixed by the number of the chapter accordingly.

Appendices are presented at the end of the thesis , and contain flowcharts and listings of the computer programs used during this research.

ACKNOWLEDGEMENTS

The author would like to thank Professor L.Maunder , Director of the Stephenson Engineering Laboratories , for the provision of laboratory facilities at the University of Newcastle -upon-Tyne , enabling the experimental work to be carried out.

Financial support was provided by the Science Research Council.

The author is indebted to his project supervisor , Dr.J.R. Hewit , for the advice and encouragement given throughout the project.

Computing facilities were provided by Professor E.S.Page and the staff of the University Computing Laboratory.

Thanks are also due to Mr.R.Hunter and the departmental workshop staff , in particular Mr.W.Burgess and Mr.W.Young , for help provided during the construction of the experimental rig.

Finally , the author would like to thank Mr.A.McGilligan for the photographic work , and Mrs.M.English for typing this thesis.

SUMMARY

The aim of the work described in this thesis is to design, build, and test an active, chatter suppression system for use on a lathe.

Many methods have been developed to minimise the effects of regenerative chatter in machine tools. These include machine redesign and stiffening, the inclusion of additional damping, and the use of passive and active control systems. The method described here is a development of two of these active methods, those of Comstock and Nachtigal, which control the relative position of the cutting tool. An on-line digital computer is used to monitor the cutting force, predict the relative tool-workpiece displacement, and drive the tool to suppress chatter build-up.

The work is described in five main sections.

After the introductory section, in which the problem is outlined and past work discussed, a theoretical analysis of chattering and its suppression is presented. Digital simulation is used to confirm and expand the theoretical results. The basic on-line identification method used to investigate the machine-workpiece structure is also presented.

The third section describes the design and implementation of the experimental rig, especially the computer system and the tool positioner. Its use as a driver for a cheap, bolt-on CNC turning system is also discussed.

The fourth section details the experimental work, including calibration, cutting tests, suppressor validation and testing.

Finally, the theory, simulation and experiments are discussed and related to past work. Suggestions are made for further research and development, including other applications of the system. Conclusions are drawn about the various techniques used during the work, with comments on the effectiveness of the suppression method.

CONTENTS

NOMENCLATURE

X_w - workpiece centreline displacement

X_t - tool displacement

X_t' - quantized tool displacement

X_p - predicted workpiece centreline displacement

X_p' - sampled, predicted workpiece centreline displacement

X_c' - tool positioner control signal

F_c - cutting force

U - instantaneous depth of cut

U_0 - nominal depth of cut

K_c - cutting stiffness

M_m, C_m, K_m - effective mass, damping, stiffness for machine

M_w, C_w, K_w - effective mass, damping, stiffness for workpiece

μ - cut overlap coefficient

t - time

T - delay for one cycle of the workpiece

s - Laplace operator

$H(s)$ - transfer function for machine-workpiece dynamics

$G(s)$ - transfer function for feedback loop

w - frequency

j	-	$\sqrt{-1}$
A_1, A_2, B_1, B_2	-	discrete 2 nd. order model parameters
z	-	discrete plane (z) operator
D, H	-	quantizer parameters
S_s	-	tool positioner step size
M_t, C_t, K_t	-	effective mass, damping, stiffness for tool positioner
N_1	-	idealised controller non-linearity
ζ, w_n, K	-	damping factor, natural frequency, gain
ϕ	-	pseudo correlation functions
E	-	mean square error
x, y	-	chuck centreline horizontal and vertical axes
u, v	-	chuck centreline axes at 45 to vertical
e	-	exponential constant (2.718)
c_{k-n}, m_{k-n}	-	actual discrete model inputs and outputs
c^*_{k-n}	-	predicted discrete model outputs

1. CHATTER IN MACHINE TOOLS.

1. 1. Introduction.

The occurence of chatter in metal cutting machines is recognised as one of the most important factors limiting production rate, surface finish quality, and tool life. Over recent years much work has been done to understand the mechanism which causes chatter, to predict the occurence of chatter, and to devise ways by which it may be prevented (34, 33, 32, 1, 2, 3, 27, 31).

Chatter is defined as self-excited vibrations between the tool and the workpiece, and can be recognised by a rapid build-up in the vibration amplitude (32). The amplitude will increase until limited by such non-linearities as the tool leaving the workpiece, tool-tip fracture, or other dramatic changes in cutting conditions. The chatter frequency is associated with the natural frequency of one of the major resonance modes of the machine tool (32, 34).

It has been found through discussion with machine operators that chatter is a particular problem in many turning operations, and especially when machining long, compliant components such as gun barrels and turbine rotors. Milling operations are also prone to chatter instabilities. Many traditional solutions are discussed later in this chapter, as well as more modern passive and active methods. During this investigation the experimental work was performed on a lathe, and the theory is restricted to turning operations. However, it is possible to extend this work to other machining operations.

This chapter outlines the physical causes of chatter, discusses various chatter suppression philosophies and presents a brief review of some of the previous work in this field.

1. 2. Causes of chatter.

The machine tool in operation can be represented by a closed loop system where instability arises because of the interaction of the dynamic behaviour of the machine structure and the cutting operation (FIG1. 1).Chatter occurs primarily because of the non-rigidity of the machine structure and the time delay associated with the rotation of the workpiece. Surface irregularities caused by relative tool-workpiece motion are overlapped by successive cuts and vibration is regenerated causing chatter. The cutting force generated by the cutting process at the tool-workpiece interface causes a relative displacement between the two. The cutting force varies due to the non-homogenity of the work-piece (i.e. hard spots, weakness) which gives rise to varying relative tool-workpiece displacement and hence surface waviness. Under certain conditions the amplitude of the surface waviness increases on each successive cycle of the workpiece, resulting in chattering of the machine. A detailed breakdown of the mechanism which causes chatter is presented in FIG1. 2. The cutting operation is subdivided into the cutting process, which relates instantaineous depth of cut and cutting force and cut overlap effects, which form the feedback loop.

1. 3. Chatter suppression techniques.

An understanding of the mechanism which causes chatter immediately presents a facile solution to the problem. If the machine stiffness could be made infinite, relative tool-workpiece displacement would never occur and chatter would not build-up. In practice, infinite stiffness is not realiseable, although modern machines are designed and built to be as rigid as possible. This tends to make machines big, heavy and above all, expensive. Still the problem is not solved, the limit of chatter stability may be increased, but has not been eliminated.

Another factor influencing chatter instability is the work-piece dynamics. Even if the machine itself were rigid, certain types of workpiece could still be the cause of considerable tool-workpiece deflection.

The next approach therefore is to accept that chatter will occur under certain conditions and then to attempt to suppress it using vibration absorbtion techniques (3). Problems arise with this method due to the need for accurate tuning of the absorbers. Initially the machine has to be tested at the manufacturing stage and the dampers tuned. Periodically, thoughout the life of the machine, the dampers have to be re-tuned.

Modern machines are designed so that damping is built into the structure. The major source of structural damping arises from joints, both sliding and fixed, and is due both to frictional effects and to oil film behaviour. Many modern rubbers and plastics are also incorporated in the structure to act as absorbers.

Much resent work has been done in the analysis and developement of both passive and active dampers for machine tools (35, 36, 37, 38, 39, 40). Many types have been designed and tested, with varying success, and work is continuing. Several are self- optimising over a small dynamic range and hence can allow for small machine variations. These however cannot cope with large dynamic variations caused by some workpiece configurations. Active dampers consist essentially of a damping arrangement with feedback which incorporates a means for measuring the vibrations at some point on the structure. Their effectiveness for chatter suppression is determined by the point of vibration measurement. This technique has been applied to both hydraulic and electromagnetic exciters with considerable improvement in response (36, 37).

Other active control methods have also been tried, working on the principle of increasing the "apparent stiffness" of a machine. Analysis of the chatter mechanism has shown that it is the 'relative' tool-workpiece deflection that is the important factor influencing instability. If the tool position is controlled relative to the workpiece deflection, so that the relative displacement is maintained constant, the machine appears to have infinite stiffness. Hence, no matter how the cutting force varies, the relative tool-workpiece remains constant. So far there have been two major attempts using this approach (1, 2). Both of these attempts have shown considerable promise and are examined in more detail in the following section.

1. 4. Review of previous work.

1. 4. 1. The method of Comstock.

Comstock (1) adopted the direct approach to the problem and attempted to measure the relative tool-workpiece deflection and use this as input to a servo-controller driving the tool position. This method is outlined in block diagram form in FIG1. 3. Any relative tool-workpiece deflection causes the tool position to be altered so that the deflection is kept as small as possible. Due to imperfections in the servo-controller this deflection will never be identically zero, but should be good enough to prevent chatter build-up. Comstock claims that, when operating under experimental conditions, the cutting rate could be increased by "an order of magnitude" before the onset of chatter.

The main problem envisaged with this approach is the need for accurate, reliable measurement of the tool-workpiece deflection. The magnitude of the displacement is small (typically around 1 to 5 thousandths of an inch) necessitating a sensitive transducer, and the environment in which it must operate is very hostile. The transducer must measure the displacement of the rotating workpiece as near to the tool-workpiece interface as possible. The measurement will be subject to interference by swarf, cutting fluid containing metallic particles, high local temperatures, surface irregularity effects and possible operator interference. For this reason, it is doubted whether consistant, reliable performance could be obtained in an industrial environment.

Much work has also been done by Comstock into the development of a high-speed, small-displacement hydraulic servopositioner. Information regarding this device is difficult to obtain as it is subject to classification by the U.S. Air Force. This servo was used by Comstock in the implementation of this chatter suppression method and it is claimed to have had a natural frequency of approximately 1,000 rad/sec at displacements of 5-10 thousands of an inch. The bandwidth of the servo is critical in this application as it must be greater than that of the machine-workpiece system, or else undersirable phase effects occur. This phenomemon is discussed in greater detail later in chapter 3. These points demonstrate that the controller and servo must meet a high performance specification and hence will tend to be expensive pieces of equipment. From an economic point of view, this gives scope for consideration of other alternatives.

1. 4. 2. The method of Nachtigal.

Nachtigal's work (2) differs from that of Comstock in that the feedback signal is derived from a measure of the cutting force, which is used to control the machine-tool system. The basic system consists of an analogue model, operating on a real time cutting force signal, driving a tool servo positioner. A block diagram for the system is presented in FIG1. 4. The work includes an analysis of the machine-tool equipped with the active chatter controller and experimental results which verify this analysis. It was claimed that the following design objectives could be fulfilled using this active controller:

- Significant increase in machining rate (500% to 1,500%) without reducing the relative stability of the controlled machine tool system.
- Improvement in the transient response to disturbances at the tool-workpiece interface.
- Increase in apparant static stiffness of the system, and thereby improvement of the system's tolerance capability.
- Suppression of input forcing functions such as spindle inbalance, foundation vibration, etc.

In this method, measurement of the cutting force presents no problems. Using either strain gauges or load cells a clean, reliable signal can be obtained. The effect of the analogue model is to predict from the force input the uncontrolled, relative tool-workpiece displacement. A servo positioner translates this into the tool position. In the actual experiment, the model-driver system was simulated by an electrohydraulic activator driving a sprung tool holder. The spring, activator characteristics and tool holder mass were varied so that the tool position varied in the same manner as the relating tool-workpiece displacement. This was a purely experimental system which was to be replaced by an active controller and tool servo positioner. Nachtigal found during the experiments that the system was effective for controllers within a band ± 10% of the natural frequency of the machine-workpiece, with the system gain inversely proportional to the machine-workpiece stiffness.

It is obvious that the model characteristics will have to change if the machine-workpiece configaration changes, so that the model and machine-workpiece remain matched. Variation in the machine dynamic characteristics may occur due to wear, lubrication changes, temperature, environmental conditions, etc. The overall dynamic characteristics will also be influenced by the workpiece dimensions and material.

Work is continuing to develop the system and also to adapt it for use on several types of machine tool.

1. 4. 3. Comments on the methods of Comstock and Nachtigal.

As has been seen in the previous two sections, the concept of increasing the apparent stiffness of a machine by controlling the tool position has been found to be a feasible method for suppressing the onset of chatter. The disadvantage of Comstock's method is the inherent difficulty of measuring the relative tool-workpiece displacement. However, work is continuing to improve the practical feasibility of this approach and to test it on various types of machines.

Nachtigal successfully developed a working experimental system, but more work is needed to develop this for industrial applications. Primarily, study is required to determine the most suitable type of model and to consider the use of a variable model which could be tuned to different machine-workpiece configarations. The possibilty of developing self-tuning(adaptive) models also needs to be considered.

1. 5. Project objectives and developments.

From the analysis of previous work, it is claimed that the basic chatter suppression philosophy of controlling the relative tool-workpiece displacement is sound and that further developments of Nachtigal's work would be worthwhile. The project objective is to implement a variable model which could eventually be made self-optimising.

Initially, a study of the machine-workpiece dynamics is made as an aid to the selection of a suitable model. It is assumed that a second-order model, with suitable parameters, will be a good-enough approximation of the machine-workpiece dynamics. This has been found to be the case in much past work. (2, 24, 25, 26, 27, 28, 29, 31). Parameter estimation techiques are used as a guide to the 'best' values for the model parameters. In this case, 'best' will be those which give the least mean square error between the model output and the actual machine-workpiece behaviour. Experimental means are also used as an aid to parameter estimation.

A minicomputer with analogue-digital conversion equipment is used to monitor the machine behaviour and perform the parameter estimation. A least-squares algorithm (18) is used to perform this task.

The chatter suppression method is outlined in block diagram form in FIG1. 5. The modelling and controlling function are performed using a minicomputer, with a stepper motor acting as the driver. A minicomputer was chosen for the following reasons:

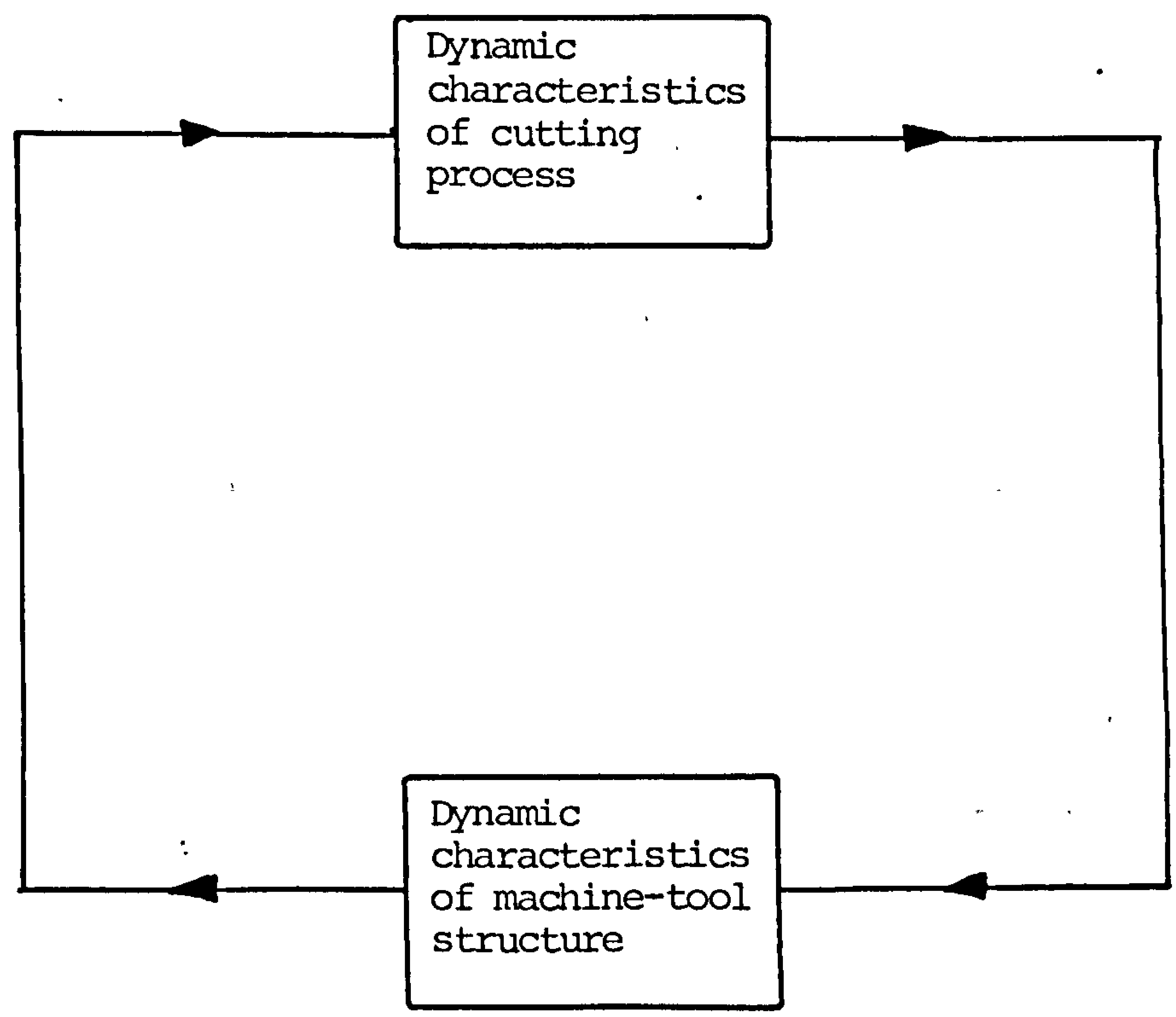
- -- The ease with which the model and controller characteristics could be varied by program modification.

-- The possibility of using sophisticated model functions.
-- To enable the possibility of developing self-optimising models.
-- The existance of modern CNC machines which already contain facilities which could be used at no extra cost to implement the method.
-- The possibility, in a workshop environment, of of using one computer to control more than one machine, hence spreading the cost.
-- The competitive price of computer equipment compared to complex analogue equipment.
-- The development of microprocessors which will allow this method to be implemented very cheaply, with little extra work.

A stepping motor is chosen as the driver because of the ease with which it can be interfaced to the computer. Also, as long as a count is kept of the number of steps moved by the motor, the exact position is known without feedback.

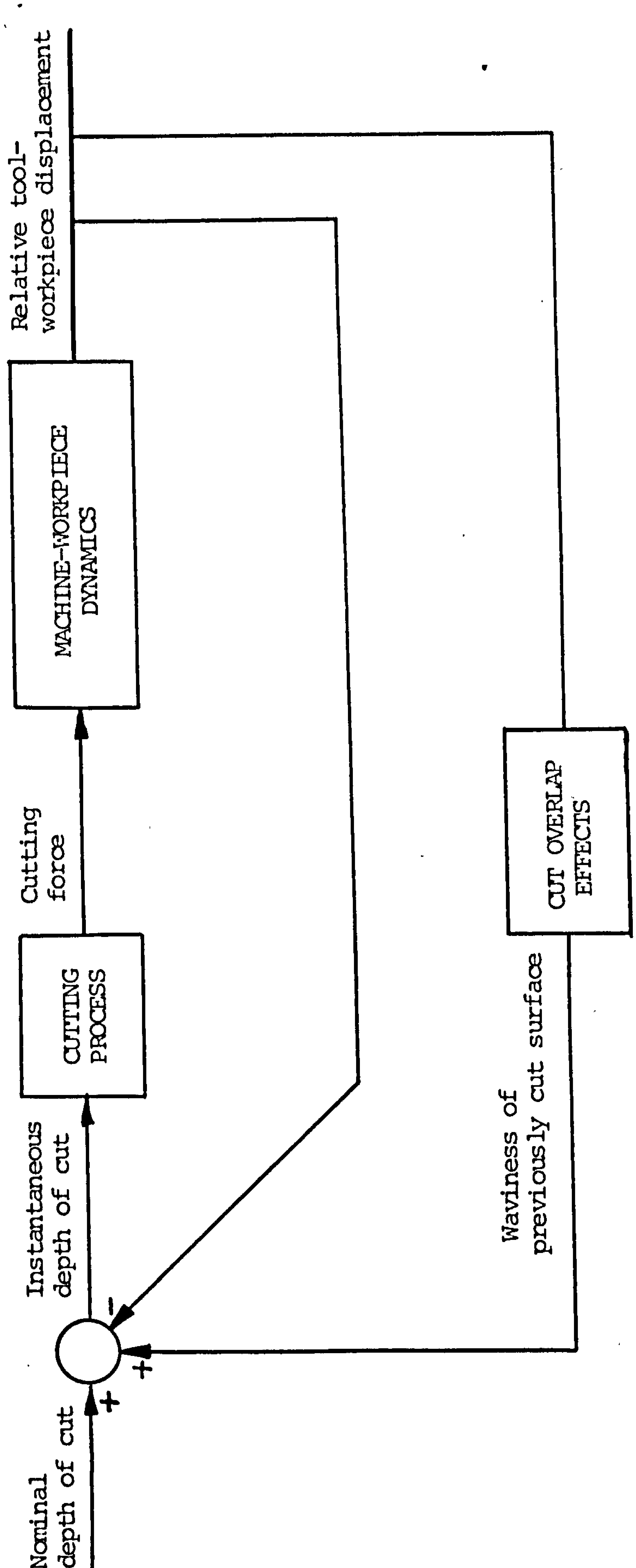
The effect of this system is for the tool to track the relative tool-workpiece displacement in a quantised manner (see FIG1. 6.). Analysis and simulation of the machine system is performed, both with and without the chatter suppressor, to assess its effectiveness and stability. Experiments are performed to validate the analysis and simulation, and to confirm the practical feasibility of the method. All experimental work is done on a medium sized turning lathe, although the basic principles could be developed for other types of machine.

It is found during the project, that by re-programming the chatter suppressor it can be used as a simple, 'bolt-on' CNC device for lathes. Many axisymmetic shapes can be produced by varying the tool position in a pre-determined manner relative to the feedrate. The way in which the tool is moved is calculated by the computer based on the desired shape and the feedrate. This by-product is discussed in greater detail in Chapter 6.



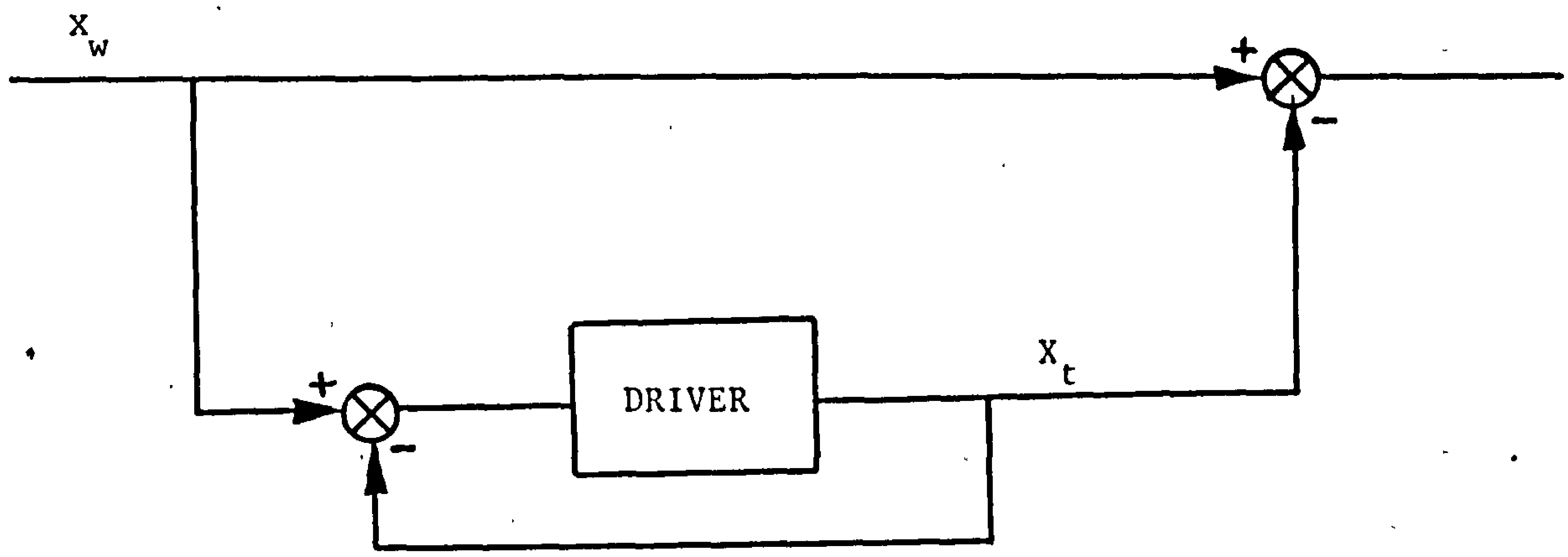
Representation of the machine tool as a closed loop system

FIG. 1.



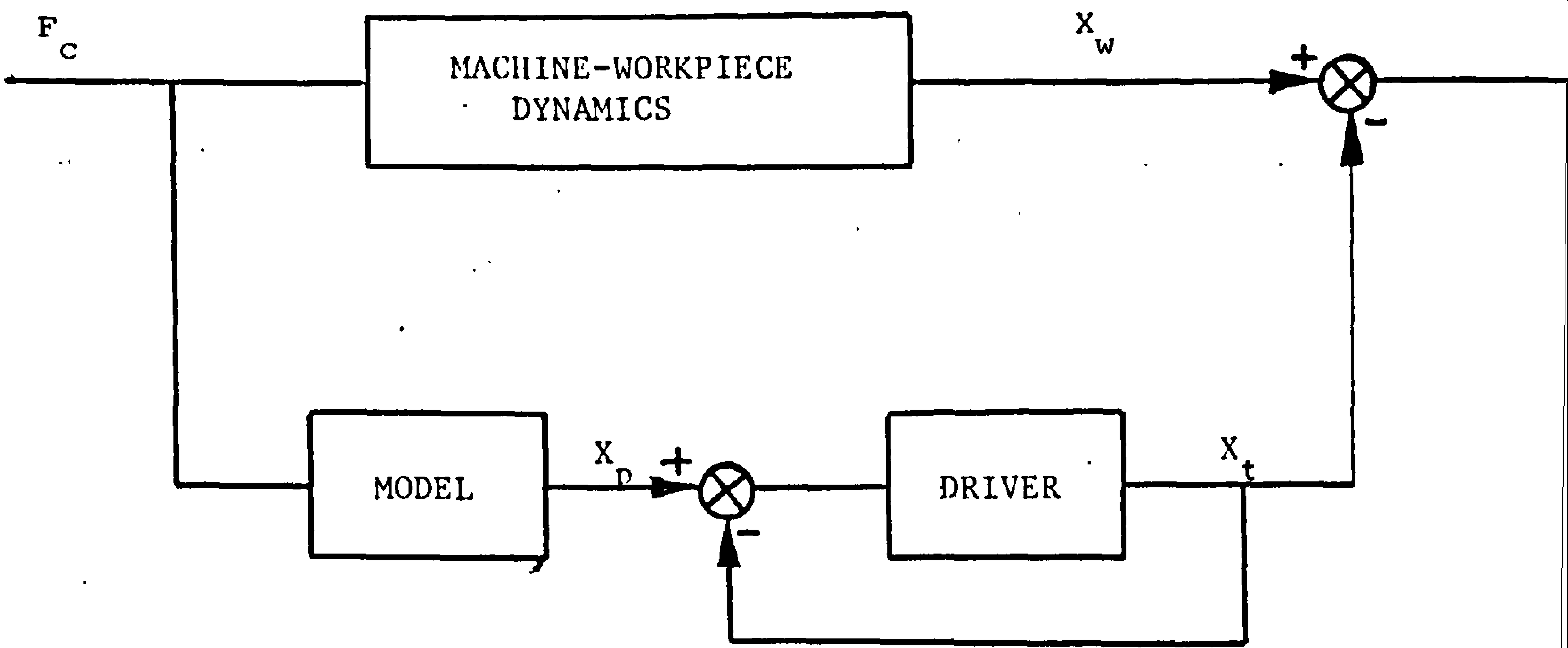
Block diagram for regenerative chatter

FIG. 2.



Comstock's method.

FIG1. 3.



Nachtigal's method.

FIG1. 4.

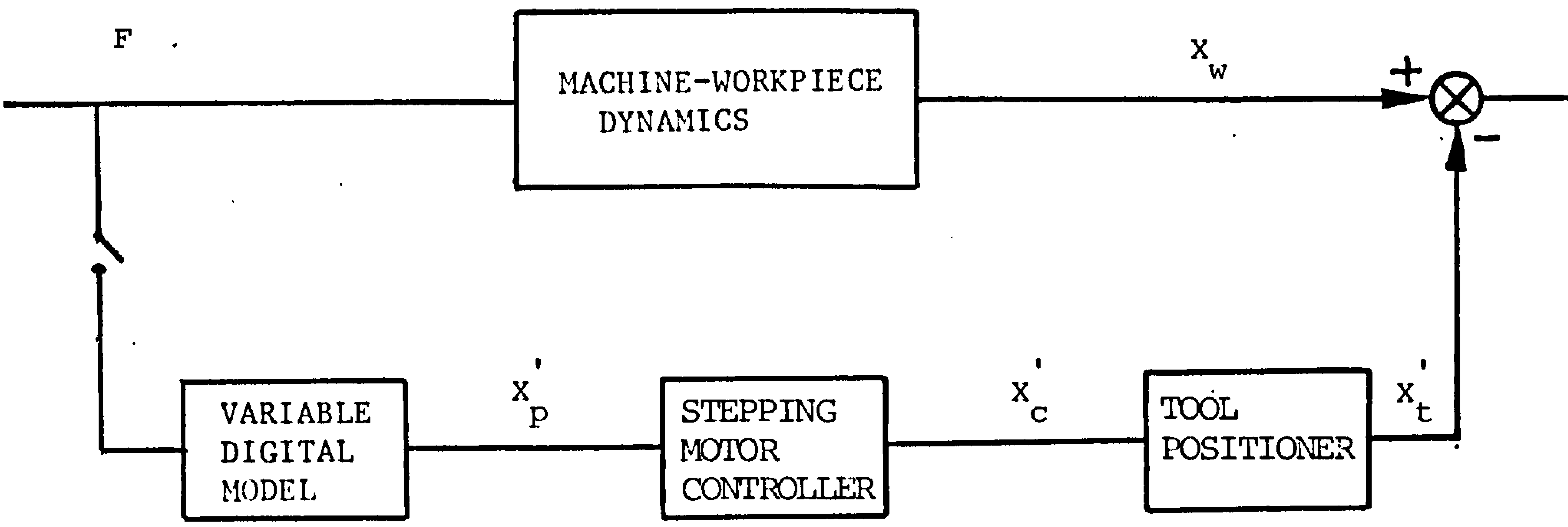
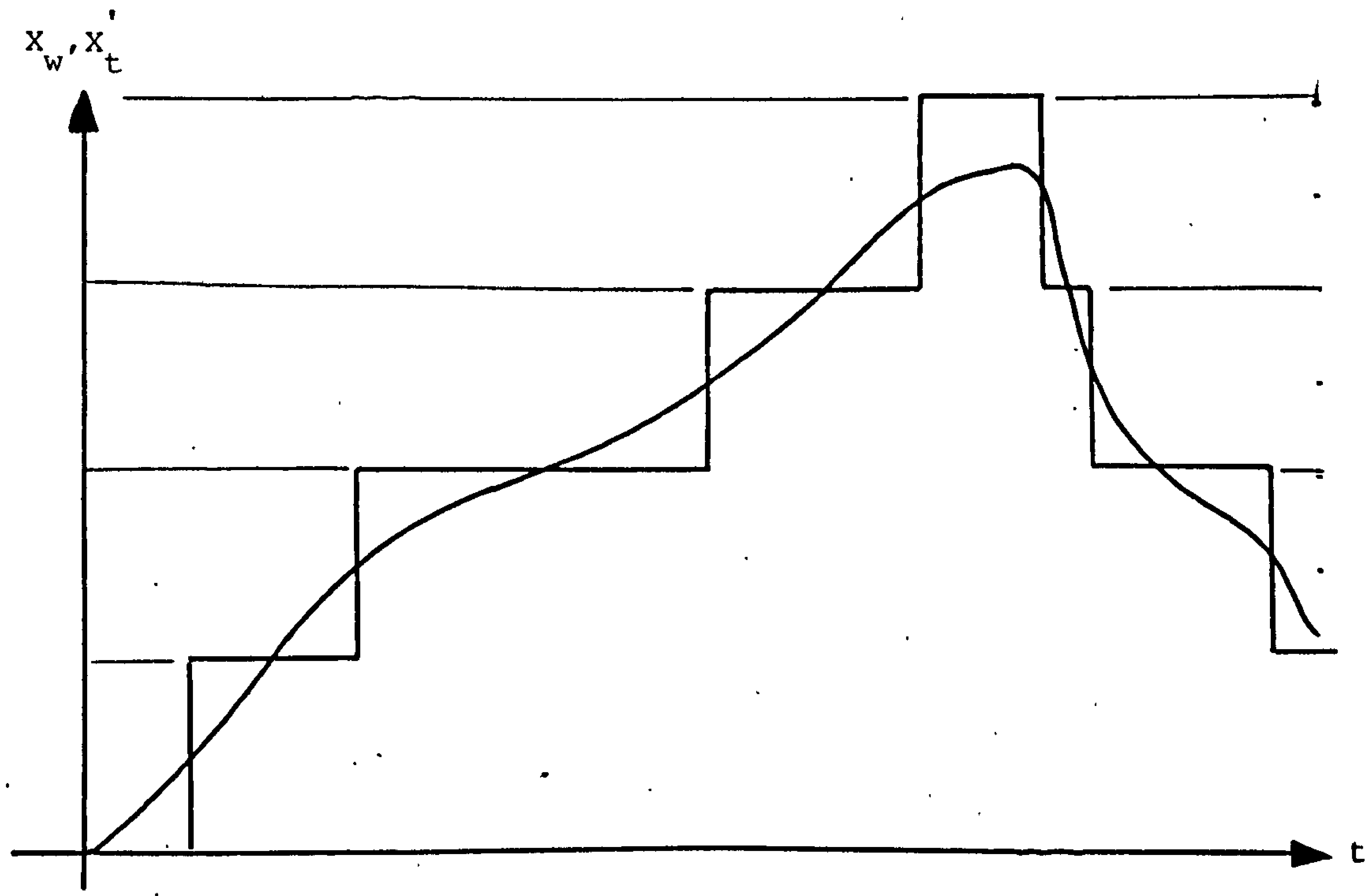


FIG1. 5.



Proposed control method.

FIG1. 6.

2. THEORY OF REGENERATIVE CHATTER.

2. 1. Introduction.

Many dynamic systems can be represented schematically by an arrangement of masses, springs and dampers. Movement will only occur when a disturbance is applied, and any vibration set-up by transient changes in loading will gradually be damped out. Steady-state vibration will only be produced if the disturbance is periodic. Resonance occurs when the frequency of the disturbance is close to one of the natural frequencies of the system.

In machine tools, periodic forces can be introduced by unbalanced rotating components. Usually speed ranges are selected so that the frequencies of these forces do not occur near any known resonance points. Vibrations can also be caused by non-linearities such as clearances, uneven wear and friction, even when no exciting force is present.

Chatter is a vibration phenomenon associated with chip thickness variation and the rotation of the workpiece. As described in the previous chapter, the unstable loop which causes chatter can be represented by the block diagram shown in FIG1.2.

2. 1. 1. The cutting process.

The dynamics of the cutting process are very complex, and much work has been done to gain an understanding of this process (27, 31, 33, 34). However, for the purpose of this analysis, it is sufficient to represent the process by means of an expression which relates cutting force to instantaneous depth of cut. For a given cutting operation many variables can be considered as constants, these are :

-- Rotational speed.
-- Feed rate.

-- Tool material and geometry.

-- Workpiece material and geometry.

-- Environmental conditions.

and the cutting process can be approximated by the linear relationship:-

$$F_c = K_c \cdot U \qquad 2.1$$

2. 1. 2. The machine-workpiece system.

The combined effects of the machine and workpiece dynamics determine how the structure will respond to the force generated by the cutting process. The machine itself is a distributed mass system and much work has been done to analyse its dynamic behaviour (24, 25, 26, 28, 29, 31). It has generally been found that a reasonable model is a simple mass, spring, damper system. This is because most machine tools exhibit one major resonance with other minor modes. It is usually found that the lowest frequency mode has the greatest amplitude.

Next we need to consider the effect of the workpiece on the overall dynamic behaviour of the system. Again it is convenient to approximate the workpiece by a simple mass, spring, damper system. The combined effects of the machine and workpiece can be represented schematically as shown in FIG2.1. The cutting force is generated at the tool-workpiece interface and is transmitted to the machine structure via the workpiece. The equations of motion for this system are as follows:

$$M_m.\ddot{X}_m + C_m.\dot{X}_m + K_m.X_m = C_w.(\dot{X}_w - \dot{X}_m) + K_w.(X_w - X_m) \qquad \text{—— 2.2}$$

$$M_w.\ddot{X}_w + C_w.(\dot{X}_w - \dot{X}_m) + K_w.(X_w - X_m) = F_c \qquad \text{—— 2.3}$$

For the purpose of this analysis, the overall relationship between the cutting force (Fc) and the relative tool-workpiece displacement (Xw) is of interest. This can be obtained by converting equations 2. 2 and 2. 3 via Laplace Transform, and then combining to eliminate Xm. This gives:-

$$\frac{x_w}{f_c} = \frac{\left[M_m.s^2 + (C_m + C_w).s + (K_m + K_w)\right]}{\left[M_w.s^2 + C_w.s + K_w\right].\left[M_m.s^2 + (C_m + C_w).s + (K_m + K_w)\right] - \left[C_w.s + K_w\right.} \qquad \text{—— 2.4}$$

This ratio is the transfer function describing the overall dynamics of the machine-workpiece structure, and can be expressed as :

$$G(s) = \frac{x_w}{f_c} = \frac{A_2.s^2 + A_1.s + A_0}{B_4.s^4 + B_3.s^3 + B_2.s^2 + B_1.s + B_0} \qquad \text{—— 2.5}$$

where:-

$$A_2 = M_m \qquad \text{—— 2.5a}$$

$$A_1 = C_m + C_w \qquad \text{—— 2.5b}$$

$$A_0 = K_m + K_w \qquad \text{—— 2.5c}$$

$$B_4 = M_m . M_w \qquad \text{2.5d}$$

$$B_3 = M_w.(C_m + C_w) + M_m . C_w \qquad \text{2.5e}$$

$$B_2 = M_w.(K_m + K_w) + C_w.(C_m + C_w) + M_m.K_w - C_w^2 \qquad \text{2.5f}$$

$$B_1 = C_m.(K_m + K_w) + K_w.(C_m + C_w) - 2.C_w.K_w \qquad \text{2.5g}$$

$$B_0 = K_w.(K_m + K_w) - K_w^2 \qquad \text{2.5h}$$

2. 1. 2. 1. Special cases.

There are two special cases which are of interest. The first is where the machine has a much higher stiffness than the workpiece, i.e. $Km >> Kw$, so that the machine can be considered as effectively rigid. Hence the dynamics of the system are totally dependant on the workpiece characteristics. This is represented schematically in FIG2. 2. The transfer function is a simple second-order type:-

$$G(s) = \frac{x_W}{f_C} = \frac{1}{M_W.S^2 + C_W.S + K_W} \qquad 2.6$$

This relationship can also be obtained from equation 2. 4, by dividing top and bottom by Km, and neglecting any terms with Km in the denominator.

The second case is where the workpiece is much stiffer than the machine, i.e. Kw>> Km. Hence, the extra mass of the workpiece merely modifies the effective mass of the machine. This is represented schematically in FIG2. 3. The transfer function in this case is:-

$$G(s) = \frac{x_W}{f_C} = \frac{1}{(M_W + M_m).S^2 + C_m.S + K_m} \qquad 2.7$$

This transfer function can also be obtained from equation 2. 4, by dividing top, and bottom by Kw, and neglecting any terms with Kw in the denominator.

2. 1. 2. 2. The general case.

In general this type of system will exhibit two resonance modes. At the lower frequency both masses will be moving in-phase and at the higher frequency they will be out-of-phase. The resonance frequencies, and the amplitude characteristics at these points will depend on the relative charactistics of two subsystems.

2. 1. 3. The feedback effects.

The instantaneous chip thickness is determined by the cut, the relative tool-workpiece displacement, and the waviness of the previously cut surface overlapped by the tool, This waviness having been formed by the relative tool-workpiece displacement on the preceeding cycle. Depending on the type of cutting operation and the tool geometry, only a fraction of the preformed surface will be overlapped. Hence, the instantaneous depth of cut can be expressed in terms of the following relationship:-

$$U(t) = U_o - X_w(t) + \mu . X_w(t-T) \qquad 2.8$$

The coefficient μ allows for the fractional overlap of successive cuts. This expression can also be written in terms of Laplace Transforms:-

$$U(s) = U_o - H(s).x_w(s) \qquad 2.9$$

Where:-

$$H(s) = 1 - \mu . e^{-sT} \qquad 2.9a$$

2.2. The chatter model.

The equations derived in sections 2. 1. 1, 2. 1. 2, and 2. 1. 3, can be combined to give an overall block diagram for the chatter model as shown in FIG2. 4. The frequency responses of both the machine-workpiece transfer function and the feedback transfer function are presented in the next sections, followed by an analysis of the open loop frequency response.

2. 2. 1. The frequency response of the machine-workpiece system.

The frequency response of the machine-workpiece system is obtained by making the substitution of jw for S in equation 2.5 giving:-

$$G(jw) = \frac{C_1 + j.C_2}{D_1 + j.D_2} \qquad 2.10$$

Where:-

$$C_1 = A_0 - A_2.w^2 \qquad 2.10a$$

$$C_2 = A_1.w \qquad 2.10b$$

$$D_1 = B_0 - B_2.w^2 + B_4.w^4 \qquad 2.10c$$

$$D_2 = B_1.w - B_3.w^3 \qquad 2.10d$$

This rationalises to give:-

$$G(jw) = P + j.Q \qquad 2.11$$

Where:-

$$P = \frac{C_1.D_1 + C_2.D_2}{D_1^2 + D_2^2} \qquad 2.11a$$

$$Q = \frac{C_2 . D_1 - C_1 . D_2}{D_1^2 \quad D_2^2} \qquad \text{———————— 2.11b}$$

These equations give rise to a polar plot with the general form shown in FIG2. 5. The equivalent form of the Bode diagram is shown in FIG2. 6a, and FIG2. 6b. The in-phase resonance occurs at the point when $W \approx W_1$ and the out-of-place resonance at the point when $W \approx W_2$. Examples of several basic combinations are presented in the figures FIG2.7 to FIG2.9. In all the examples the machine characteristics (dimensionless) were taken to be:-

$$M_m = 0.03$$

$$K_m = 120{,}000$$

$$C_m = 0.1$$

In FIG2. 7, the workpiece was made significantly less stiff than the machine (K_W = 12,000), and the effective mass of the workpiece was varied from greater to less than the effective mass of the machine. In FIG2. 8, the stiffnesses of the machine and workpiece were set equal, and in FIG2. 9, the stiffness of the workpiece was significantly greater than that of the machine (K_W = 1200,000).

It can be seen that the gain at the in-phase resonance (lower frequency mode) is much greater than that at the out-of-phase resonance. For all but FIG2. 8a., the gains at the out-of-phase resonances were so small that they could not be shown on the same scale as the in-phase resonances. For each figure, it can be seen that as the effective mass of the workpiece is decreased the gains at the in-phase resonances decrease, and the frequency at which the resonances occur decrease.

The purpose of this investigation is to show that it is reasonable, for many machine-workpiece configurations, to assume that the machine-workpiece system can be approximated by a simple second-order system. This approximation is helpful when performing the stability analysis for both the controlled and uncontrolled chatter system. It is also useful when selecting a suitable form for the controller model.

2. 2. 2. The frequency response of the feedback loop.

The frequency response of the feedback loop can be obtained from the following relationship:-

$$H(jw) = 1 - \mu . e^{-jwT} \qquad 2.12$$

By writing:-

$$e^{-jwT} = \cos(wT) - j.\sin(wT) \qquad 2.12a$$

We have:-

$$H(jw) = [1 - \mu.\cos(wT)] + j.[\mu.\sin(wT)] \qquad 2.13$$

This expression can be represented by the polar plot shown FIG2. 10, or the Bode diagram shown in FIG2. 11a, and FIG2. 11b.

2. 2. 3. The open loop frequency response.

The open loop frequency response for the system shown in FIG2. 4, is given by the following expression:-

$$K_c.G(jw).H(jw) \qquad 2.14$$

By writing:-

$$G(jw) = A(w).e^{j.\alpha(w)} \qquad 2.15$$

$$H(jw) = B(w).e^{j.\beta(w)} \qquad 2.16$$

This gives:-

$$K_c.M(w).e^{j.\phi(w)} \qquad 2.17$$

Where:-

$$M(w) = A(w).B(w) \qquad 2.17a$$

$$\phi(w) = \alpha(w) + \beta(w) \qquad 2.17b$$

This gives rise to the family of generalised open loop polar plots as shown in FIG2. 12. This form is generated by the interaction of the periodic effects of the feedback loop and the resonance effects of the machine-workpiece system. The main feature is the major resonance loop which is displaced by the effects of the feedback effects. Some polar plots of actual systems are shown in FIG2. 13. The system parameters (dimensionless) associated with all the plots are as follows:-

$M_m = 0.003$		
$K_m = 120{,}000$	Machine parameters	
$C_m = 0.1$		
$\mu = 1.0$	Feedback parameters	
$T = 0.2$		
$K_c = 1.0$	Cutting gain	

and the numbers attached to each plot decribe the workpiece parameters as in FIG2. 7, 2. 8, and 2. 9.

2. 2. 4. Frequency response analysis.

2. 2. 4. 1. Simplified stability criterion.

It was shown by Nachtigal (2) that the characteristic equation may be written as:-

$$1 + \frac{K_c}{K_m}\left[1 - \mu.e^{-sT}\right].G(s) = 0 \quad \text{——— 2.18}$$

Hence, at the boarderline of stability the expression gives:-

$$\frac{K_c}{K_m} G(jw) = \frac{-1}{1 - \mu e^{-jwT}} \quad \text{——— 2.19}$$

It can be shown that the right-hand side of equation 2. 19 has a real part no greater than -0. 5. Thus, a criterion for unconditional stability becomes:-

$$Re\left[\frac{K_c}{K_m} G(jw)\right] > -0.5 \quad \text{——— 2.20}$$

This relationship will usually give a pessimistic limit for K_c as the stability limit is more accurately determined from the minimum real value on the real axis, which is usually greater than the minimum real value.

2. 2. 4. 2. The Nyquist stability criterion.

For the types of plot shown in FIG2. 12, the limit of stability can be determined using the Simplified Nyquist Stability Criterion. For a given cutting process (i.e. fixed G(s) and H(s)) a value of Kc can be found that will give a plot that goes through the point (-1,j0). This is the limiting value of Kc below which the system will be stable, and hence chatter will not occur. This will be a more realistic estimate than that derived by Nachtigal.

For the systems shown in FIG2. 13, the approximate limiting values of Kc are as follows:-

(1) $K_c \leqslant 420$

(2) $K_c \leqslant 230$

(3) $K_c \leqslant 13$

(4) $K_c \leqslant 40$

(7) $K_c \leqslant 250$

2. 2. 4. 3. Chatter frequency.

The behaviour of a system, when chattering, can be determined by considering the effect of closing the loop. Oscillations will only be propogated around the loop, allowing the build-up of chatter, when the open loop phase is -180° and the gain is greater than unity. Hence, the chatter frequency can be predicted by examination of the polar plot to see when these conditions are fulfilled. It can be seen from FIG2. 13, that the predicted chatter frequencies for the systems considered, are as follows:-

① $w_c = 348$

② $w_c = 601$

③ $w_c = 1028$

④ $w_c = 782$

⑦ $w_c = 972$

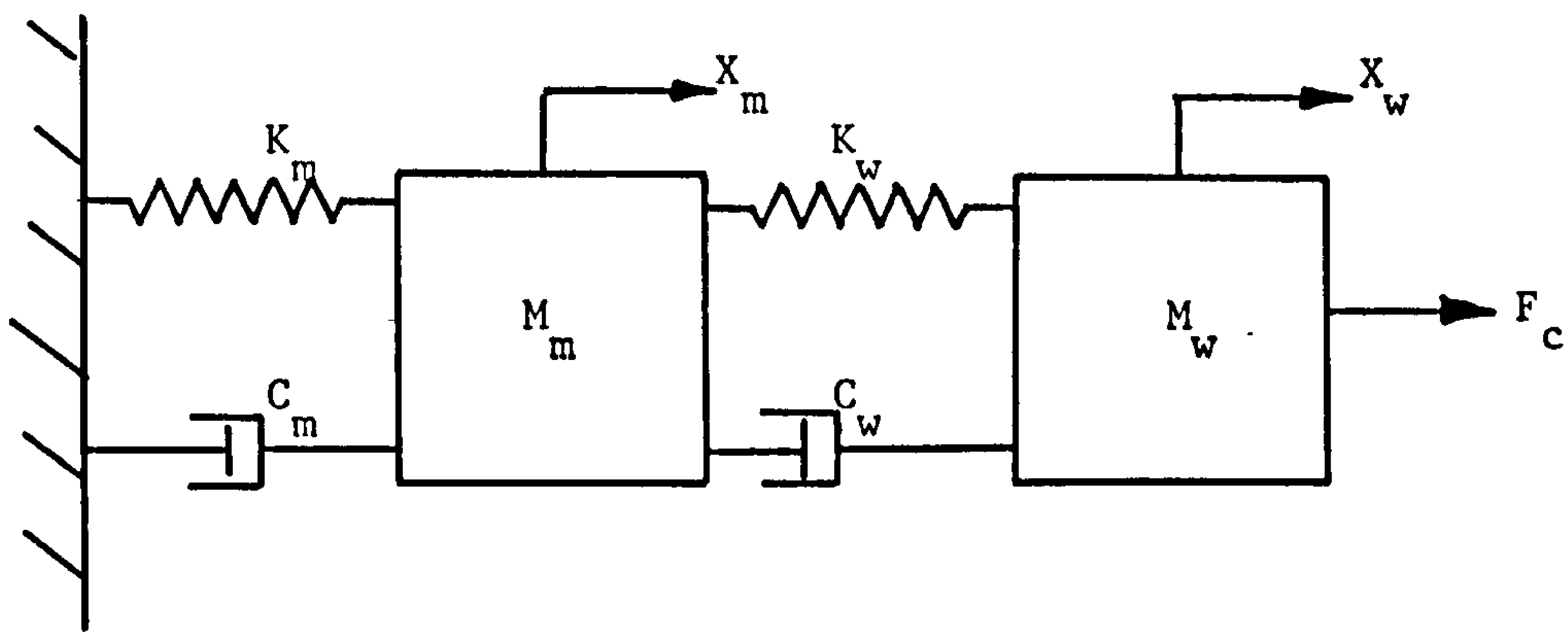
2. 2. 4. 4. Review of frequency response analysis.

As has been shown, the frequency response analysis can be used to estimate the stability limits and chatter frequencies of machining systems. The stability limit is determined by the interaction of the machine-workpiece dynamics and the feedback effects. The chatter frequency usually occurs near the dominant natural frequency of the machine-workpiece structure. Although in this analysis a model has been used for the machine-workpiece dynamics, it is possible to analysise actual systems by experimentally finding the frequency response and using this in place of the model. Much work has been done (24, 25, 26, 28, 29) into experimental determination of machine tool frequency responses.

2. 3. Chatter simulation.

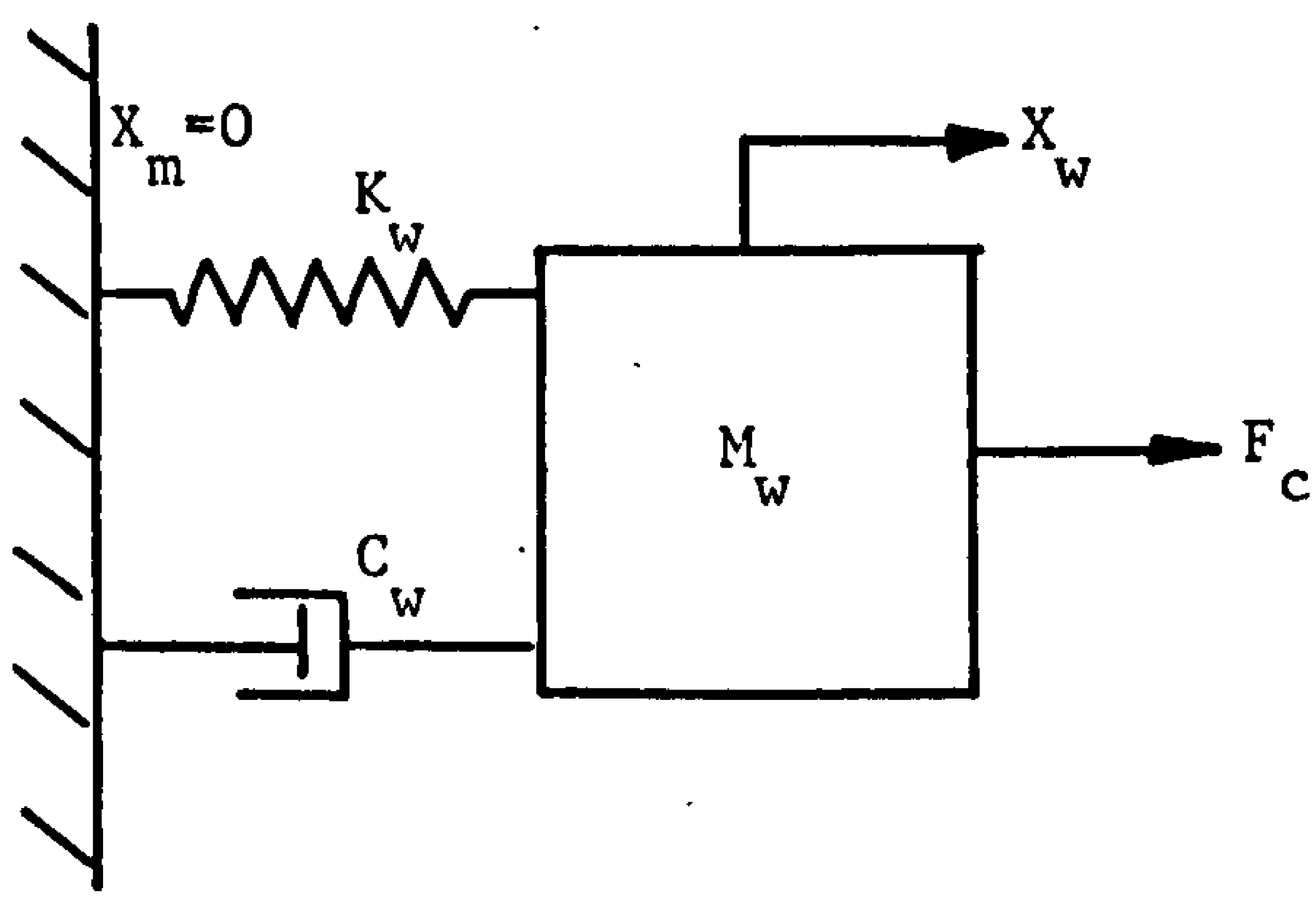
In order to support the findings of the frequency analysis and to investigate the transient behaviour of the machine tool system, a dynamic simulation is performed. This is implemented on an IBM 360, using the digital simulation language CSMP (41). The model used in the simulation has been described in section 2. 1, and is presented in block diagram form in FIG2. 4. A digital approach is chosen in preference to an analogue method to facilitate case of simulation of the delay term in the feedback loop. Systems (1), (2), (3), (4), (7) (as described in sections 2. 2. 1, and FIG'S 2. 7a, 2. 7b, 2. 8a, 2. 9a) are simulated to verify the stability limits predicted in sections 2. 2. 4. 2, and the chatter frequencies predicted in sections 2. 2. 4. 3. Results are presented only for systems (1) & (2) as these are found to be entirely representative of the general trends for all the systems. FIG'S 14 & 17 demonstrate the limits of stability and chatter frequencies for systems (1) and (2) respectively. The limits of stability for K_c are within 8% of the values predicted by the analysis, and the chatter frequencies are within 3%. FIGS2. 15 & 2. 16 and FIGS2. 18 and 2. 19 show chatter build-up for systems (1) & (2) respectively, for values of Kc 3 and 5 times greater than the stability limit. For all the systems, the agreement between the simulation results and the analysis is always better than 10% for the stability limit and 5% for the chatter frequency, and are usually considerably better.

The programme used to perform the simulation is described in APPENDICES A.3 and B.3



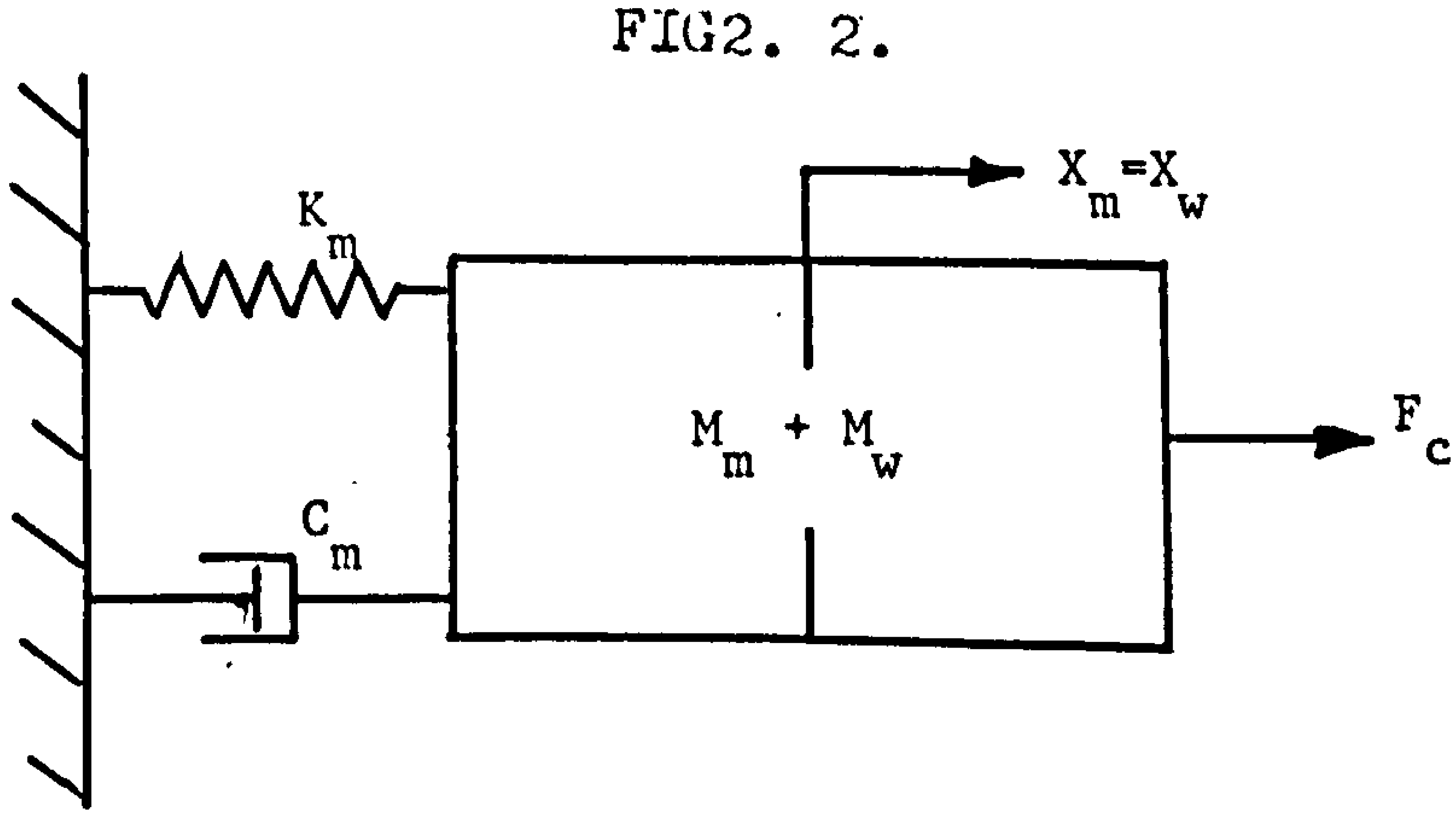
General model of machine-workpiece system.

FIG2. 1.



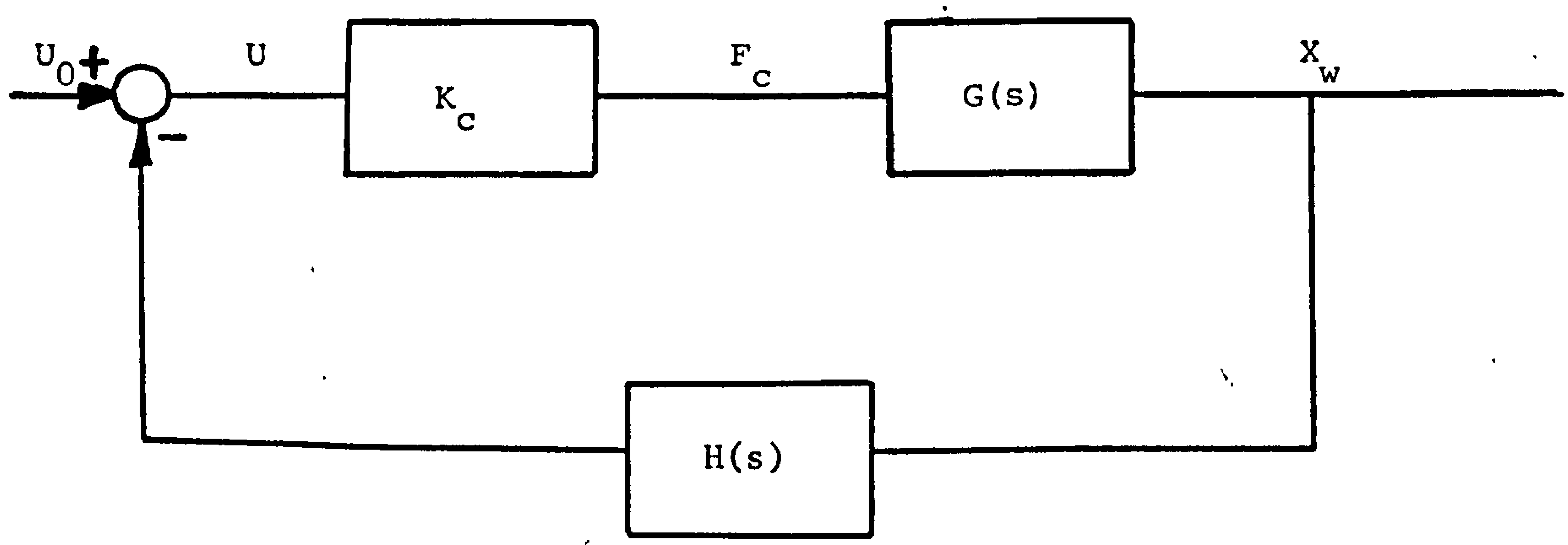
Approximate model of machine-workpiece system for $K_w \ll K_m$.

FIG2. 2.



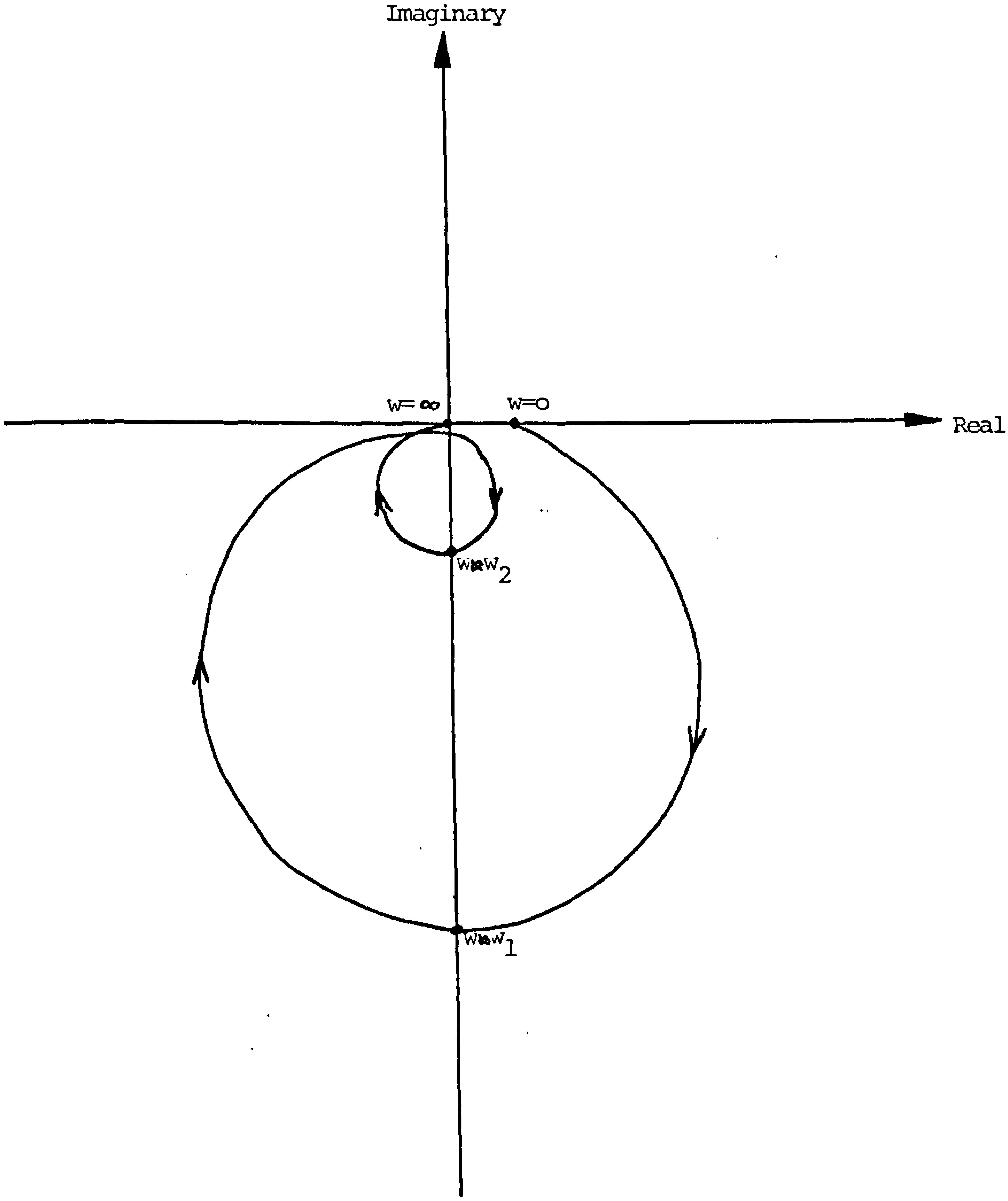
Approximate model of machine-workpiece system for $K_m \ll K_w$.

FIG2. 3.



Block diagram for regenerative chatter.

FIG2. 4.



Polar plot for machine-workpiece model

FIG2. 5.

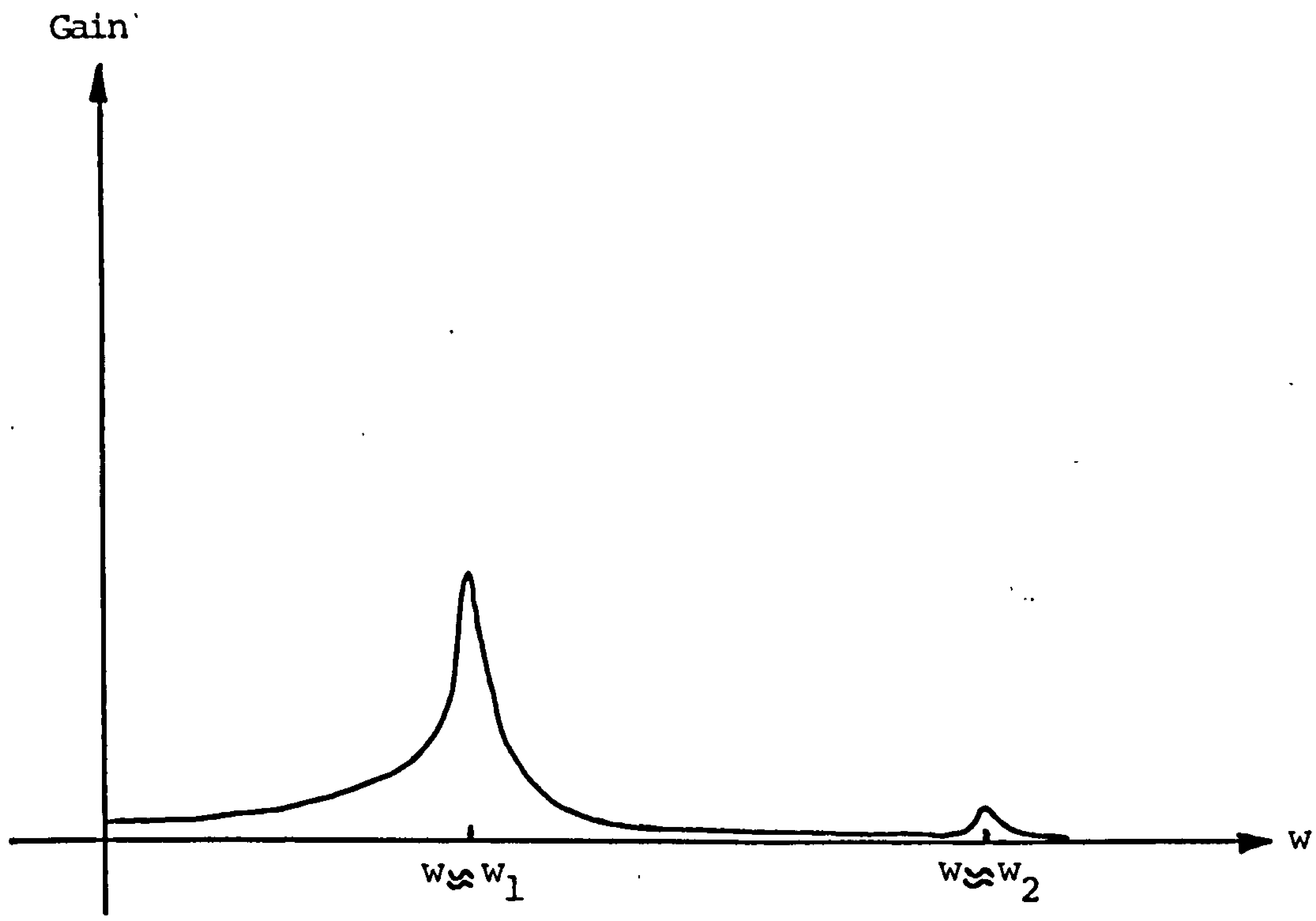
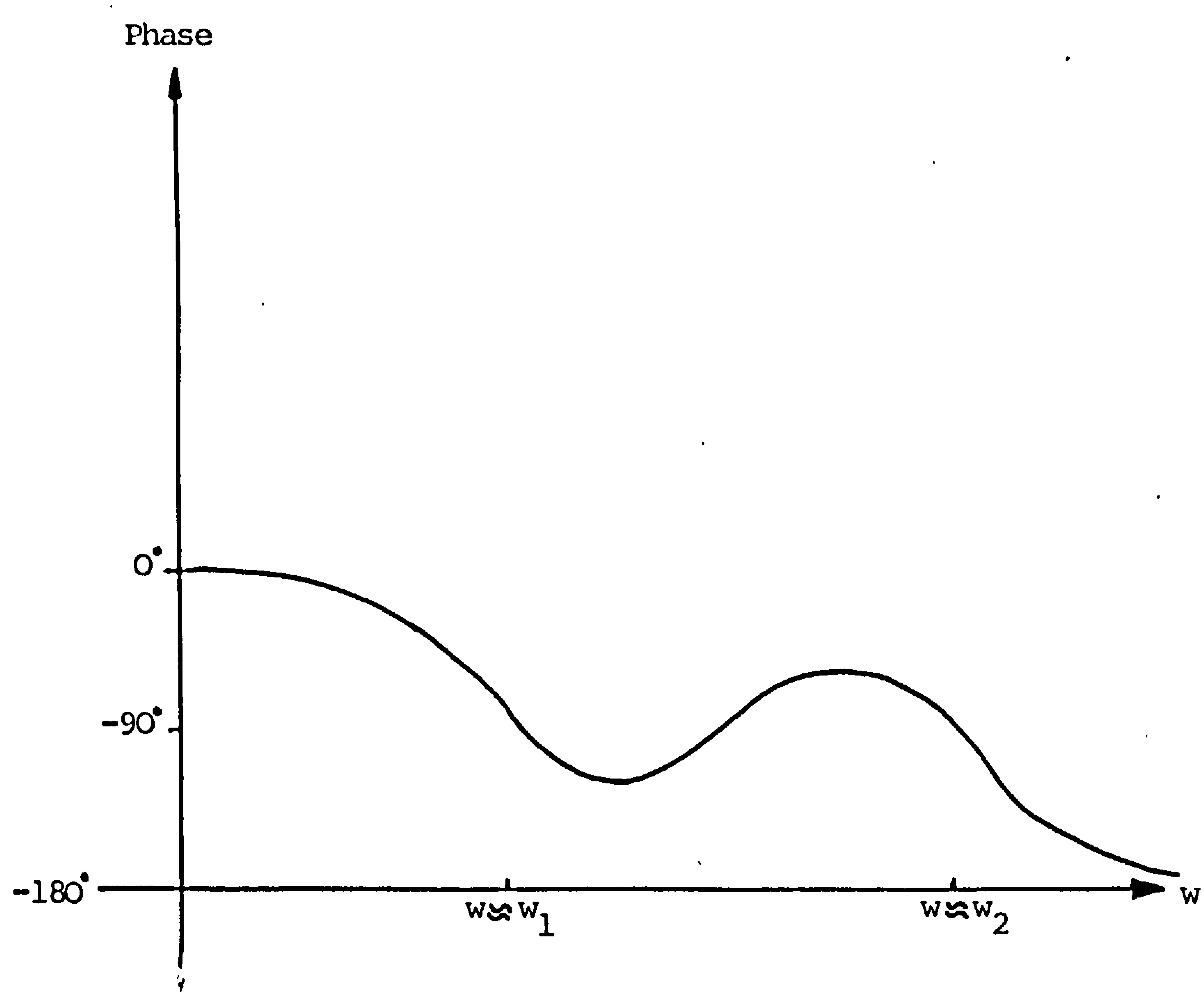
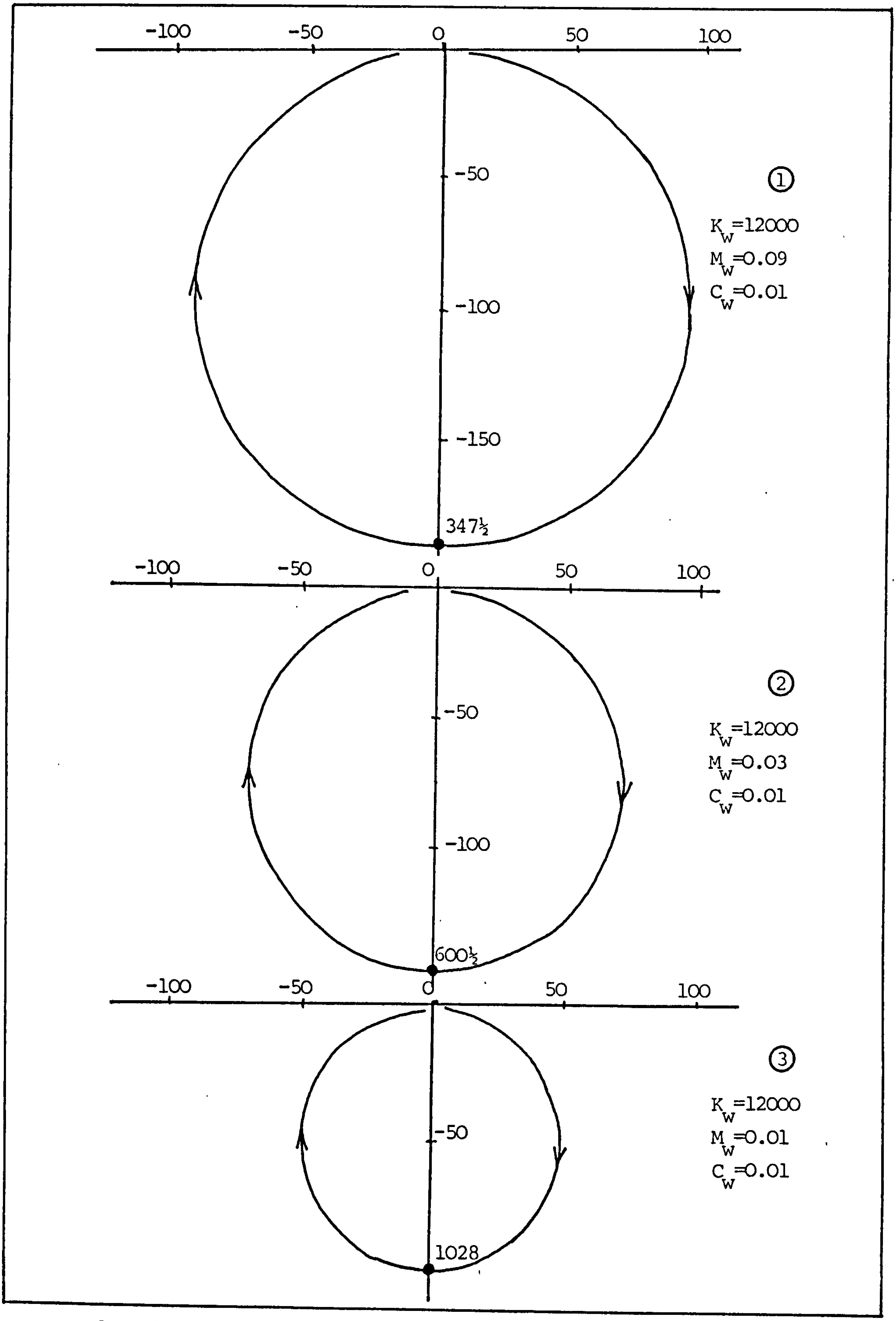


FIG2. 6a.



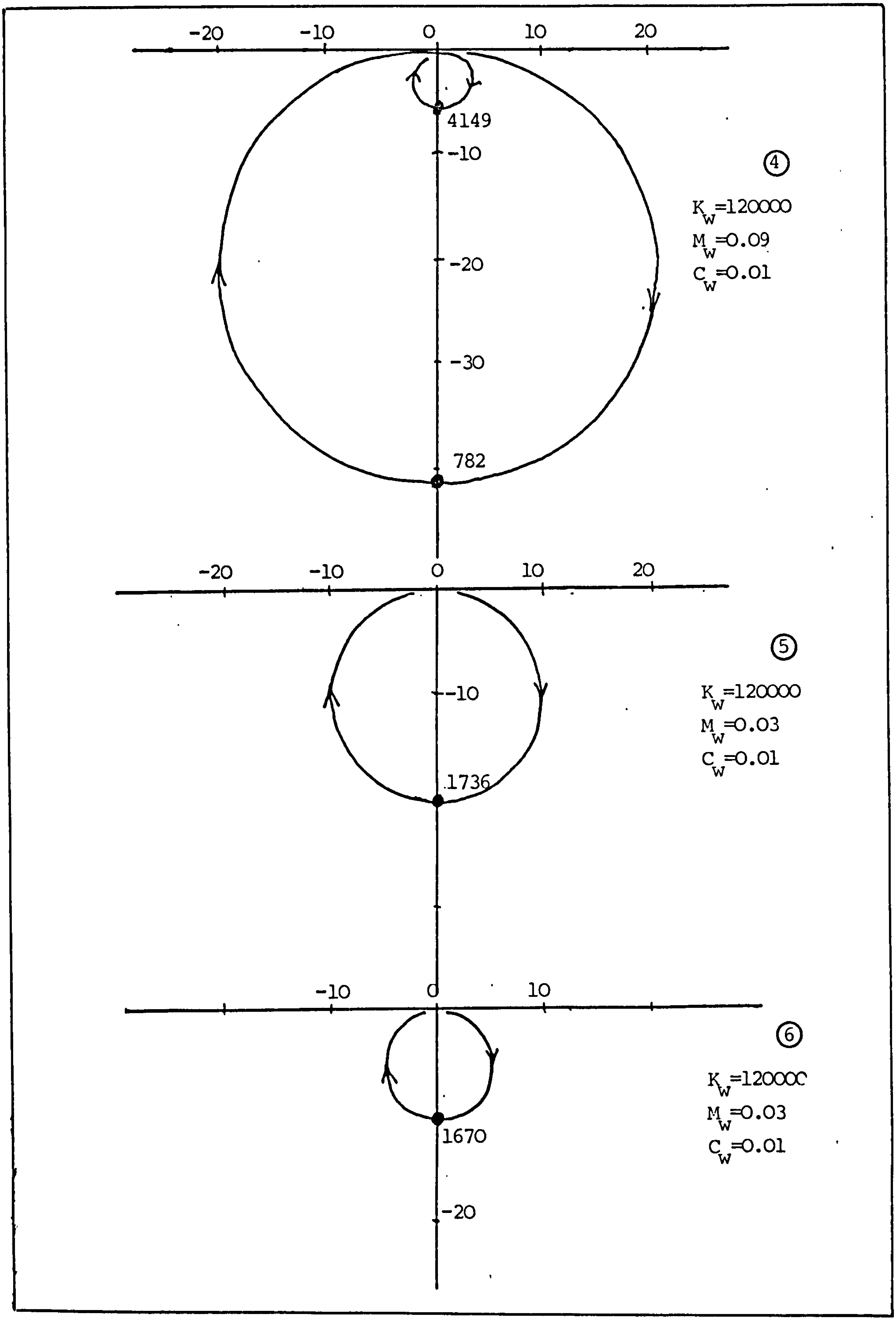
Bode diagram for machine-workpiece model

FIG2. 6b.



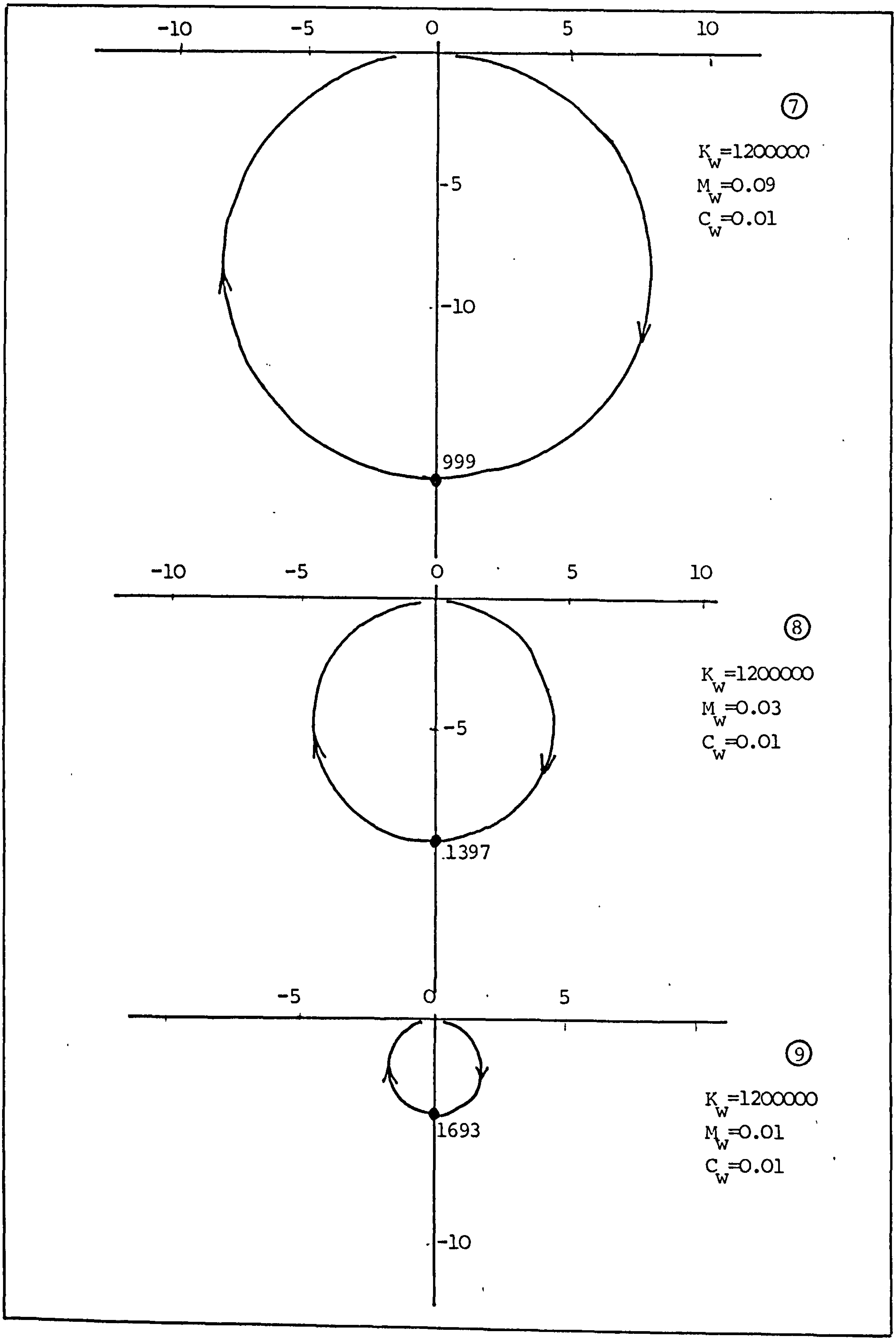
Polar plots for specific combinations of machine and workpiece.

FIG. 7.



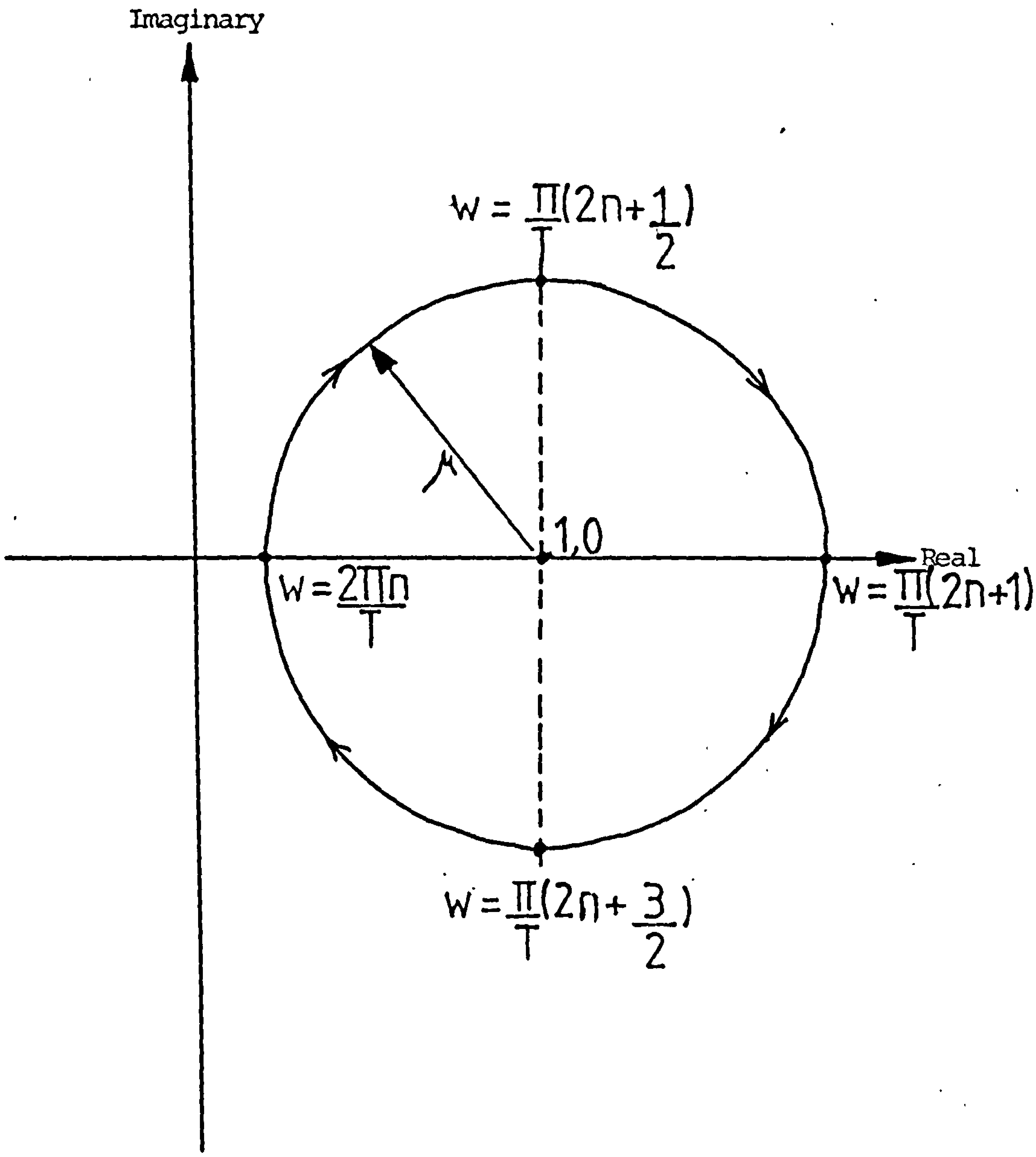
Polar plots for specific combinations of machine and workpiece

FIG2. 8.



Polar plots for specific combinations of machine and workpiece

FIG2. 9.



Polar plot for the feedback transfer function

FIG2. 10.

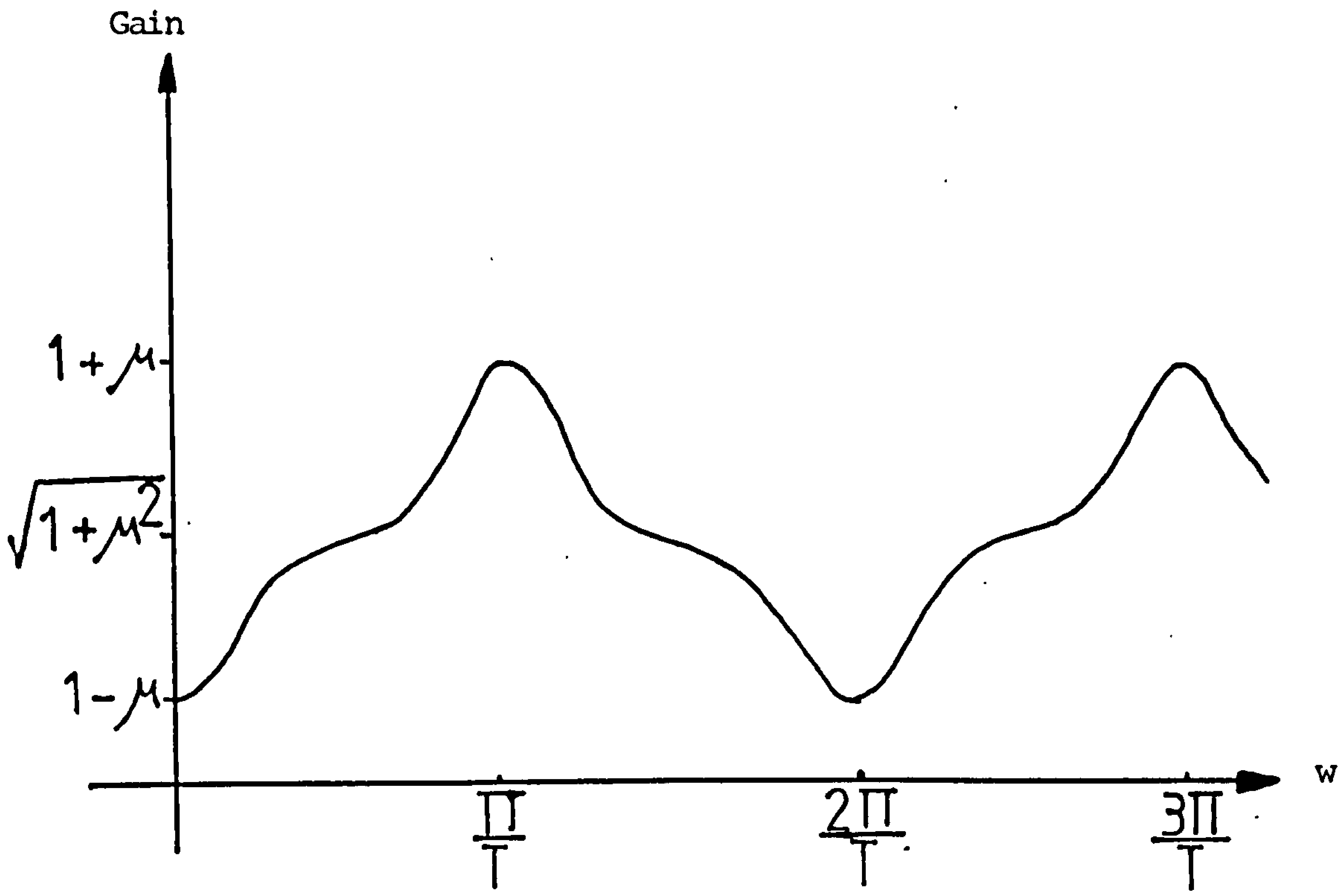
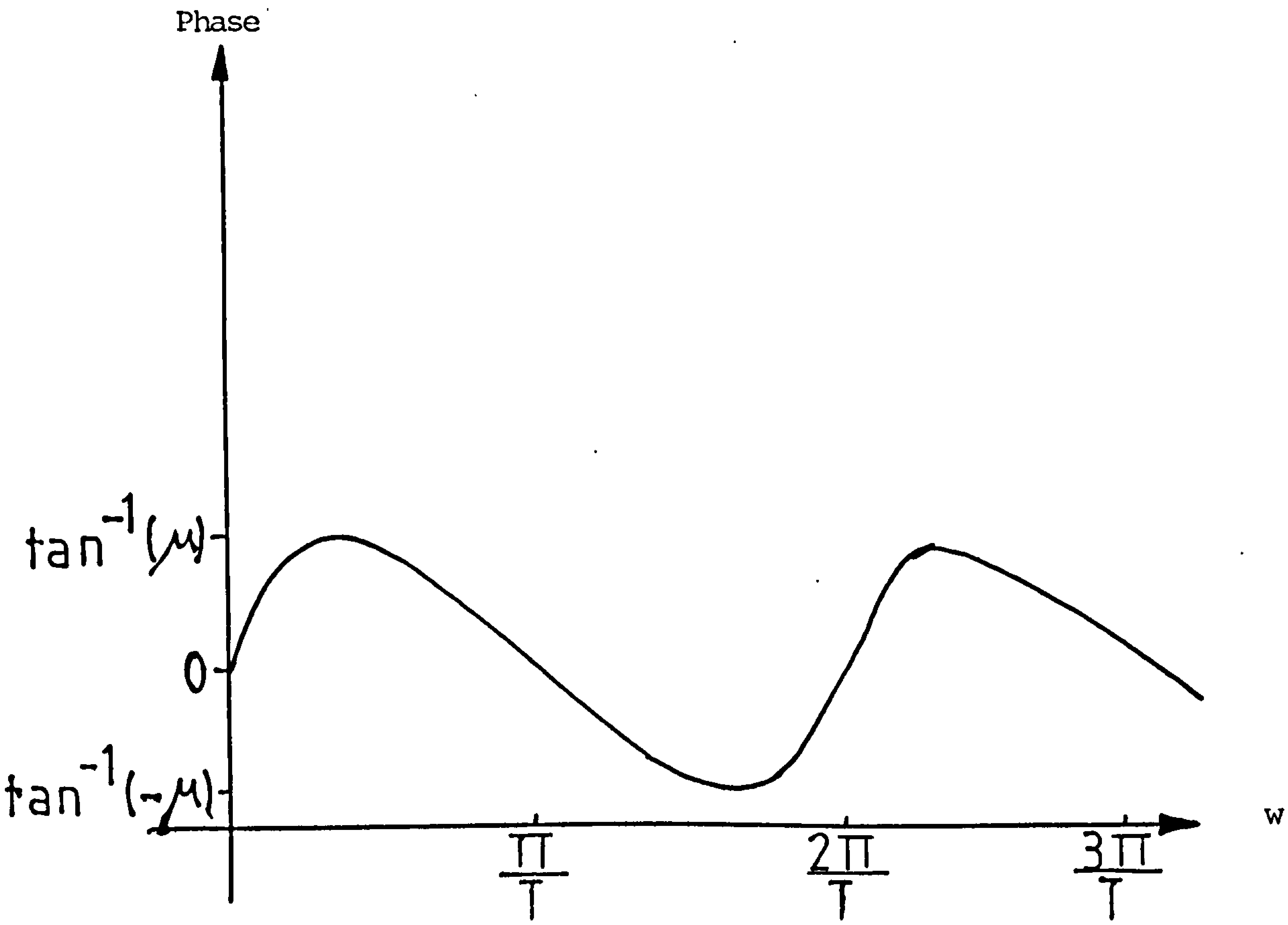
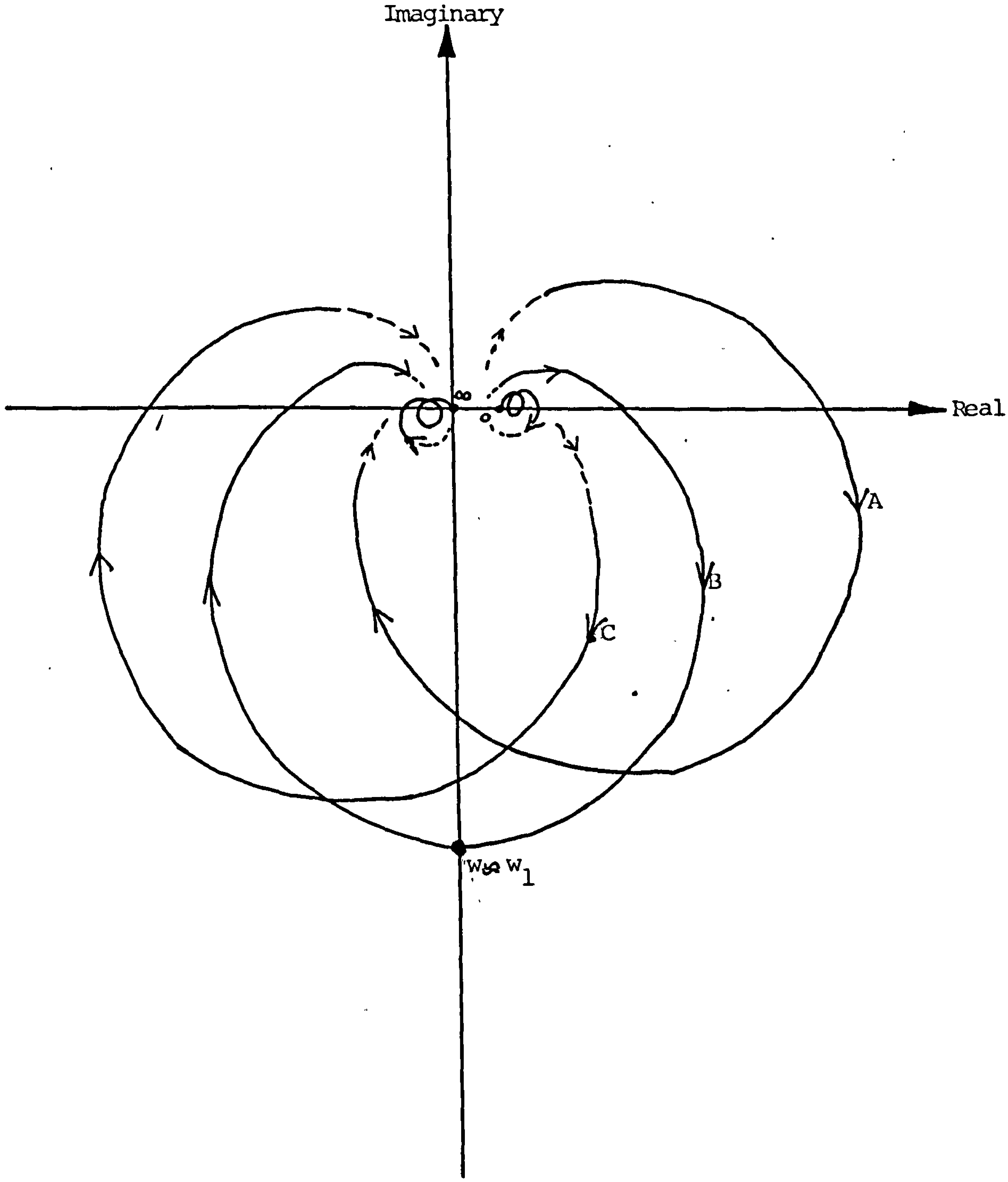


FIG2. 11a.



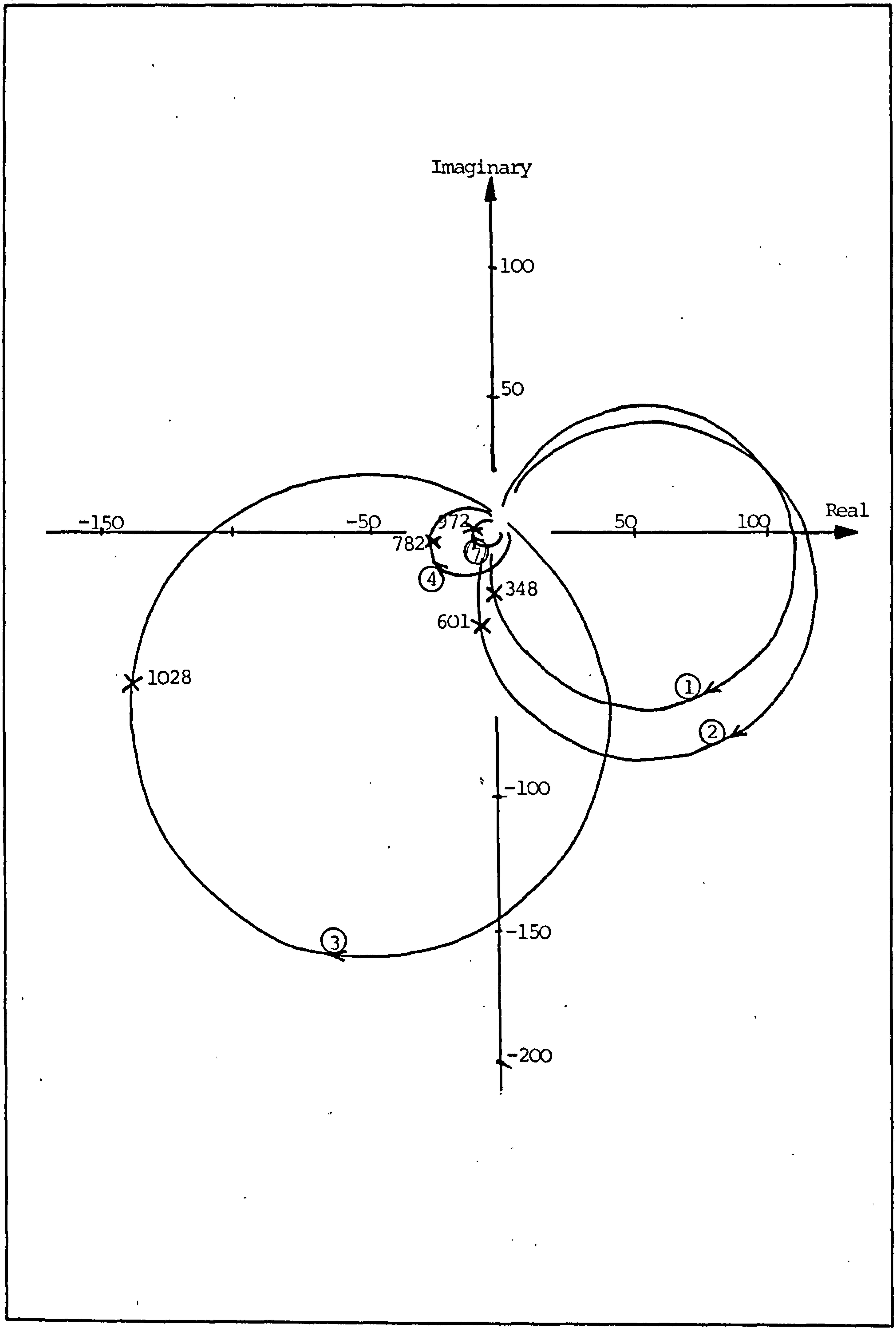
Bode plot for feedback element

FIG2. 11b.

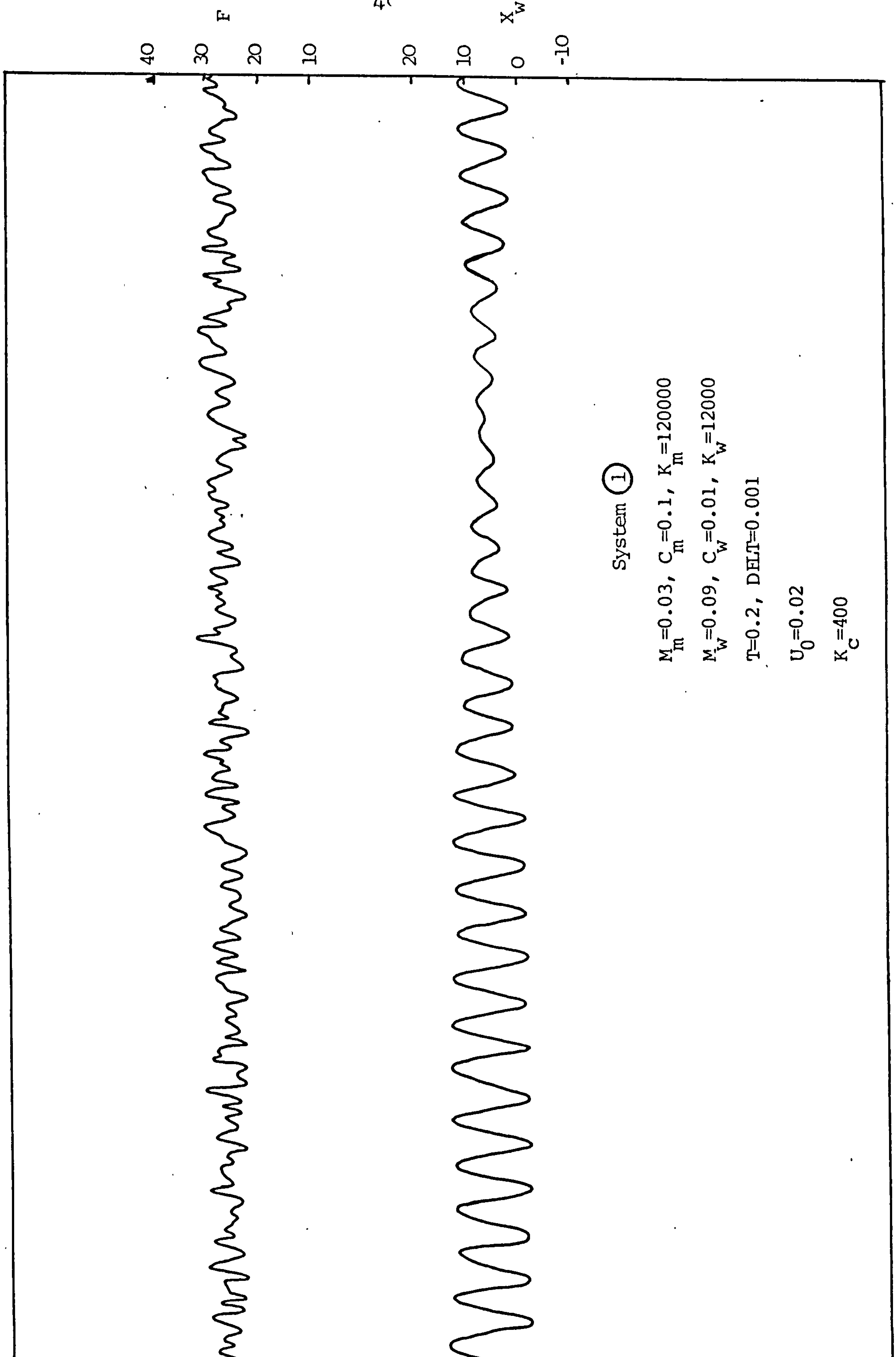


Generalised polar plot for open loop response

FIG2. 12.



Some specific open loop responses
FIG2. 13.

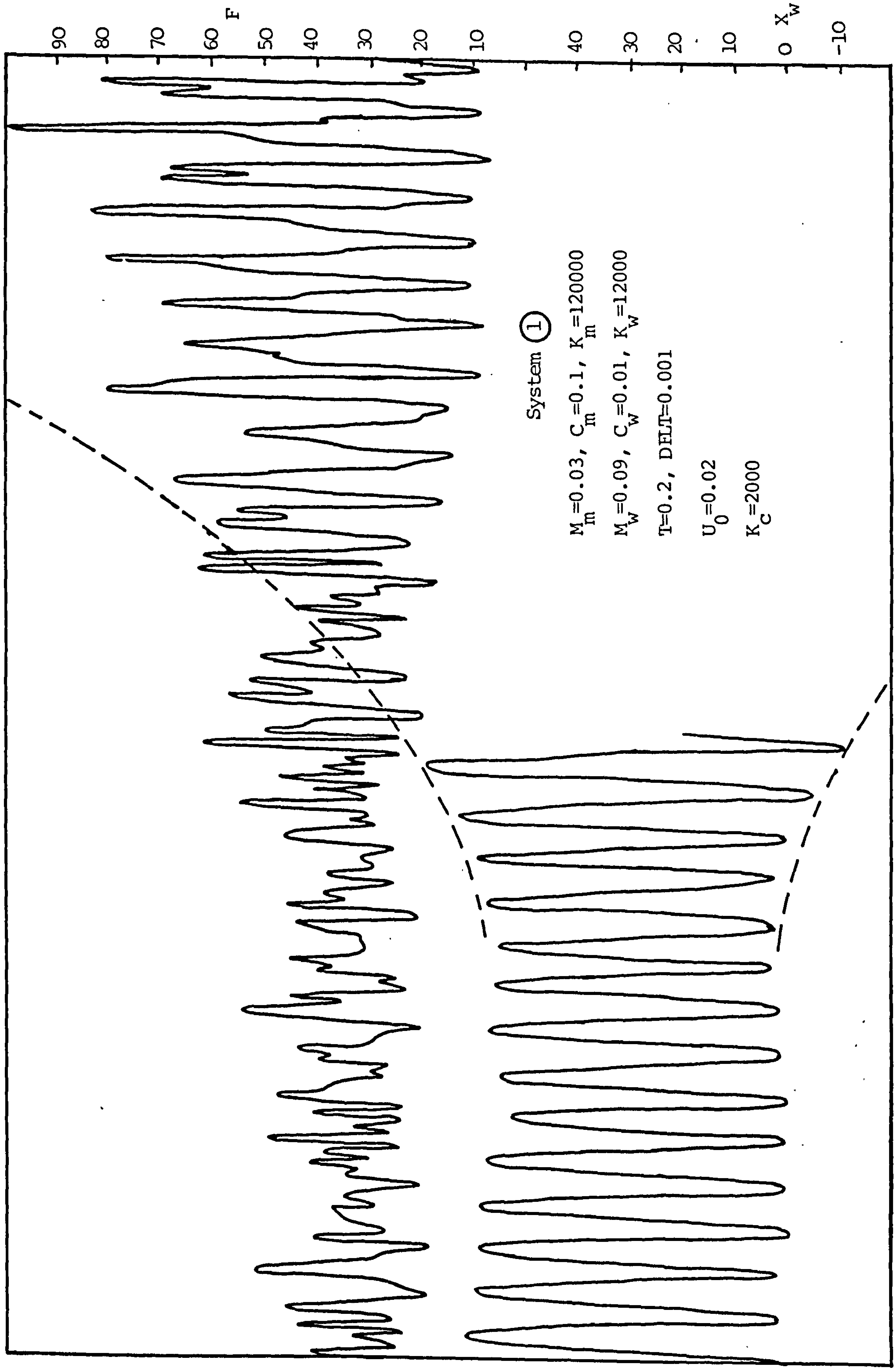


Chatter simulation - System (1) ,limit of stability

FIG2. 14.

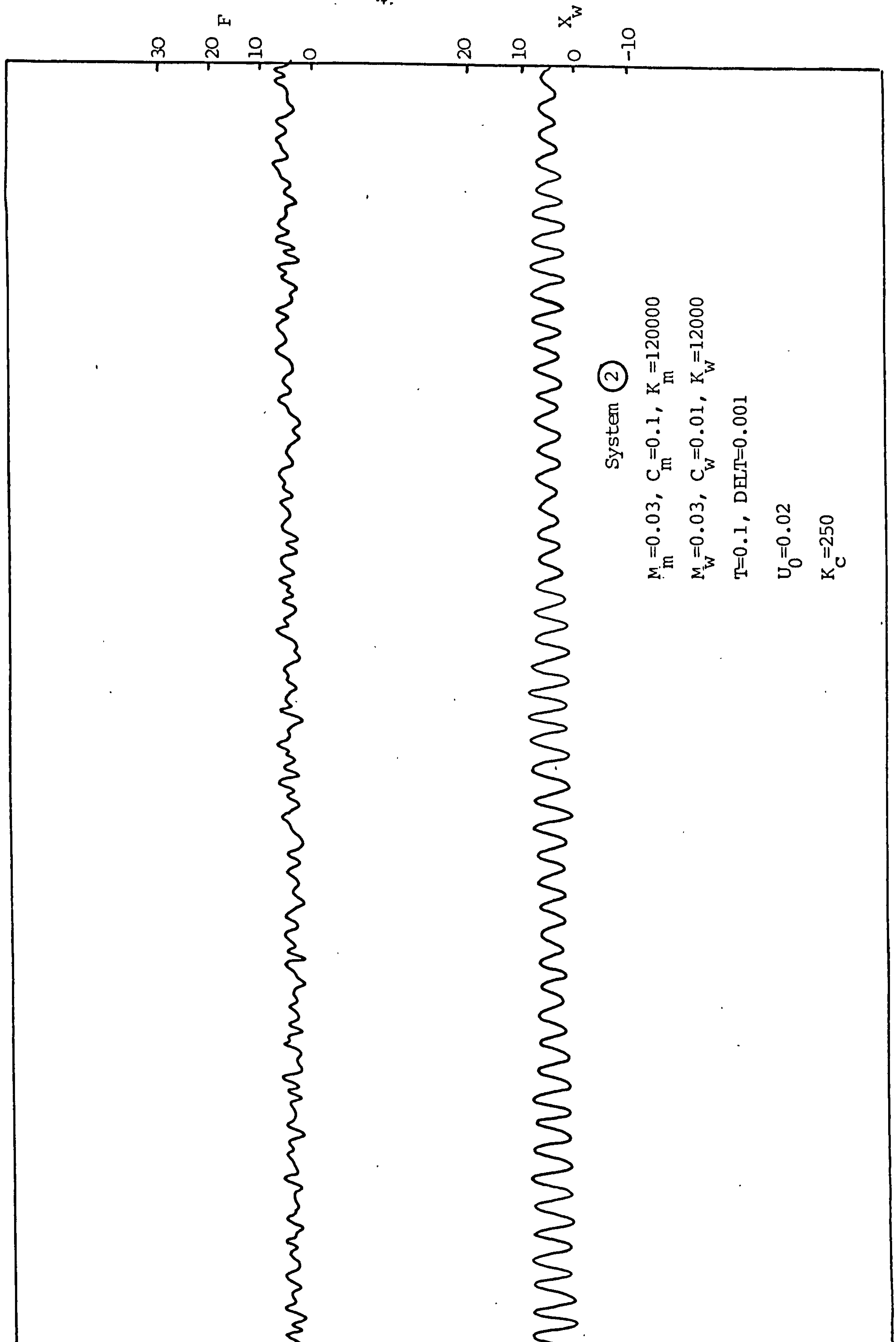
Chatter simulation - System (1) ,chatter buildup

FIG. 15.



Chatter simulation - System (1) ,chatter buildup

FIG2. 16.

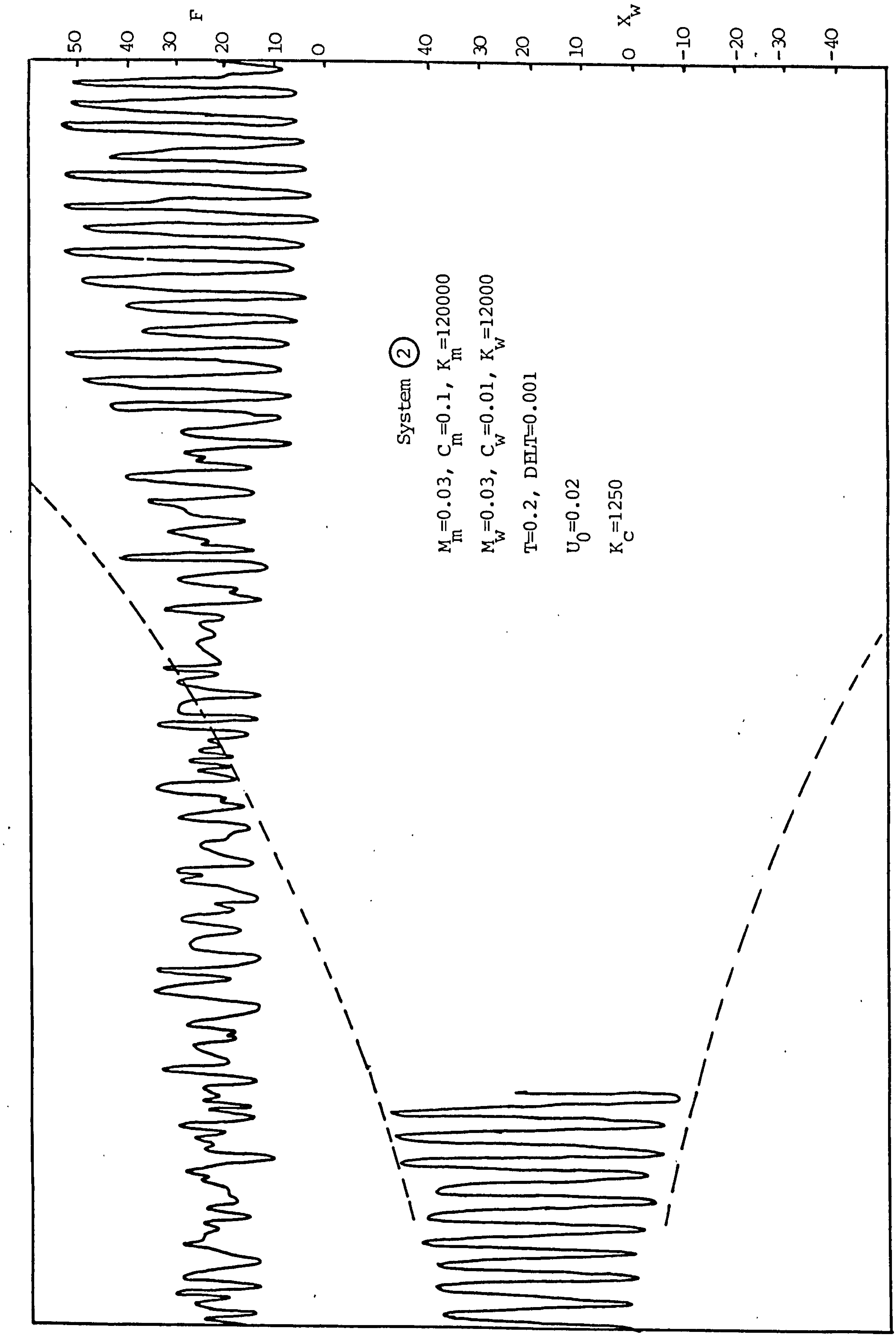


Chatter simulation - System (2), limit of stability

FIG2. 17.

Chatter simulation - System (2) ,chatter buildup

FIG2. 18.



Chatter simulation - System (2) ,chatter buildup

FIG2. 19.

3. CHATTER SUPPRESSION ANALYSIS.

3. 1. Introduction.

The control philosophy is based on the concept of creating a machine-workpiece-controller system with an infinite apparent stiffness; i.e. no matter what variations occur in the cutting force, the relative tool-workpiece displacement remains constant and equal to the nominal depth of cut. This is achieved by means of an active tool positioner. The basic system is presented in block diagram form in FIG3. 1. Ideally X_w will equal X_t at all times, so that the relative tool-workpiece displacement is maintained constant, and chatter will never build-up.

The next consideration is to choose a suitable input signal to the controller. As mentioned in section 1. 4, Comstock uses a measure of the relative tool-workpiece displacement (FIG1. 3) and Nachtigal uses a measure of the cutting force (FIG1. 4). It is proposed in this thesis to develope Nachtigal's method, by using a variable, digital model to predict the relative tool-workpiece displacement, and use a digital control algarithm to drive a stepping-motor tool positioner. The system is presented in block diagram form in FIG1. 5.

It is shown in the previous chapter that the machine-workpiece dynamics can reasonably be approximated by a second-order system. Hence, it is proposed to use a digital, second-order model to represent the machine-workpiece system. In terms of Z-transforms this can be respresented as follows (8, 15, 16, 18):-

$$G(z) = \frac{X_p'(k)}{F_c'(k)} = \frac{A_1.Z^{-1} + A_2.Z^{-2}}{1 + B_1.Z^{-1} + B_2.Z^{-2}} \qquad 3.1$$

where $Z^{-n} = e^{-nT}$; i.e. a delay of n sample intervals. Therefore the output at the k th. sample instant is given by:-

$$X_p'(k) = A_1.F_c'(k-1) + A_2.F_c'(k-2) - B_1.X_p'(k-1) - B_2.X_p'(k-2) \qquad 3.2$$

This model is used to predict the relative tool-workpiece displacement at a given instant, from previously sampled values of cutting force and displacement.

A digital controller is then used to convert these predicted values into control pulses to drive the stepper motor to the corresponding tool position. At its simplest, the controller merely calculates the number of steps and direction that the motor needs to move from its present position to get to the predicted position.

By using a digital computer to implement both the model and controller it gives very wide scope to introduce more complex models or sophisticated controllers to improve the overall performance. The only limitations on system complexity are the computer power and the time available between samples. There will be no financial cost penalties as with analogue or fixed digital controllers.

In order to simplify the analysis of the system it is assumed the stepper motor has zero inertia and no damping. The overall effect of the controller and stepper motor is to behave in a manner that can be approximated by a quantizer. A block diagram of the simplified system is presented in FIG3. 2. If it is assumed that the model is an exact representation of the machine-workpiece dynamics, this system reduces to that shown in FIG3. 3a, which simplifies to the non-linearity shown in FIG3. 3b. Both of these approximations must be considered when assessing the accuracy and usefulness of this analysis. The overall block diagram for the controlled system is shown in FIG3. 4, where N_1 is the non-linearity shown in FIG3. 3b.

3. 2. Stability analysis.

The behaviour and stability of this type of system can be determined for the open loop characteristic:-

$$K_c.G(jw).N_l.H(jw) \qquad 3.3$$

and the interaction between the linear and non-linear parts. The non-linearity can be analysed using the Describing Function method. However, because the input will generally not have a zero mean, it is necessary to use the Dual-Input Describing Function (17). For the purpose of this analysis it is assumed that the input can be approximated by steady-state level with a superimposed sine wave:-

$$x(t) = B + A.\sin(w.t) \qquad 3.4$$

The effect of the non-linearity on a signal of this type is shown in FIG3. 5. The DC gain (17) for the non-linearity can be expressed by:-

$$N_A = \frac{1}{2\pi B}\int_0^{2\pi} y(B + A.\sin\theta).d\theta \qquad 3.5$$

and the AC gain (17) by:-

$$N_B = \frac{1}{\pi A}\left[\int_0^{2\pi} y(B + A.\sin\theta).\sin\theta.d\theta + j.\int_0^{2\pi} y(B + A.\sin\theta).\cos\theta.d\theta\right] \qquad 3.6$$

where:-

$$\theta = w.t \qquad 3.6a$$

and $y(B + A\sin\theta)$ is the output from the non-linearity. It can be shown(17) that for the non-linearity of FIG3. 5., these give:-

$$N_B = 1 - \frac{D}{A}\sum_{i=1}^{n}\left[p\left[\frac{[(2i-1)/2].H + B}{A}\right] - p\left[\frac{[(2i-1)/2].H - B}{A}\right]\right] \quad \text{—— 3.7}$$

where:-

$$p(\gamma) = \begin{cases} -1/2 & \text{---------- } \gamma < -1 \\ [1/\pi].\sin(\gamma) & \text{------- } |\gamma| \leq 1 \\ 1/2 & \text{---------- } \gamma > 1 \end{cases} \quad \text{—— 3.7a}$$

and:-

$$N_A = 1 - \frac{D}{A}\sum_{i=1}^{n}\left[q\left[\frac{[(2i-1)/2].H + B}{A}\right] - q\left[\frac{[(2i-1)/2].H - B}{A}\right]\right] \quad \text{—— 3.8}$$

where:-

$$q(\gamma) = \begin{cases} [2/\pi].\sqrt{1 - \gamma^2} \\ 0 \end{cases} \quad \text{—— 3.8a}$$

Using these expressions for the DC and AC gains the relationship between the input and output for the non-linearity can be approximated as follows:-

$$y(A+B.\sin\theta) = N_B.B + N_A.A.\sin\theta \qquad 3.9$$

This gives an output of the same form as the input but with a DC component of $N_B.B$ and an AC amplitude of $N_A.A$ It can be seen from the expressions for N_B and N_A that there is coupling between the DC component and the AC gain, and the AC amplitude and the DC gain. This gives rise to two sets of functions, one set for N_A vs A for various fixed B and one set for N_B vs B for various fixed A. Some examples of these functions are presented in FIG3. 6, and 3. 7. At this stage, it is obvious that stability analysis using the Describing Function method becomes unwieldly. However, it is useful to obtain a qualitative insight into the behaviour of the controlled system.

It can be seen from FIG'S 3. 6, and 3. 7, that both the AC and DC gains exhibit similar trends. When the respective variable amplitudes are near zero the behaviour of the non-linearity is strongly influenced by the corresponding fixed amplitude. If the fixed amplitude is near a quantization level a small initial increase in the variable amplitude will cause a relatively large decrease in the output (one quantization level), hence the non-linearity exhibits a large negative gain. Whereas, with the fixed amplitude away from a quantization level, it takes a larger initial increase in the variable amplitude to cause a quantization jump, and hence the effective gain is smaller. In both cases the gain is unity until the first quantization jump occurs. Beyond this initial region the gain varies cyclically about zero due to the effect of successive quantization levels. Due to the limiting behaviour of the non-linearity the overall trend is for the gains to tend to zero as the variable amplitudes tend towards infinity.

Although the Describing Function method does not, in this application, give a successful quantitative analysis of the proposed chatter suppression method, it does prove useful in indicating qualitative trends. As is usually the case, the results of the Describing Function analysis must be viewed with caution owing to the approximations involved, however it is clearly indicated that the overall effect is stabilising.

3. 3. Chatter suppression simulation

Simulation of the chatter suppression method gives another method of studying the behaviour of the controlled system. It enables a more comprehensive and realistic examination of the control method. Digital simulation is used to facilitate simulation of the delay term and the quantizer. A block diagram of the overall system considered in the simulation is presented in FIG3. 8.

The control method is applied to the machine-workpiece systems (1) and (2), as described in section 2. 3, and whose uncontrolled behaviour is shown in FIG'S 2. 15, and 2. 16, and FIG'S 2. 18, and 2. 19, respectively. Parameters for the controller and tool positioner are based on values for the experimental controller and tool positioner described in the next chapter. The step size and equivalent mass, spring, damper values are as follows:-

$$S_s = 0.00067$$

$$K_t = 17000$$

$$M_t = 0.033$$

$$C_t = 0.2$$

The second-order model parameters are chosen to represent three basic cases:

-- The 'best' second-order approximation of machine-workpiece dynamics.
-- The natural frequency of the model below that of (i).
-- The natural frequency of the model above that of (i).

'Best' is taken to mean a model that has a polar plot that coincides with the major loop of the machine-workpiede plots shown in FIG'S 2. 7a, and 2. 7b.

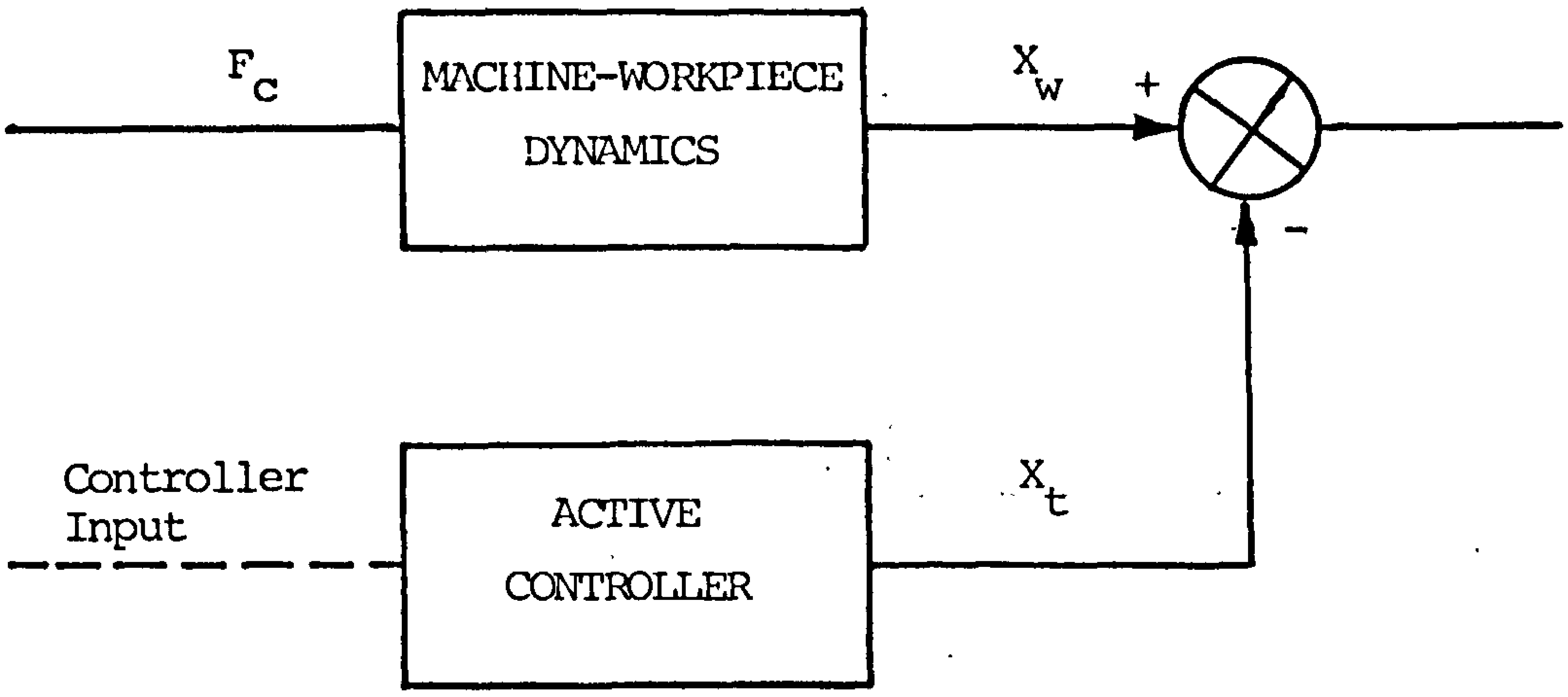
Similations are performed with values of K_c 3 and 5 times greater than the limiting values for both systems. Results are presented for system (1) in FIG'S 3. 9, and 3. 10, and for system (2) in FIG'S 3. 11, and 3. 12. It can be seen that although there is some vibration present, the systems have not become unstable. FIG'S 3. 13, and 3. 14, are both for system (1) with a value of K_c of 3 times greater than the limiting value. In FIG3. 13, the model natural frequency is 5% below the 'best' value, and is just at the limit of stability. In FIG'S 3. 14 the model natural frequency is 5% above the 'best' value, and is severely unstable.

It is shown by these results that the control method can suppress chatter. However, the selection of a suitable model is critical, as mis-match by as little as 5% of the natural frequency can cause severe instability.

Other simulations show that the bandwidth of the controller must be greater than that of the machine-workpiece dynamics for successful chatter suppression. Investigations into the effects of the controller step size show that this is not a critical variable. However, there is a maximum size above which that suppression method does not work. This value depends on the system being controlled. It is generally found that the smaller the step size the more effective the control method.

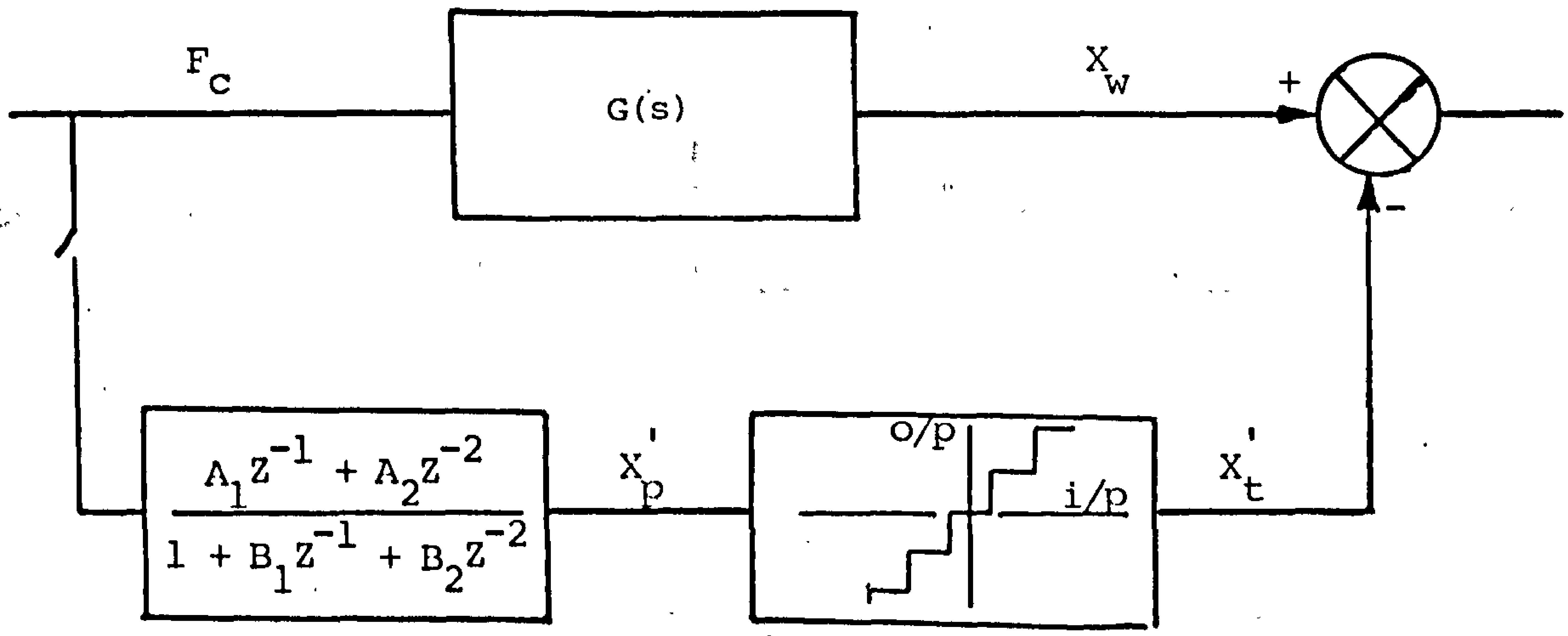
The second-order model is shown to be a sufficiently good approximation to the machine-workpiece dynamics for effective operation of the control method. Selection of suitable model parameters is critical for successful application of the method. It is indicated that increases in K_c of approximately 10 times are achieved by use of this control method.

Details of the simulation programme are given in APPENDICES A.5 and B.5



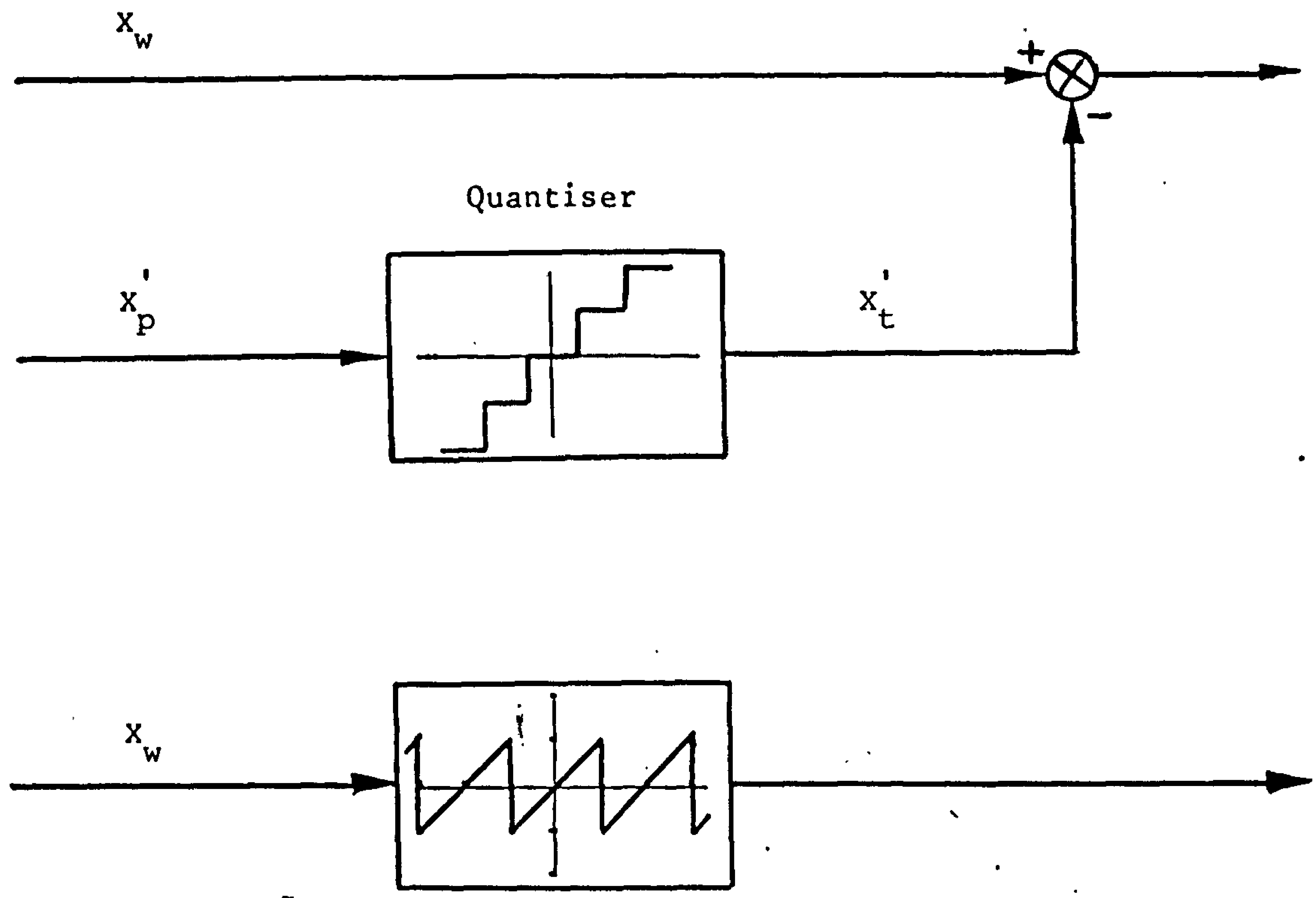
Basic active chatter controller

FIG3. 1.



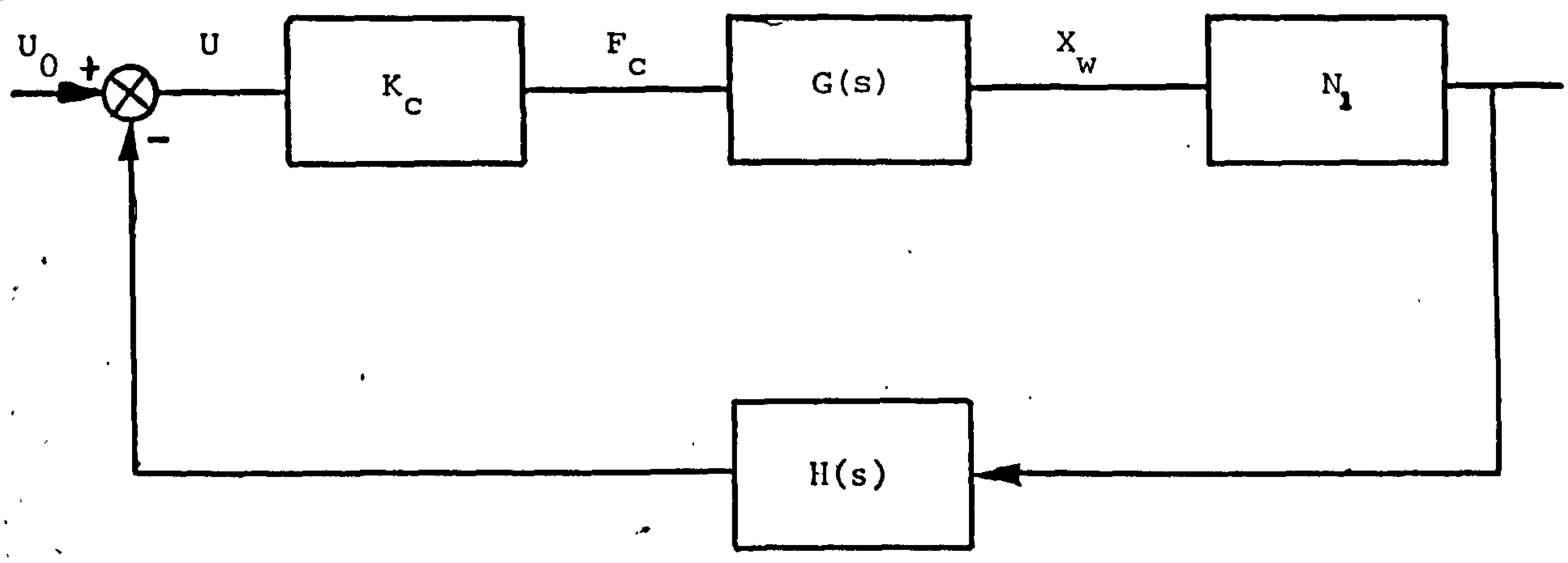
Block diagram of simplified chatter controller

FIG3. 2.



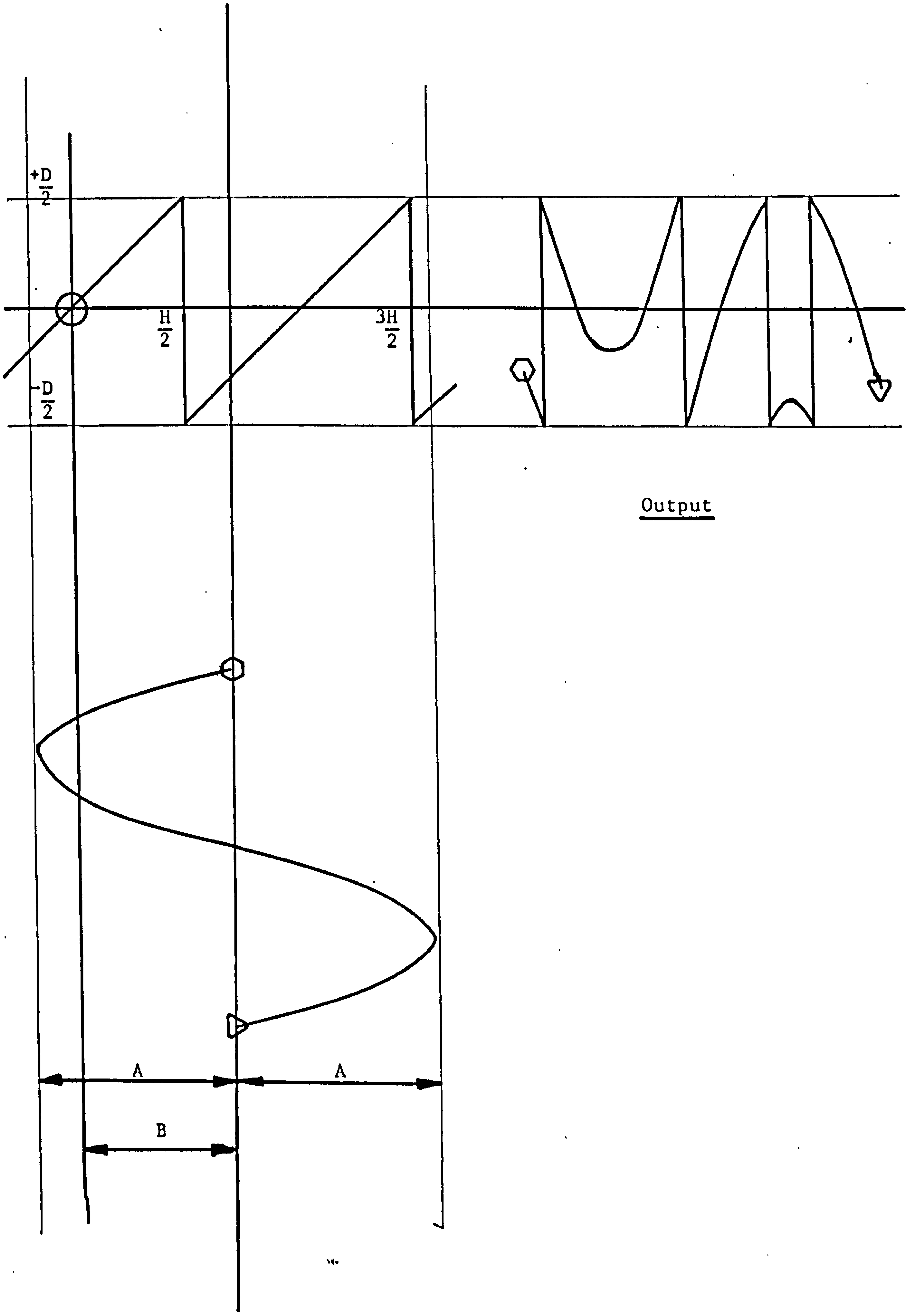
Equivalent ideal controller.

FIG3. 3.



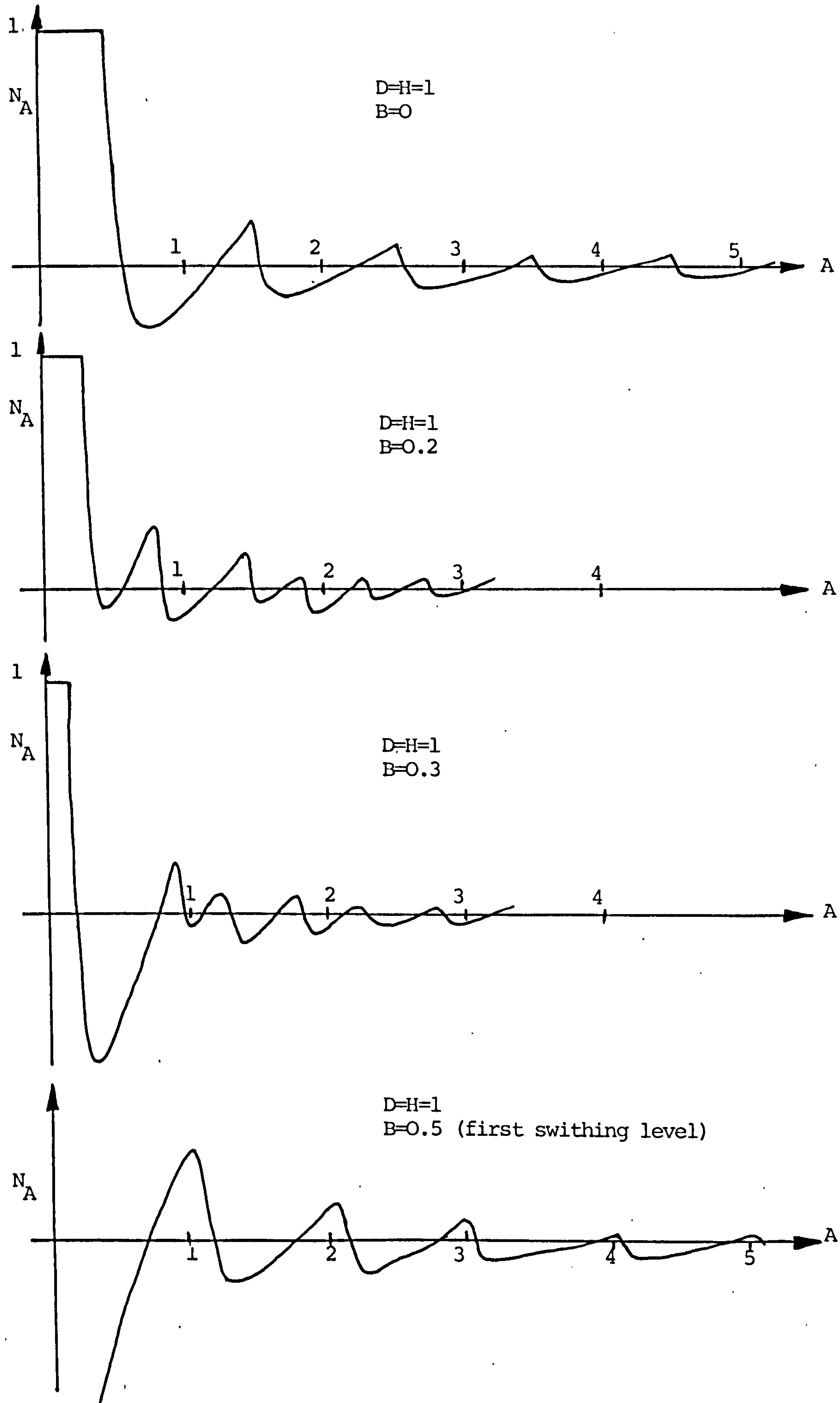
Block diagram of controlled system.

FIG3. 4.



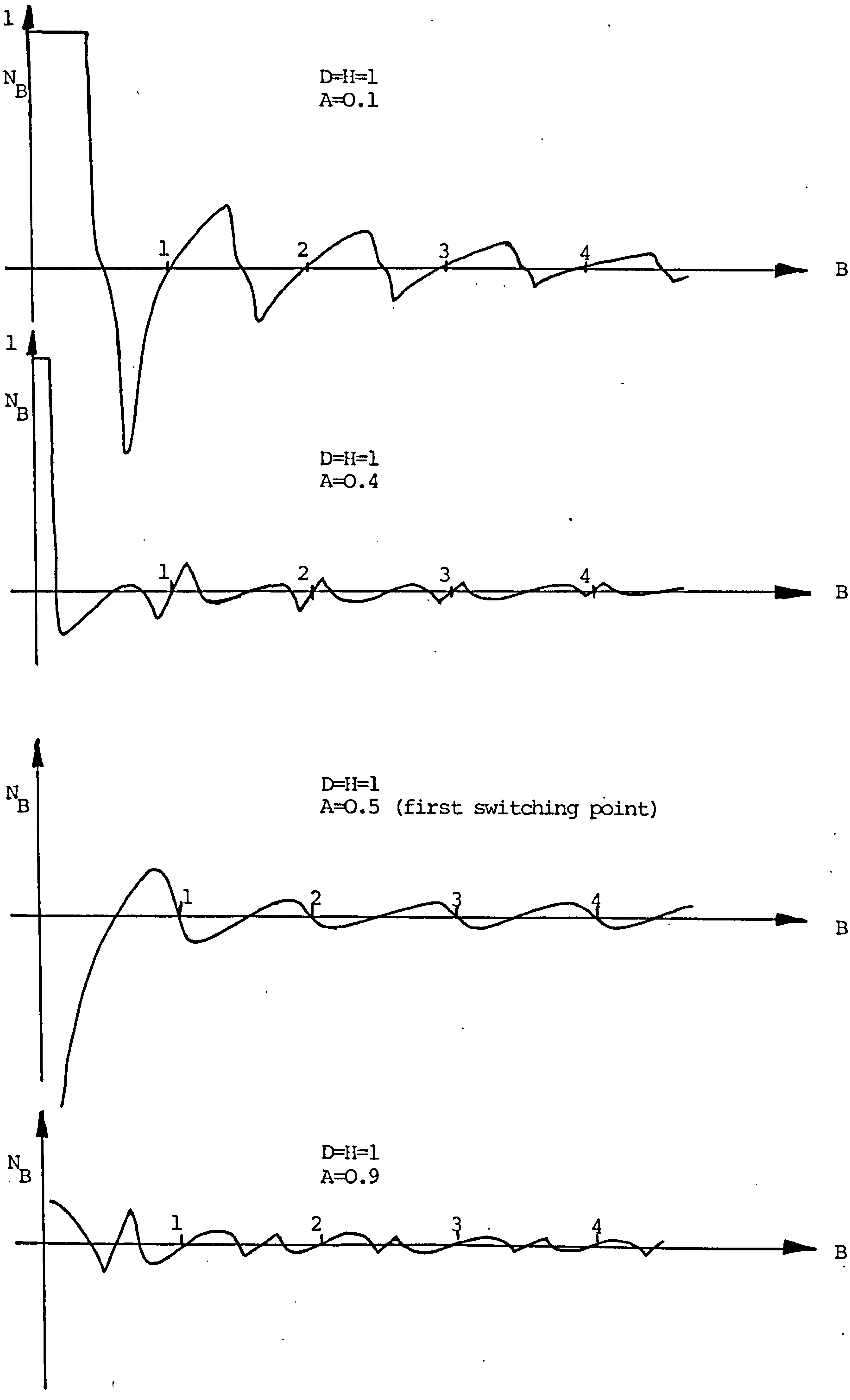
Effect of nonlinear controller.

FIG3. 5.



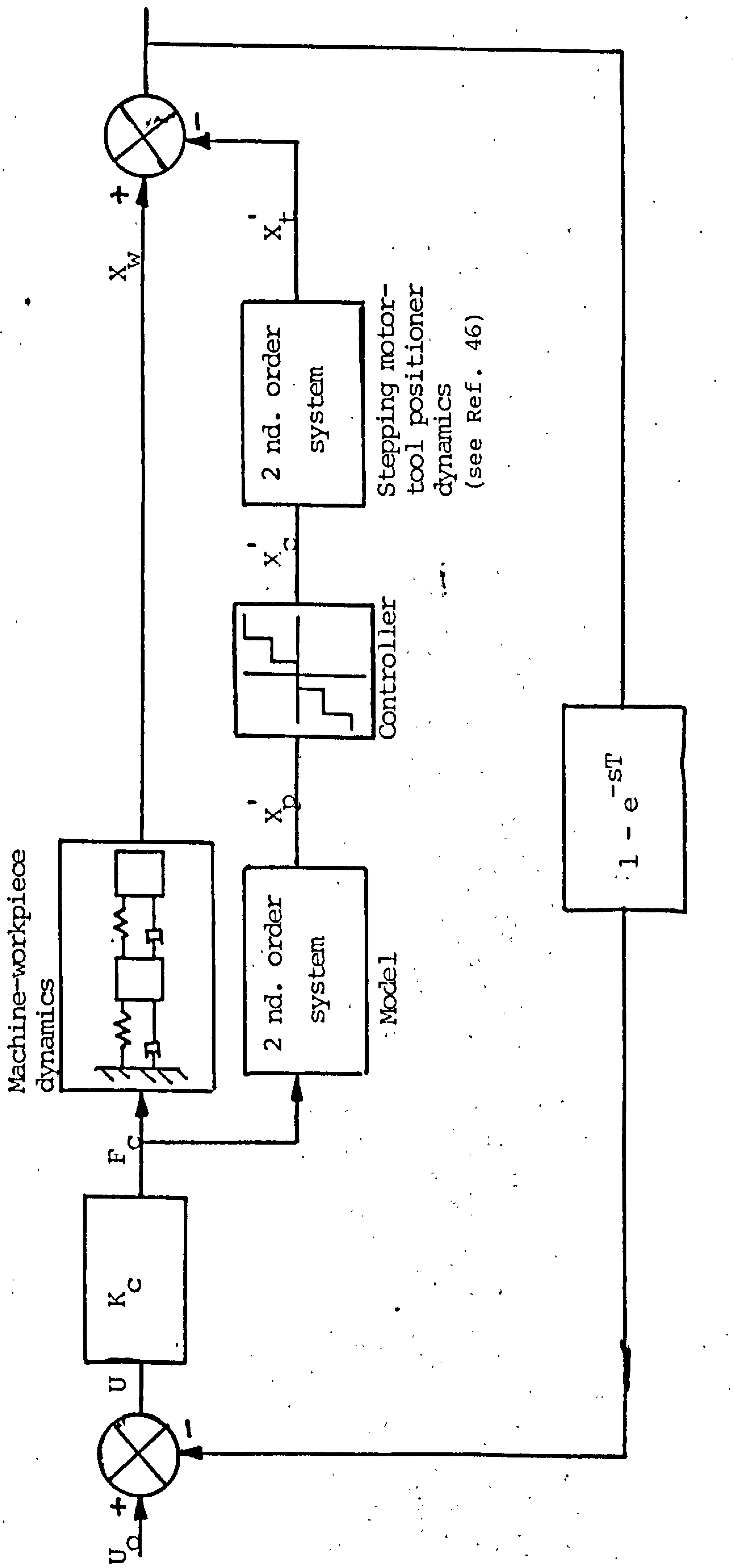
Some examples of N_A vs A for varions B

FIG3. 6.



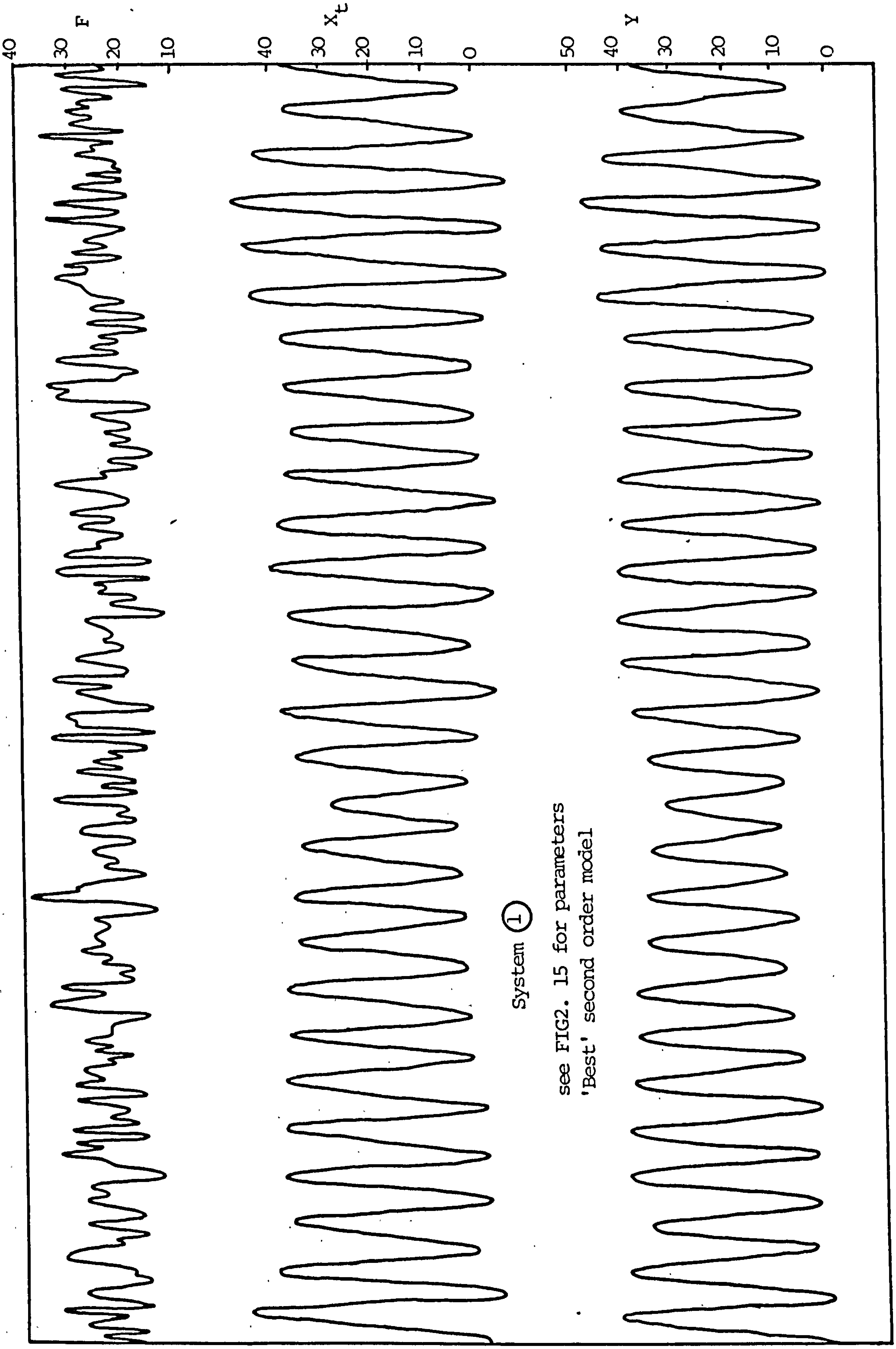
Some examples of N_B vs B for various A

FIG3. 7.



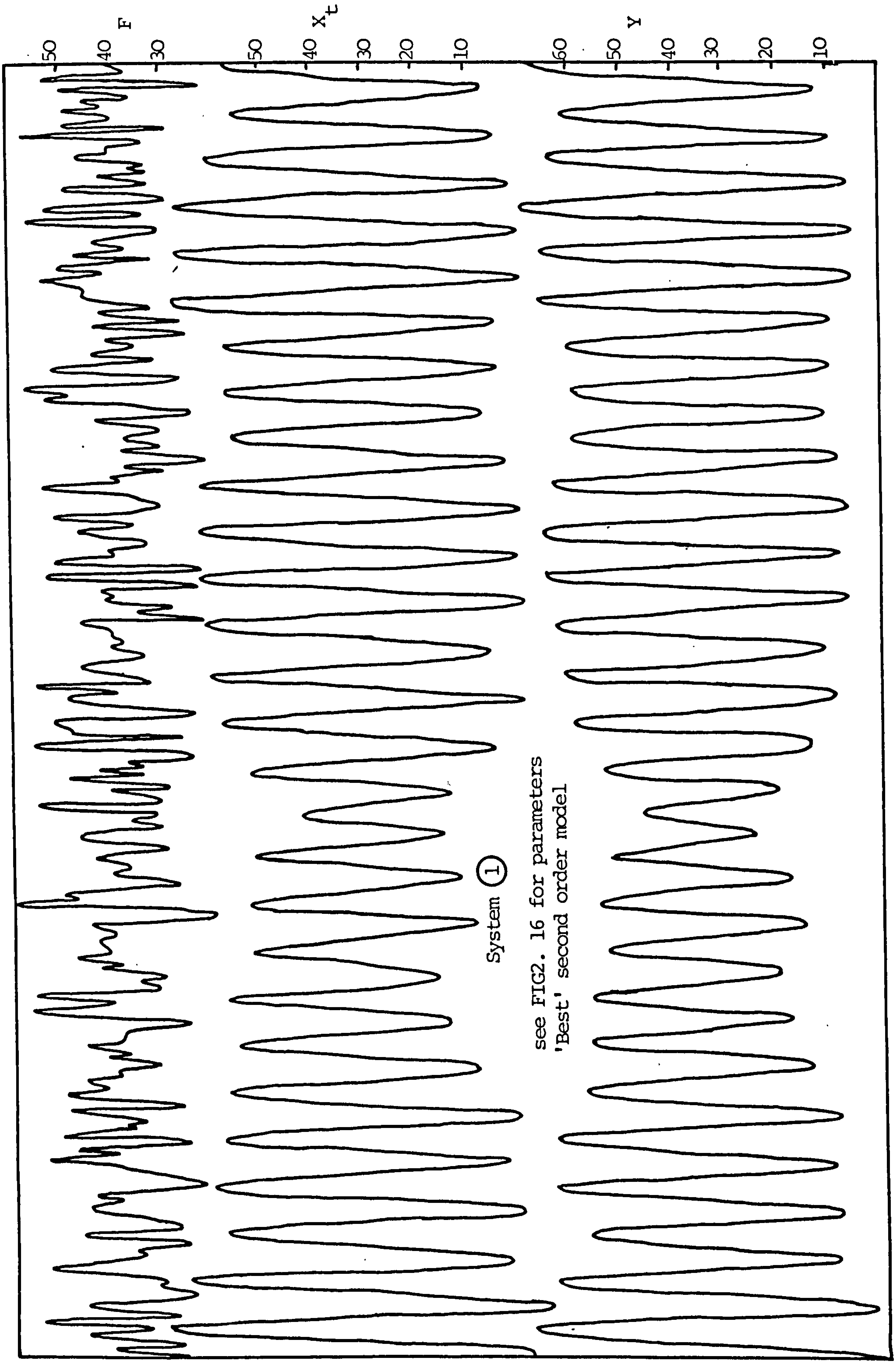
Simulated chatter suppression system

FIG3. 8.



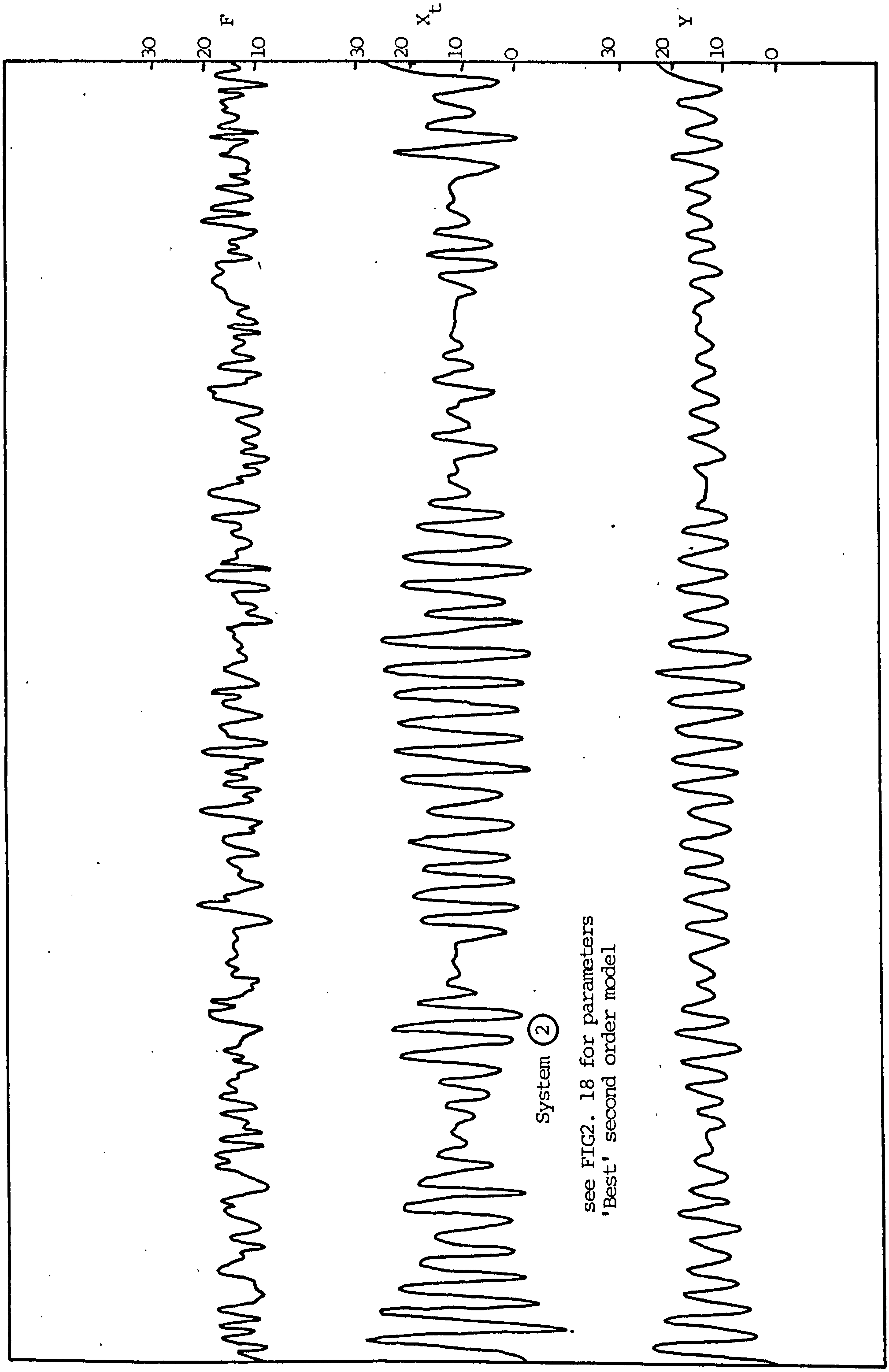
Chatter suppression simulation - System (1) ,3 times normal stability limit

FIG3. 9.



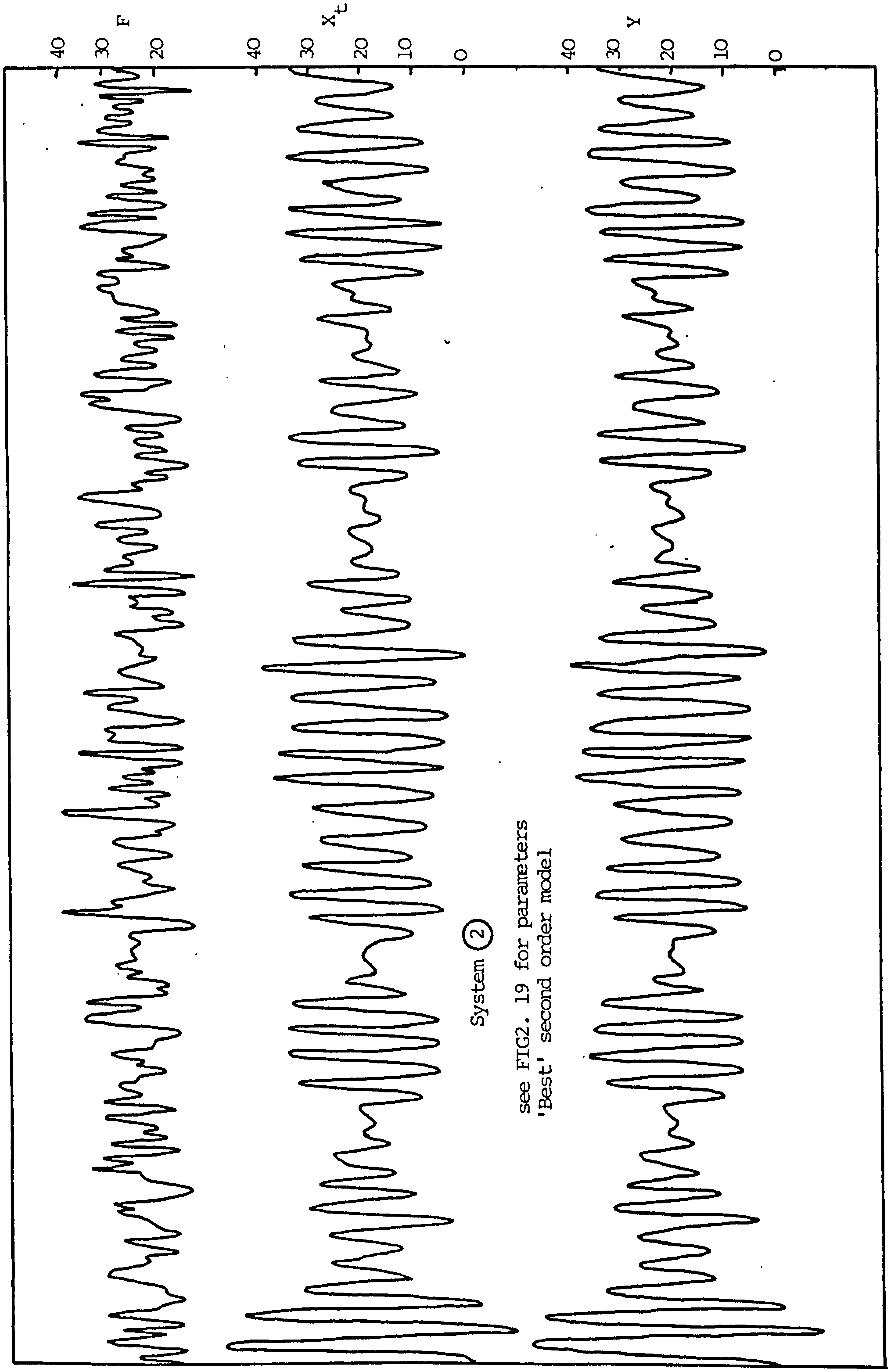
Chatter suppression simulation - System (1) ,5 times normal stability limit

FIG3.10.



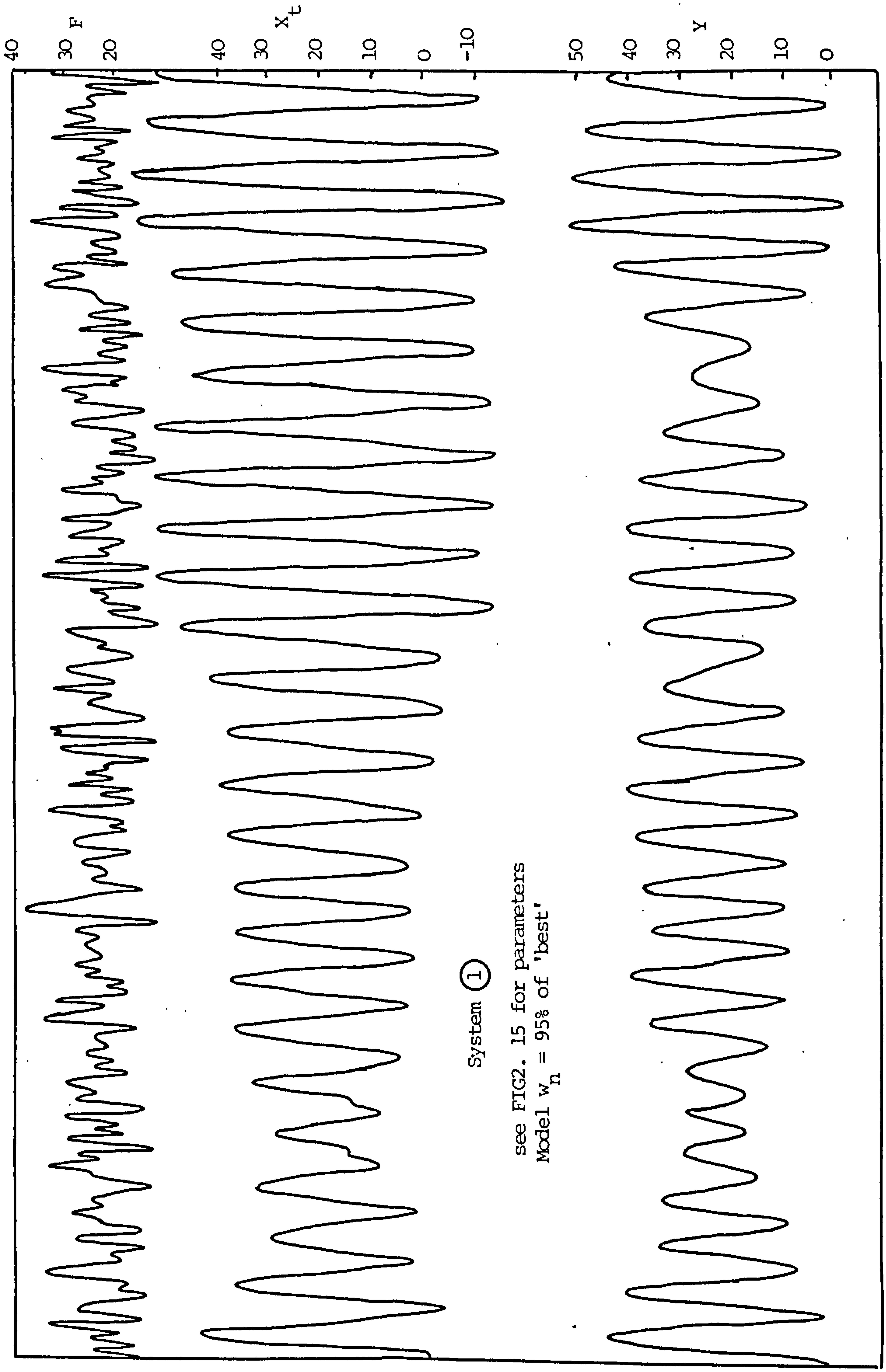
Chatter suppression simulation - System (2) ,3 times normal stability limit

FIG3. 11.



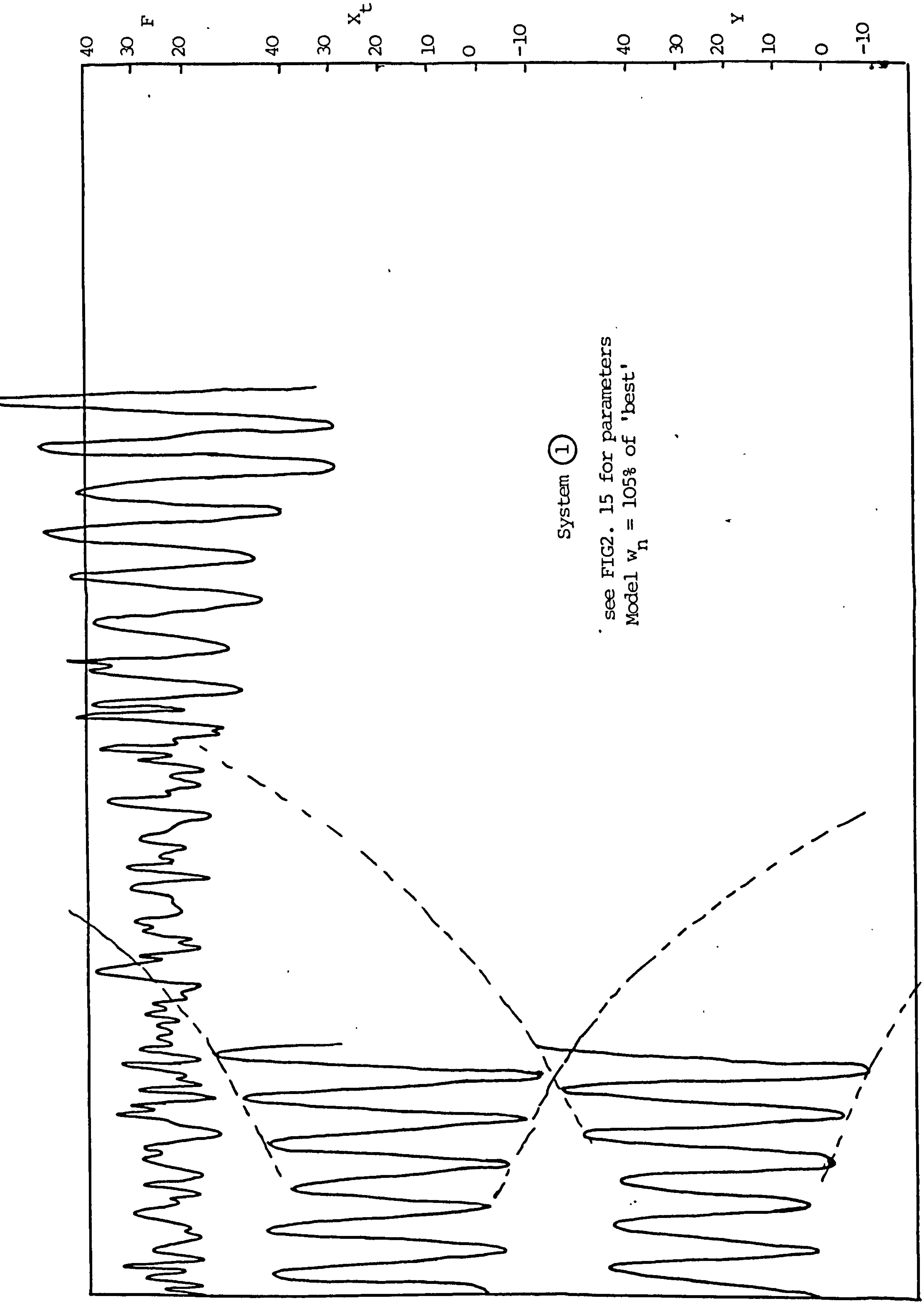
Chatter suppression simulation - System (2) ,5 times normal stability limit

FIG3. 12.



Chatter suppression simulation - System 1 ,mismatched model

FIG3. 13.



Chatter suppression simulation – System (1) ,mismatched model

FIG3. 14.

4. INVESTIGATION OF MACHINE-WORKPIECE DYNAMICS.

4. 1. Introduction.

In the stability analysis it is assumed that both the machine and the workpiece dynamics can be approximated by second-order systems. It is then shown that the resulting machine-workpiece system also behaves like a second-order system.

The purpose of this investigation is to verify the assumptions about the machine and the workpiece dynamics, and to test the predicted behaviour of the machine-workpiece system. Two methods are used during the investigation:

-- Impulse response testing
-- On-line system identification.

4. 2. Impulse response testing.

It is not proposed to elaborate on the theory of the impulse response method as it is well known (8, 13, 14, 15). Both the machine and the workpiece are tested independantly as well as combinations of machine and workpiece. The vibration induced by the impulses is monitored and compared to a generalised second-order impulse response (see FIG4. 1). The effective damping factor and the natural frequency can be deduced from the response using the following equations:-

$$\zeta = \sqrt{\frac{\left[\log_e(M_1/M_2)\right]^2}{\left[2.\pi\right]^2 + \left[\log_e(M_1/M_2)\right]^2}} \qquad \text{———} \; 4.1$$

$$w_n = \frac{2.\pi}{T.\sqrt{1 - \zeta^2}} \qquad \text{———} \; 4.2$$

Details of the tests performed are given in Chapter 6.

4. 3. On-line system identification.

Several system identification techniques are reviewed (18, 23, 24, 25, 28, 29), the one proposed by Kalman (18) finally being chosen. It has the following advantageous features:

-- simple, on-line method
-- easy implementation
-- no special input signal required
-- immediate availability of results
-- small sampling period

The parameters of a model chosen to represent the system to be identified are estimated from measurements of the input and output to the system. In this case the model is chosen to be second-order. This can be represented in discrete form by the following linear difference equation:-

$$c_k = A_1.m_{k-1} + A_2.m_{k-2} - B_1.c_{k-1} - B_2.c_{k-2} \quad \text{—— 4.3}$$

where m_{k-n} is the input and c_{k-n} is the ouput at the k-n th. sample. The A's and B's are the system parameters. It can be seen from this equation that the output at a given sampling instant can be calculated from a knowledge of the input and output at the previous two sampling instants, and the system parameters. If the actual values of the system parameters are not known they may be guessed, and used to predict an approximate output. This predicted value is then compared with the actual output and the error used to revise the preview estimates of the system parameters. In practice, the measurements of the system input and output are usually corrupted by noise and the method will give rise to incorrect estimates of the model parameters. So as to eliminate this effect, the prediction error can be calculated for many samples and the model parameters estimated using the mean squared error:-

$$E = \frac{1}{N} \cdot \sum_{k=1}^{N} \varepsilon_k^2 = \sum_{k=1}^{N} (c_k^* - c_k)^2 \qquad 4.4$$

Where c_k^* and c_k are the predicted and measured outputs respectively. The predicted output can be calculated from equation 4.3 using past measured values of the input and the output. This leads to the following expression for the mean squared error:-

$$E = \frac{1}{N} \cdot \sum_{k=1}^{N} (A_1 . m_{k-1} + A_2 . m_{k-2} - B_1 . c_{k-1} - B_2 . c_{k-2} - c_k)^2 \qquad 4.5$$

This error term is then minimised with respect to the model parameters so that:-

$$\frac{\partial E}{\partial A_1} = \frac{\partial E}{\partial A_2} = \frac{\partial E}{\partial B_1} = \frac{\partial E}{\partial B_2} = 0 \qquad 4.6$$

The following four simultaneous equations are obtained from these expressions:-

$$\begin{bmatrix} \phi_{N-1}^{mm}(0) & \phi_{N-1}^{mm}(-1) & -\phi_{N-1}^{cm}(0) & -\phi_{N-2}^{cm}(1) \\ \phi_{N-1}^{mm}(-1) & \phi_{N-2}^{mm}(0) & -\phi_{N-1}^{cm}(-1) & -\phi_{N-2}^{cm}(0) \\ -\phi_{N-1}^{cm}(0) & -\phi_{N-1}^{cm}(-1) & \phi_{N-1}^{cc}(0) & \phi_{N-1}^{cc}(-1) \\ -\phi_{N-2}^{cm}(1) & -\phi_{N-2}^{cm}(0) & \phi_{N-1}^{cc}(-1) & \phi_{N-2}^{cc}(0) \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} \phi_{N}^{cm}(-1) \\ \phi_{N}^{cm}(-2) \\ -\phi_{N}^{cc}(-1) \\ -\phi_{N}^{cc}(-2) \end{bmatrix} \qquad 4.7$$

The ϕ's are pseudo-correlation functions defined by:-

$$\phi^{cc}_{N-r}(r-s) = \sum_{k-1}^{N} c_{N-r} . c_{N-s} \qquad \text{4.7a}$$

$$\phi^{cm}_{N-r}(r-s) = \sum_{k-1}^{N} c_{N-r} . m_{N-s} \qquad \text{4.7b}$$

$$\phi^{mm}_{N-r}(r-s) = \sum_{k-1}^{N} m_{N-r} . m_{N-s} \qquad \text{4.7c}$$

Gaussian Elimination(42) is used as a convenient method of solving these equations.

The parameters obtained from this estimation technique can be converted into the more familiar system parameters:

-- natural frequency (w_n)
-- damping factor (ζ)
-- gain (K)

using the following transformations:-

$$w_n . \zeta = \frac{1}{2T} . \log_e \left[\frac{1}{B_2} \right] \qquad \text{4.8}$$

$$w_n \sqrt{1 - \zeta^2} = \frac{1}{T} . \cos^{-1} \left[\frac{-B_1 . e^{w_n . \zeta . T}}{2} \right] \qquad \text{4.9}$$

$$K = \frac{A_1 . w_n . \sqrt{1 - \zeta^2} . e^{w_n . \zeta . T}}{\sin^{-1} \left[T . w_n . \sqrt{1 - \zeta^2} \right]} \qquad \text{4.10}$$

The natural frequency (w_n) and damping factor (ζ) can be calculated by solving equations 4.8 and 4.9 simultaneously. It is noted that the constant A_2 is theoretically zero if the model is an exact representation of the system being identified.

The identification method is implemented as an on-line computer programme. The inputs are digital representations of the cutting force and workpiece displacement (see next chapter). The output being the best estimates of the model parameters (A's and B's)

This identification programme is used mainly to test the dynamic characteristic of the combined machine-workpiece systems under actual cutting conditions. The force generated by the cutting process is the input to the system and the workpiece centreline displacement is the output. In order to identify the overall dynamics of the machine-workpiece systems (that used in the chatter and suppression analyses) the displacement should be measured relative to the cutting point (tool tip). However, because of the instrumentation limitations discussed in section 5.2, the lathe bed is used as the reference point. The errors due to this approximation are expected to be small as the structure between the tool and the lathe bed can be considered to be rigid. Details of the tests are given in Chapter 7.

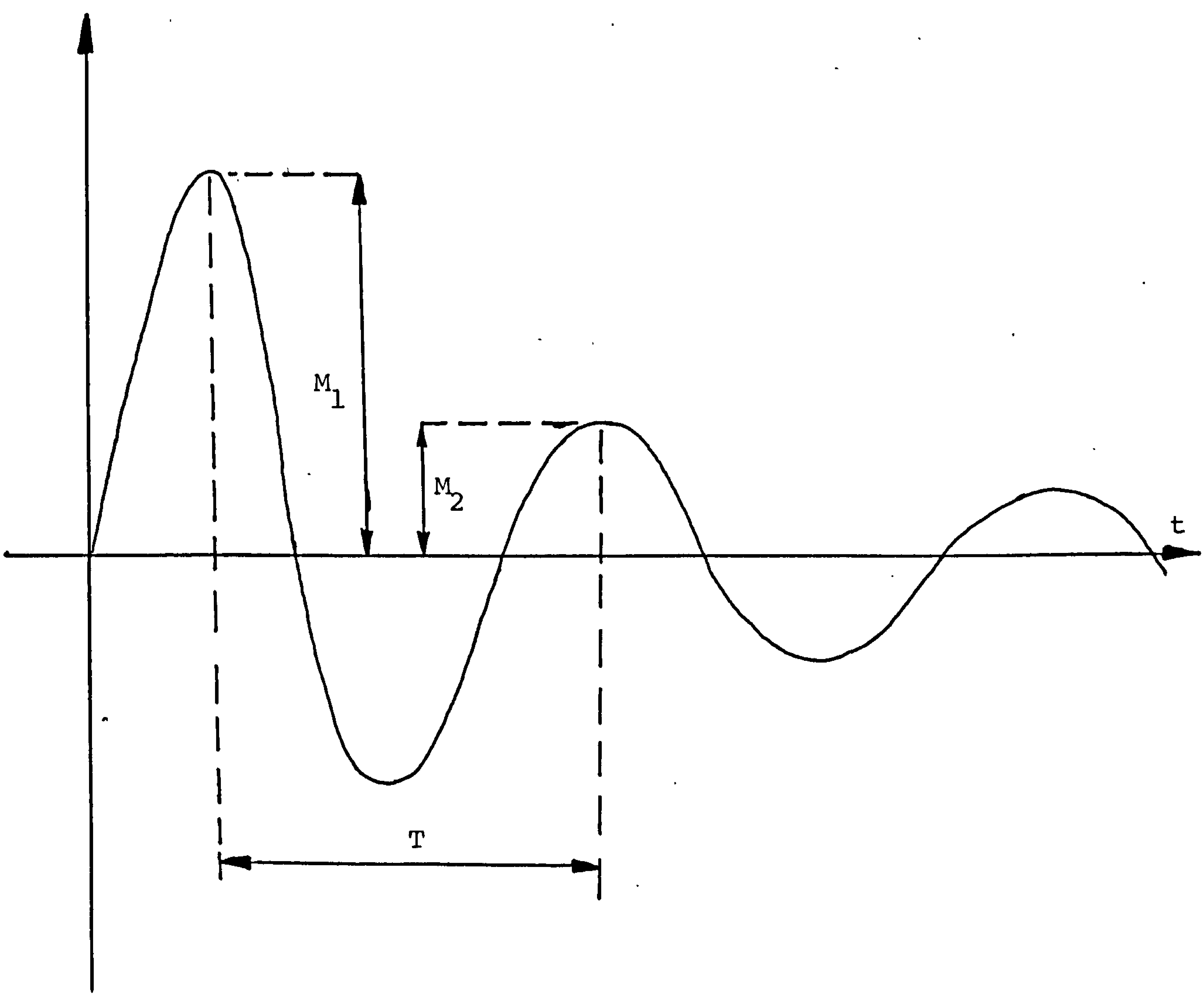
4. 4. Discussion of the investigation methods.

The impulse response method is an unsophisticated, but proven method of investigating system behaviour. It is a relatively simple task to monitor the response of the system to the impulse and deduce the nature of the system from this response.

The parameter estimation technique, although fairly well established, has never been used in this demanding application. It is hoped to show that sensible results are obtained when the system is represented by a second-order model.

Results of both the methods are compared and used to validate, or otherwise, the assumptions made in stability analysis.

Kalman's method has been shown to give erroneous results if the input signals have a low signal-to-noise ratio. It is expected that this will not be the case in this application. However, if suspect results are obtained, several methods are available (19, 20, 21, 22, 23), by which this basic technique may be improved.



Typical second-order impulse response

FIG4. 1.

5. EXPERIMENTAL RIG.

5. 1. Introduction.

The experimental rig is designed in order to investigate the machine-workpiece structure and the proposed chatter suppression method. It is based on a Colchester Triumph 2000 fixed bed turning lathe and features a tool positioner specially designed for the chatter suppression tests. A Data General Nova 820 minicomputer with analogue-to-digital conversion equipment is used to perform the machine-workpiece modelling and controller functions. A customised interface is used to convert the computer generated control pulses into a form suitable for driving the tool positioner. Instrumentation was designed to enable measurement of the cutting force and workpiece displacement.

Descriptions of the individual pieces of apparatus used in the rig is presented in three parts. The first part deals with the instrumentation for the rig, the second the computer system, and the third the chatter controller.

Wherever possible 'off-the-shelf' equipment is used in the rig, however some of the more specialised electronic apparatus is designed and built by the author with considerable cost savings. The tool positioner is designed by the author.

5. 2. Instrumentation.

The instrumentation system is required to measure the cutting force and the workpiece displacement. This is preformed in several distinct stages:

-- transducers convert the physical variables into electronic signals.
-- these signals are converted into proportional voltage signals.
-- the voltage signals are filtered to prevent errors during sampling.

-- the filtered voltages are sampled and digitised into a form suitable for input to the computer.

A diagram of the overall instrumentation system is given in FIG5. 1.

5. 2. 1. Workpiece displacement measurement.

The workpiece displacement is measured as part of the tests to identify the machine-workpiece structure. Ideally, it is the displacement of the workpiece centreline, relative to the cutting tool tip, that is required if the overall machine-workpiece structure is to be identified. This cannot be measured directly, however, it can be estimated by monitoring the workpiece surface.

This displacement is typically of the order of 1-5 thousands of an inch varying at frequencies up to 300Hz, and the surface to be monitored is moving at speeds up to 10 ft/sec. These requirements necessitate a high sensitivity, no-contact transducer, an obvious choice being an inductive type. The transducers used are Southern Instruments G. 324B with type M. 1822 oscillator and TE7 FM pre-amplifier. A detailed description and specification of this system are given in reference 43. The output is a DC voltage proportional to the displacement. A diagram of the overall system is shown in FIG5. 2.

If the transducers are mounted near the cutting point they are subject to an environment of high localised temperatures, cutting fluid and swarf. This would lead to a noisy signal, with doubtful accuracy and reliability.

In order to provide an environment suitable for the inductive transducers, they are mounted on a support which is clamped to the lathe bed, and monitor the surface of a reference disk attached to the workpiece. This introduces a small measurement error due to the shift of the reference point. However, this does not significantly affect the accuracy with the machine-workpiece structure is identified.

The reference disk is made from aluminium and is rigidly attached to a mild-steel test workpiece. Two transducers are mounted on a mild-steel support so they measure the displacements of the disk in directions at 45° to the vertial through the workpiece centreline. A schematic diagram of this arrangement is shown in FIG5. 4. This arrangement is chosen to facilitate rigid mounting of the transducers. Tangential and radial adjustment of the transducers enables initial set-up and calibration. PLATE5. 1. shows the transducer mounting and the overall displacement measurement system. To ensure the disk is accurately centred it is trued 'in-situ' prior to the tests.

The measured displacements are used to calculate the horizontal and vertical values using the following equations:-

$$x = \frac{v - u}{\sqrt{2}} \qquad 5.1$$

$$y = \frac{v + u}{\sqrt{2}} \qquad 5.2$$

These equations do not take into account the coupling between movement of the disk in one direction and the measured displacement in the other which is due to the circular nature of the disk. However, the error introduced in this case is negligible as the diameter of the disk is large compared to the displacement.

The horizontal displacement is used primarily in the identification tests. A displacement in this direction has a much larger effect on chatter instability as it causes a radial relative movement between the tool and the workpiece. The vertical displacement is measured to provide information regarding the machine-workpiece dynamics.

5. 2. 2. Cutting force measurement.

The cutting force is monitored during both the identification and chatter controller tests. These tests may have duration of between approximately 1 and 100 seconds, the force varying at frequencies up to 500Hz with amplitudes between zero and 200 lbf. It is required to measure this force in both the vertical and horizontal directions and to generate DC voltage signals proportional to these force components. A system based on piezo-electric load cells is used to perform this function with charge amplifiers to convert the electrostatic charges generated by the load cells into proportional DC voltages. A schematic diagram of this arrangement is shown in FIG5. 3. The load cells are KISTLER type 9321 (washers) and the charge amplifiers are KISTLER type 5001. Detailed descriptions and specifications for these components are given in reference 44.

So that the cells operate within their linear region under all cutting conditions, they are preloaded. In the case of the vertical direction, the cell is sandwiched between the tool positioner baseplate and the lathe saddle. A screw jack arrangement is expanded to generate the required pre-load. The overall arrangement is shown in FIG5. 5. and PLATE5. 4. The horizontal force measurement is implemented as part of the tool-positioner. Details of the clamping arrangement are shown in FIG5. 6., the design of the tool positioner is discussed later in this chapter. The cell is clamped between the tool holder/slider and the piston in which the driven ball-screw is mounted. The required pre-load is generated by tightening bolts which clamp the piston to the holder/slider. The overall arrangement can be seen in PLATE5. 5.

5. 2. 3. Signal filtering.

Because the instrumentation system involves a sampling process, it is necessary to filter the analogue signals prior to sampling. This prevents the introduction of 'aliassing' errors (9, 13) which can result because of the discontinuous nature of the sampling process. These errors are caused by signal frequency components higher than the Nyquist frequency (half the sampling frequency). In order to remove these components each signal is passed through a low-pass filter with the cut-off frequency equal to the Nyquist frequency.

The filters used for this application are a 2-pole active type, model UAF31 by Burr-Brown. These can be taylored to the required cut-off frequency and Q-factor (damping) by the addition of external resistors. A detailed description and specification for this device is given in reference 45. One filter is used for each signal, the resistors being adjusted so they all have similar characteristics.

Throughout the tests, sampling frequencies of either 1,2 and 4 KHz are used, requiring filters with cut-off points of ½,1 and 2 KHz respectively. The filter characteristics found most suitable for this application are obtained with a Q-factor of 2. It is required to filter up to a maximum of three signals.

The circuit diagram for the filter unit (three channels) is given in FIG5. 9. Values of the external resistors are given for cut-off frequencies of ½, 1 and 2KHz, and a Q-factor of 2. .

5. 2. 4. Sample-and-Hold device.

During the experimental tests it is required to sample up to three signals simultaneously. This cannot be preformed directly by the computer because of the serial nature of its input facilities. This would result in errors due to staggering of the sampling instant (see FIG5. 8). To overcome this problem a device is needed to simultaneously sample the signals and hold the sampled values until digitized and input by the computer. The operation of such a device is shown in FIG5. 9.

Control pulses from the computer trigger the 'sample' and 'hold' modes at the required times. In the 'sample' mode the signals are unaffected by the device. As the device changes to the 'hold' mode, the value of the signals at that instant are stored. The stored values of the simultaneous samples are then digitized and input to the computer.

The circuit diagram for the device is shown in FIG5. 10, the main elements being three sample-and-hold amplifiers, model SHC85 by Burr-Brown. A detailed design and performance specification is given in reference 46. The remainders of the circuit converts the control pulses from the computer into voltage levels to drive the 'sample' and 'hold' modes of the amplifiers.

The amplifiers must be switched to the 'hold' mode at least

5μsecs before the held values can be input to the digitizer. This allows time for the amplifiers to settle to the correct values. If the 'hold' mode is selected for more than 1msec, long term drift may occur resulting in voltages of up to 15 volts appearing at the amplifier output. As this could damage the digitizer, it is prevented by switching to the 'sample' mode immediately all the held values have been digitized.

The computer instructions to select the 'sample' mode for the device are :

```
SUBZL  n, n
DOA    n, 76
```

where 'n' is a number 0 to 3.
These have the effect of setting DATA15 ='1', and output this data bit to device 76 (the sample-and-hold device).

The computer instructions to select the 'hold' mode for the device are :

```
SUB    n, n
DOA    n, 76
```

where 'n' is a number 0 to 3.
These set DATA15 ='0' and output this data bit to the device.

The sample-and-hold device and filters are constructed as a single unit (see PLATE5. 2). This provides a compact processing unit to handle up to three signals.

5. 2. 5. Analogue-to-digital converter.

To complete the instrumentation chain, the sampled values must be converted into digital form. This operation is performed by an analogue-to-digital converter which, in this case, is an integral part of the computer system. It can handle up to eight different sampled signals (one at a time) and convert these into binary code. The input signals must be in the range -5 volts to +5 volts, generating proportional binary numbers in the range -512 to +511, represented in the two's compliment convention. Voltages between levels are rounded to the nearest binary number, thus the conversion error is $\pm \frac{1}{2}$ the difference between the levels. A detailed specification and operation guide can be found in reference 47.

The computer instructions required to drive the converter are as follows :

```
LDA   n, CHAN
DOAS n, ADCV
SKPDN   ADCV
JMP     .-1
DICC n, ADCV
```

where 'n' is a number 0 to 3, CHAN = channel number 0 to 8. These select the channel number of the signal to be converted, start the conversion, wait for it to be completed, and then input the digital value to the computer memory.

The time for one conversion is approximately 20 μsecs, 10 μsec conversion time and 10 μsecs to execute the associated computer instructions.

The analogue-to-digital converter is shown in PLATES 5. 6 and 5. 7.

5. 3. The Data General NOVA 820 minicomputer.

It is not within the scope of this thesis to describe in detail the operation of the computer system. All relavent information can be obtained from reference 47.

Basically it is a general-purpose 16-bit machine with four working accumulators. The configuration used throughout this reseach project consists of 8 k words of core memory, teletype, high speed paper tape reader, and analogue-to-digital converter.

All the programmes are written in the assembler language designed for this machine. Two main programmes are used during the tests, one to perform the on-line system identification, the other the chatter control function. Another programme is used to enable the chatter control system to be driven as a CNC machining device.

This is discussed in greater detail in the next chapter. Listings of all the programmes are given in Appendix B.

An overall view of the computer system is shown in PLATES5. 6 and 5. 7. The high speed paper tape reader is used to input programmes to the computer and the teletype to input numeric data and output results. The analogue-to-digital converter is used to input real-time analogue data (see previous section).

5. 4. The chatter suppresser.

The basic chatter suppression method is outlined in block diagram form in FIG1. 5. Both the model and controller are implemented as programmes executed by a digital computer. A stepping motor is used as the driver for the tool positioner as it is easily interfaced to the computer. It also offers the advantage that a high precision positioner is obtained without the need for feedback.

The sampled and digitized cutting force signal is input to the model, from which the relative tool-workpiece displacement is predicted. This is then used to generate a control signal to drive the tool positioner. Flowcharts for the overall computer programme are given in Appendix A and listings in Appendix B.

Details of the tool positioner are presented in two parts :

-- the computer interface

-- the tool holder and drive mechanism

The interface unit converts the control signals generated by the computer into pulses to drive the stepping motor. Alead screw converts the rotary motion of the motor into the required linear tool motion. The tool holder is constrained to move in the direction of the screw axis.

The overall tool positioner is designed to provide linear displacements up to a maximum about 0.1 of an inch in steps of either $\frac{1}{3}$ or $\frac{2}{3}$ of a thou. Response times of 10 msecs per step or better, are achieved.

5. 4. 1. The computer interface.

Signals output by the computer are typically short duration, low voltage pulses (see reference 47). These must be converted into voltage levels capable of switching transistors which control the stepping motor drive board. There are three inputs to the drive board :

-- Mode
-- Direction
-- Step pulse

The motor executes 200 steps /rev if the mode input is grounded, or 400 steps /rev if it is open circuit. Forward or reverse motion is obtained when the direction input is grounded or open circuit respectively. One step is moved by the motor everytime the step pulse input goes from ground to open circuit. A more detailed description of the drive board and its inputs is given in references 11 and 48.

The circiut diagram of the interface unit is given in FIG5. 11. It shows how the pulses from the computer are used to set flip-flops, whose outputs control open-collector transistor switches which are connected to the drive board inputs.

The computer instructions which generate the pulses to drive the interface and cause the motor to move one step are as follows :

```
LDA  n, CONTROL
DOBS n, 76
LDA  n, SPEED
STA  n, CNT
DSZ  CNT
JMP  .-1
NIOC 76
LDA  n, SPEED
STA  n, CNT
DSZ  CNT
JMP  .-1
```

Where 'n' is the number of the computer accumulator to be used, 0 to 3. The direction and step size (mode) are determined by 'CONTROL' which has the following legal formats.

040000 --- forward, 200 steps /rev.
140000 --- reverse, 200 steps /rev.
000000 --- forward, 400 steps /rev.
100000 --- reverse, 400 steps /rev.

The step occurs when the instruction 'NIOC 76' is executed by the computer. Several steps are produced by going 'round the instruction loop the required number of times. The speed at which the motor steps is controlled by the count 'SPEED'. This is usually calculated by the programme, prior to step output, by the relationship :-

$$\text{SPEED} = \frac{\text{TIMER}}{2 \times \text{No. of steps}} \qquad 5.3$$

Where 'TIMER' is the maximum count that can be performed by the computer between two consecutive sets of pulses (sample period). Care must be taken with the value of 'SPEED' so as to prevent the step pulse rate exceeding the motor maximum speed.

Construction details of the interface and drive unit can be seen in PLATE5. 3.

5. 4. 2. The tool positioner.

As mentioned in the previous section, the stepping motor generates either a 200 step /rev or a 400 step /rev rotary motion. This is converted into linear motion by means of a precision lead screw and re-circulating ball-nut. The ball-nut is rigidly attached to the tool holder which is supported by two linear re-circulating ball bearings. These run on two hardened steel shafts.

The basic design of the tool positioner and the ball-nut mounting are shown in FIG5. 12, FIG5. 6 and PLATE5. 5. This arrangement is used as it provides :

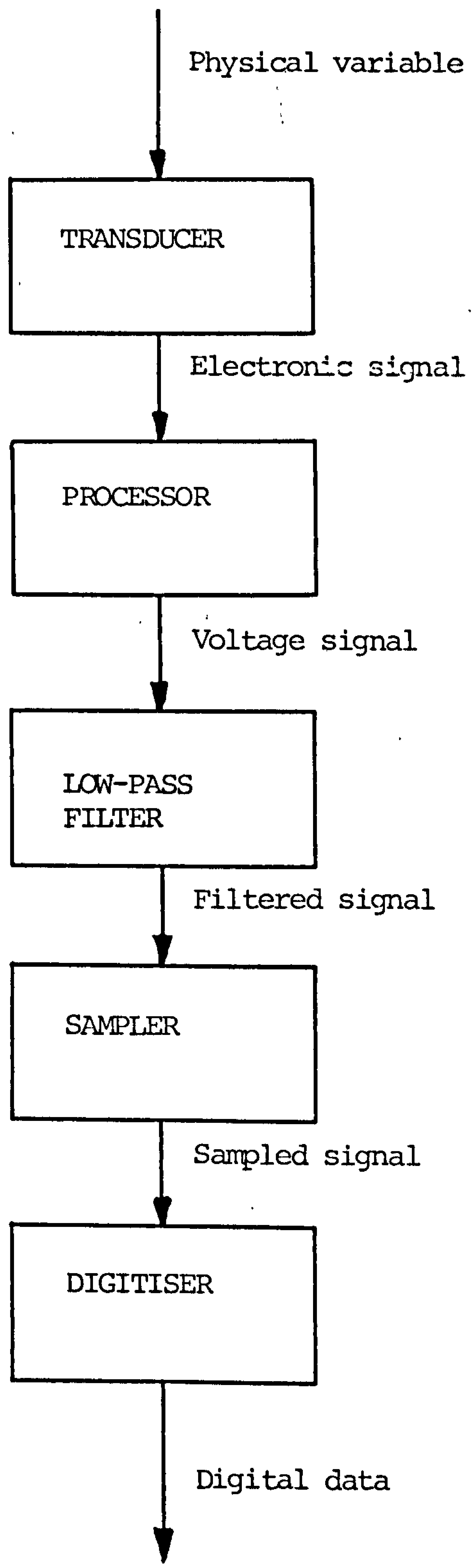
-- a compact, robust unit.
-- high rigidity in directions perpendicular to the axis of movement.

-- easy mounting on to the lathe saddle (see PLATE5. 6, PLATE5. 7 and PLATE5. 8.).
-- simple maintenance and assembley.

The lead screw and ball-nut have a pitch of 0.125 inches, giving linear step sizes 0.33 and 0.67 of a thou when combined with the stepping motor. A detailed specification for the stepping motor (SIGMA model 20-3437-D200) is given in reference 11, and for the ball-nut/screw in reference 49. The linear bearings run on 0.375 inch diameter silver steel shafts, each providing a 1 inch bearing surface. Positive linear location of the lead screw is ensured by a deep groove ball bearing mounted between the motor shaft and the screw.

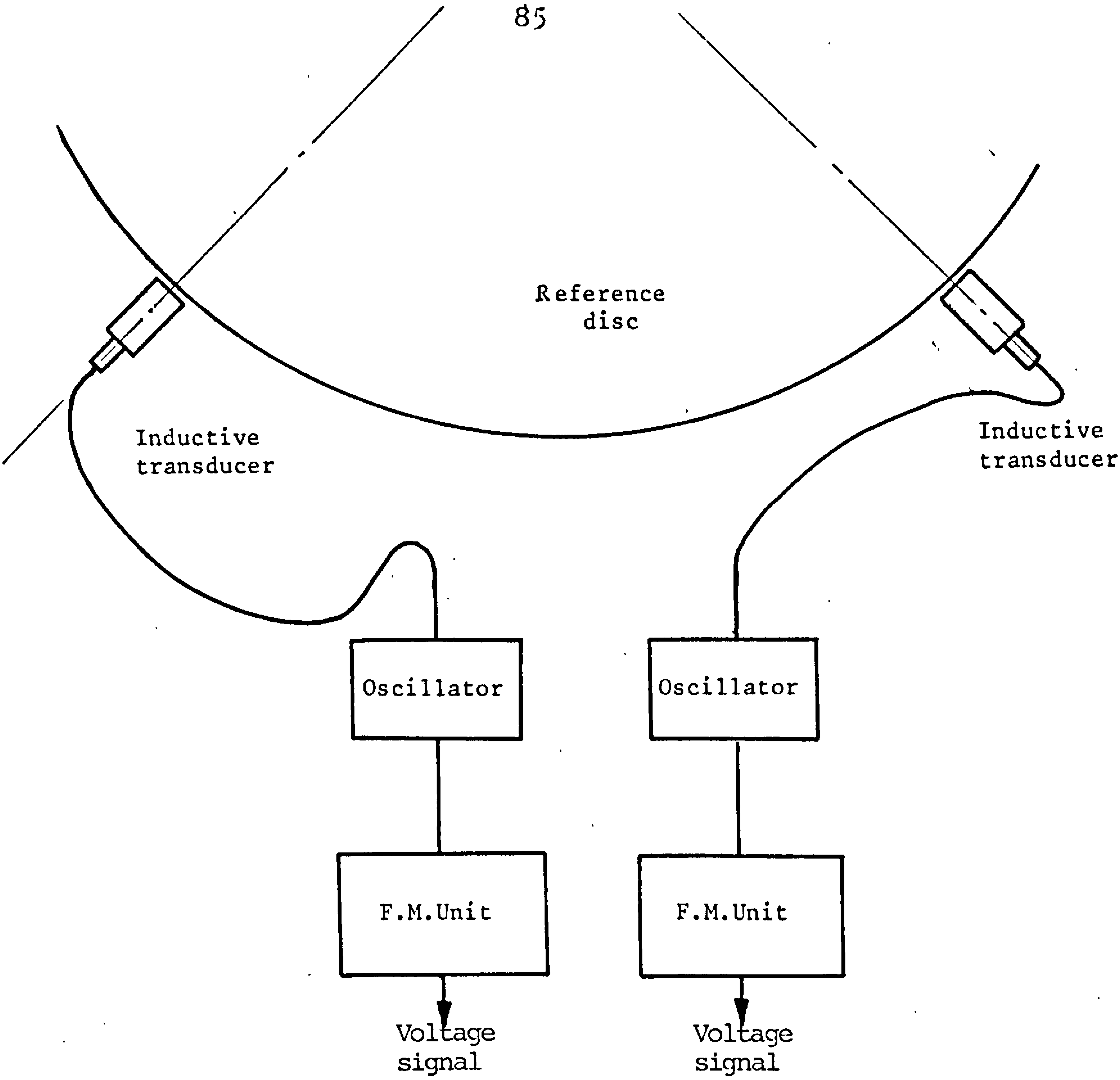
The mass of the tool holder is minimised so as to obtain the best dynamic response for the tool positioner. It is found (see section 8. 3. 1.) that the minimum response time for the positioner is 10 msecs/step.

The tool positioner described in this section is a prototype. Considerable development is required to improve the dynamic response of the system. This can be achieved by several methods , as described in references 10 and 11, which can be used to increase power input to the stepping motor. Also, current developments in stepping motor design are resulting in much faster devices.



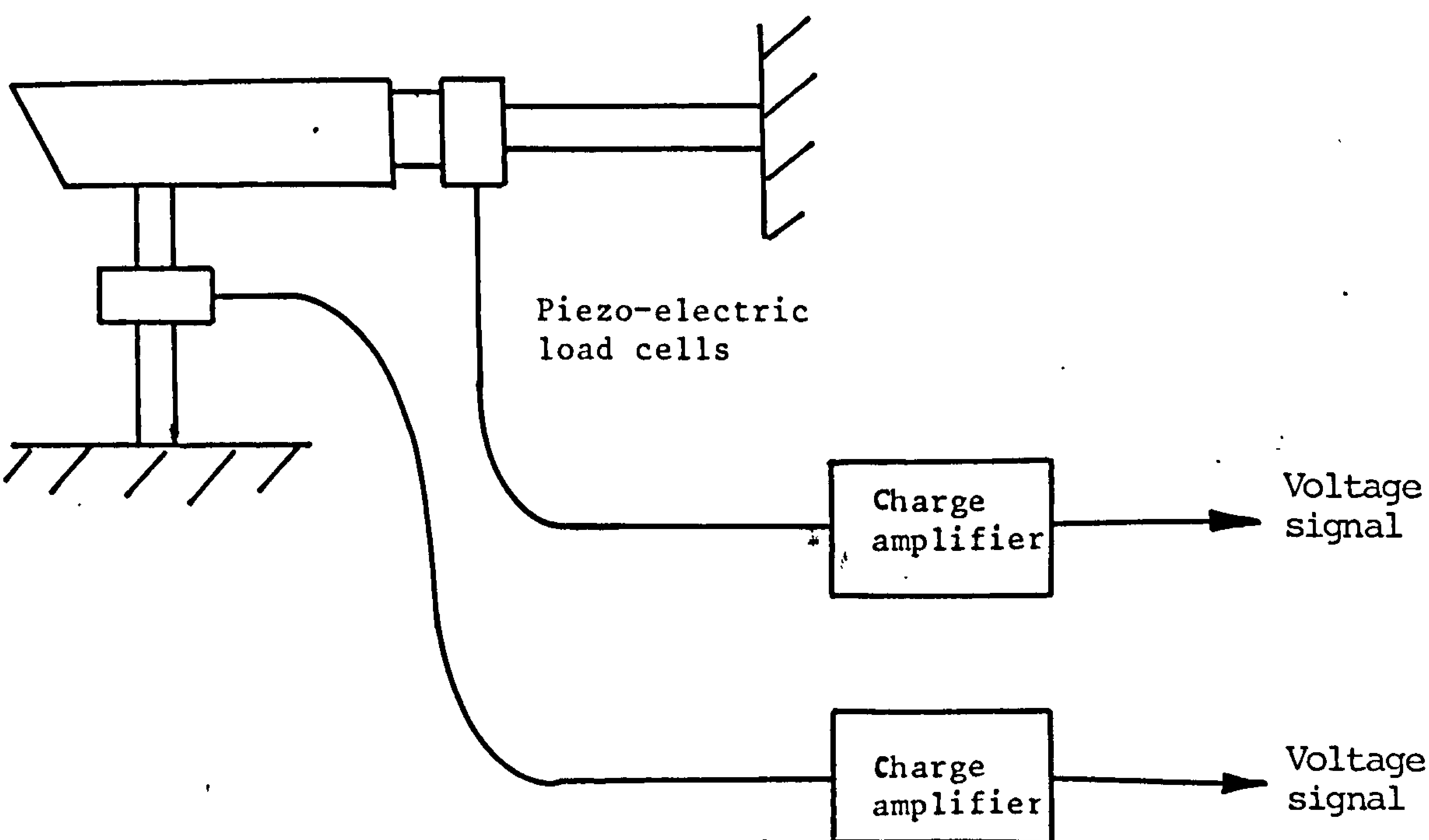
Overview of instrumentation system

FIG5. 1.



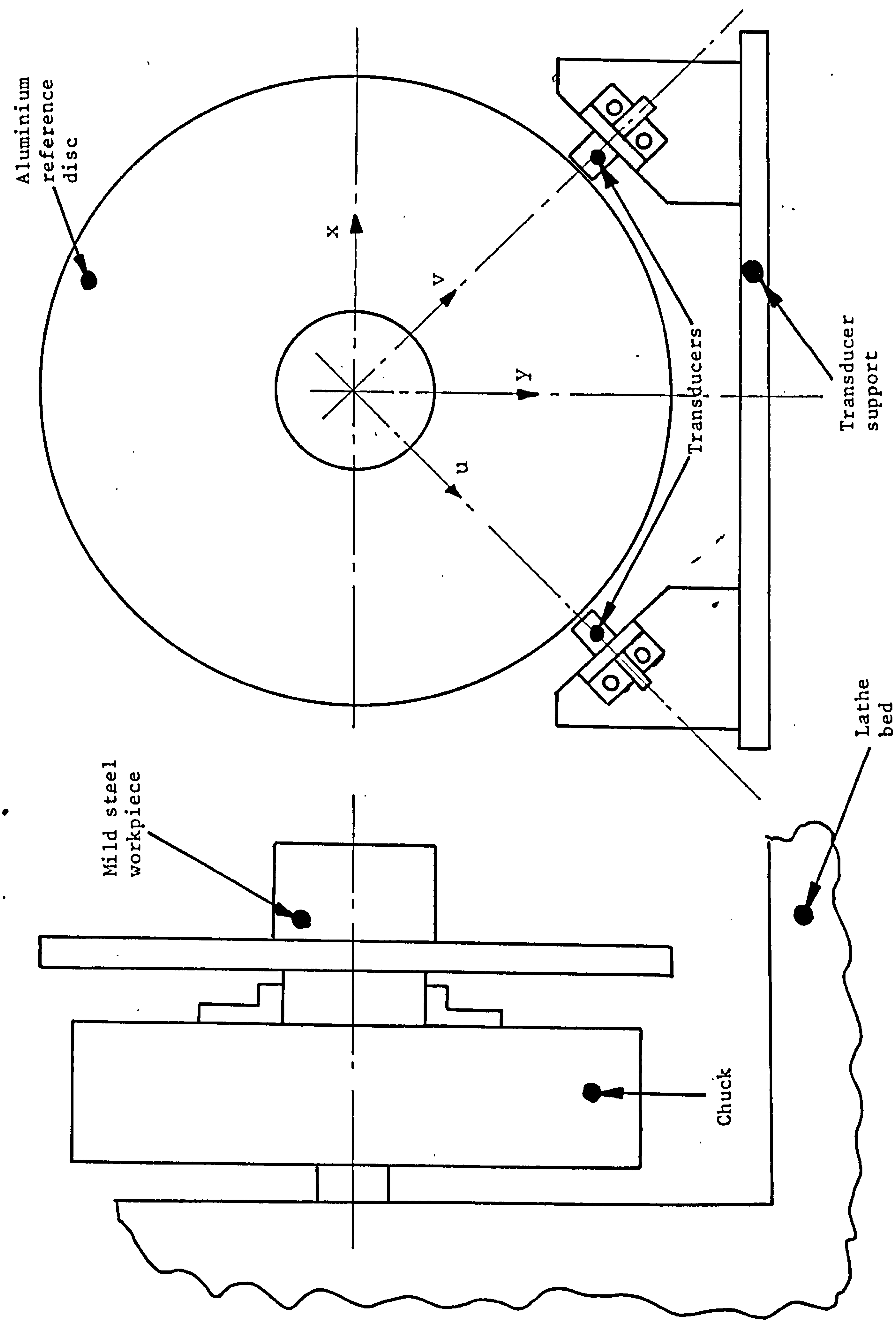
Chuck displacement signal generation.

FIG5. 2.



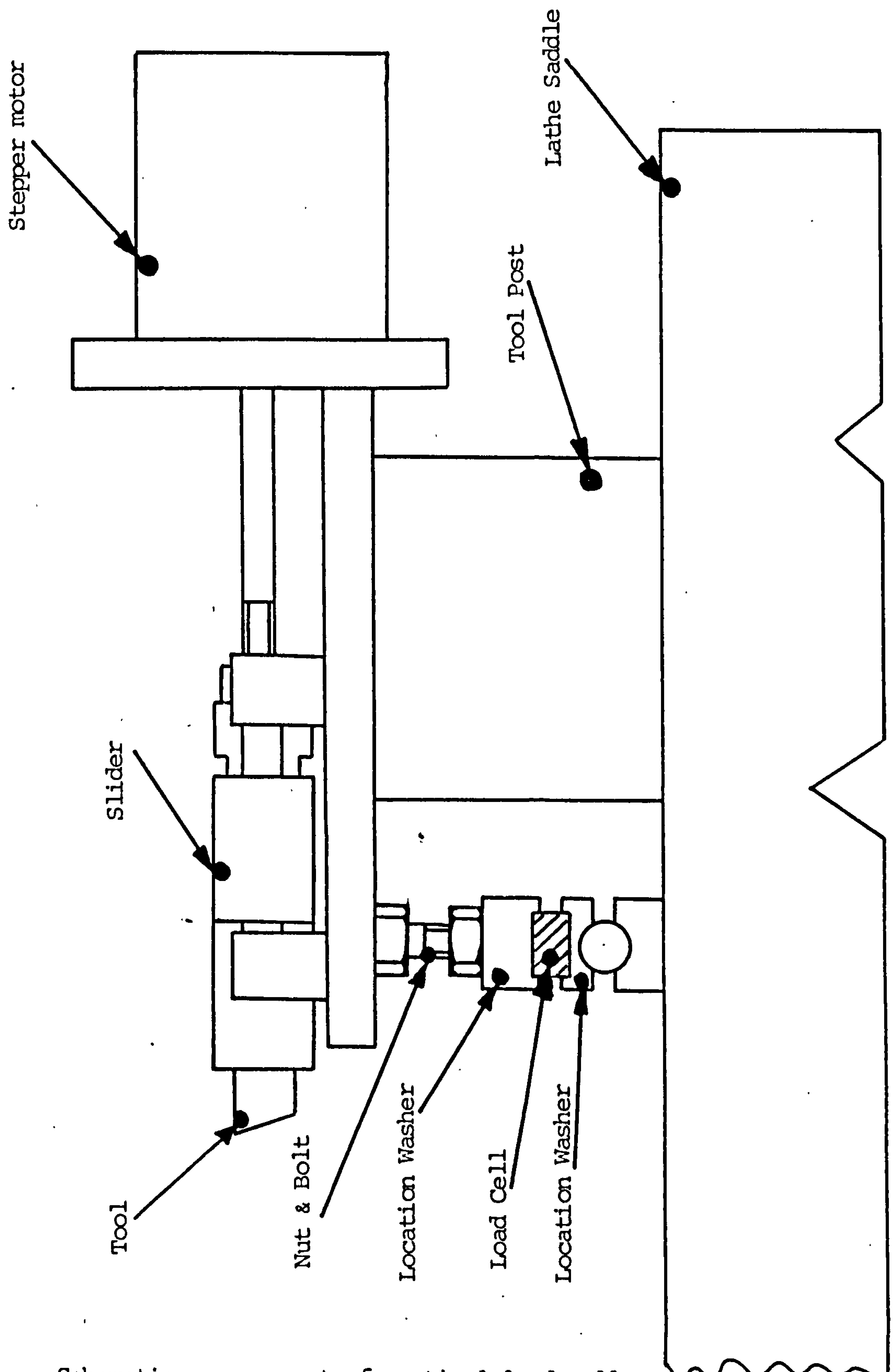
Load signal generation.

FIG5. 3.



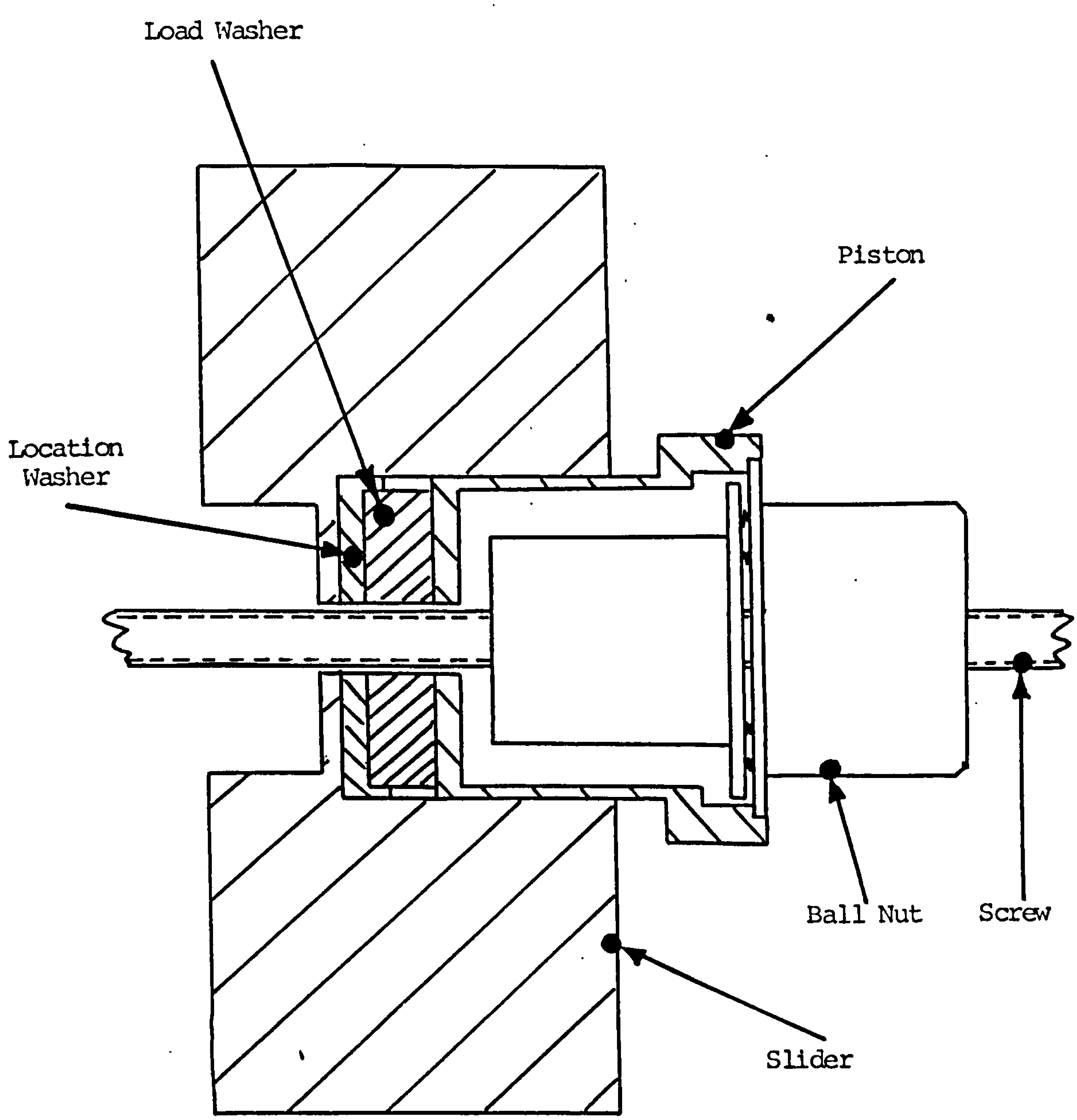
Measurement of chuck centreline displacement.

FIG5. 4.



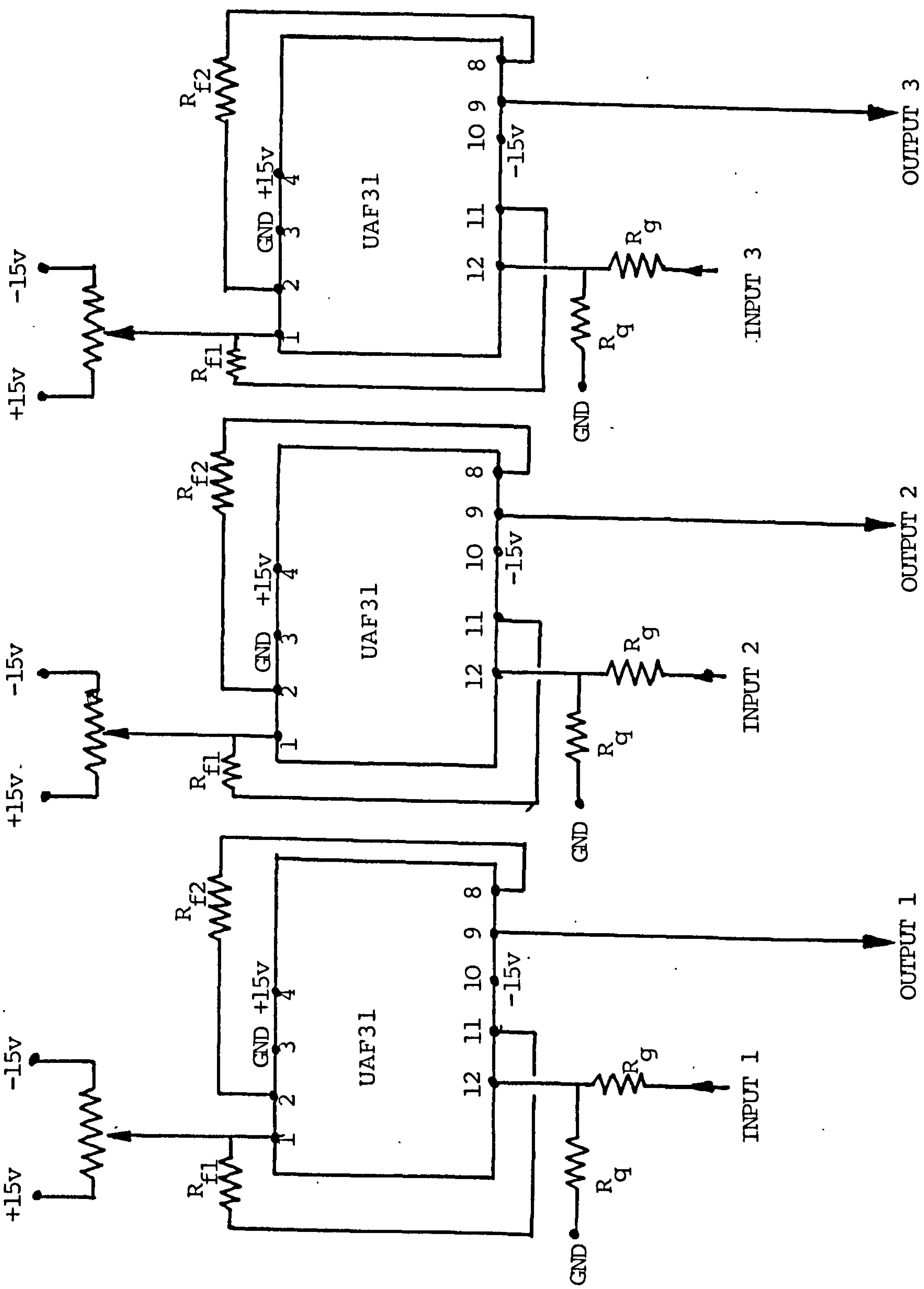
Schematic arrangement of vertical load cell.

FIG5. 5.



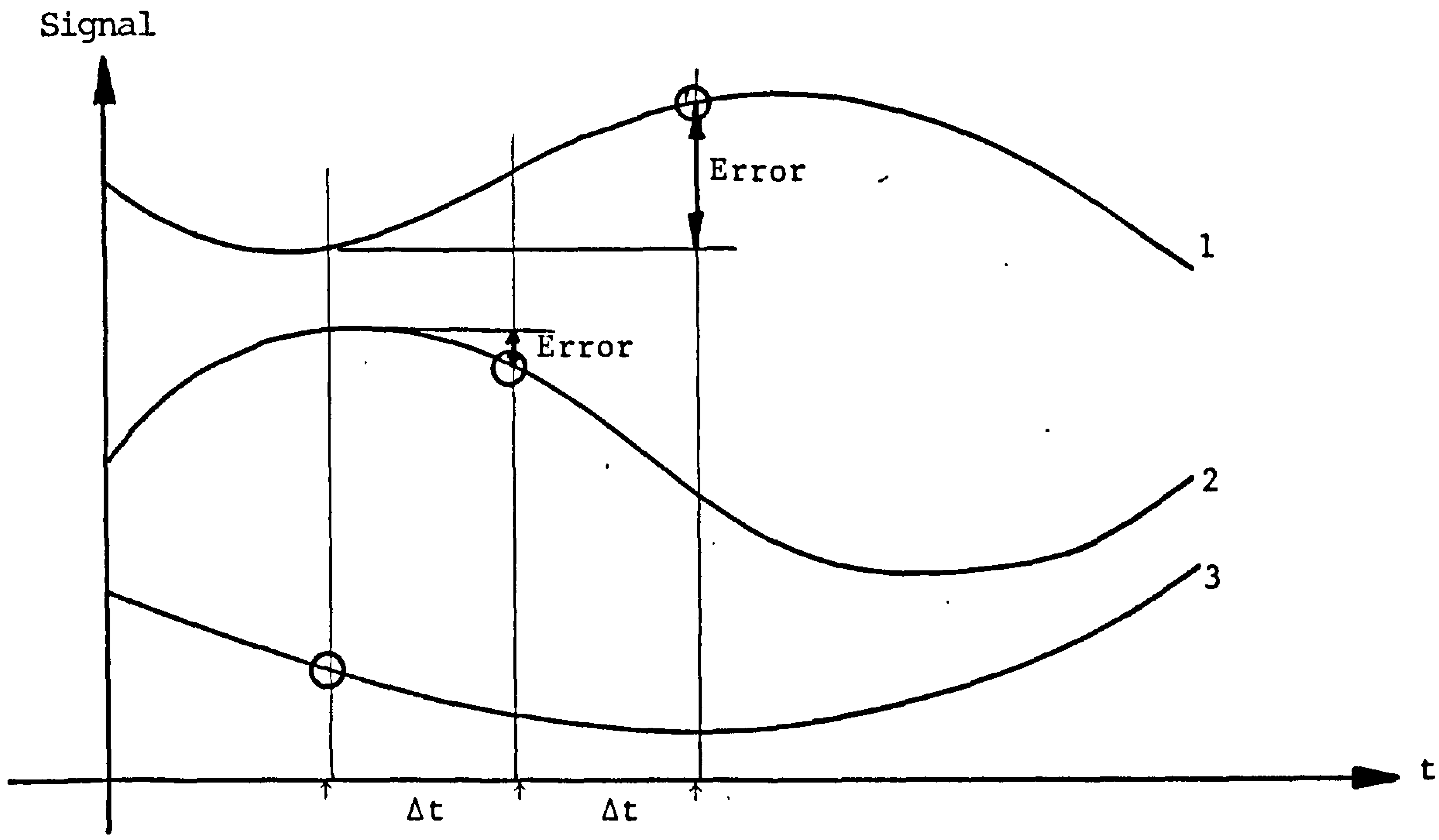
Schematic arrangement of horizontal load washer.

FIGS. 6.



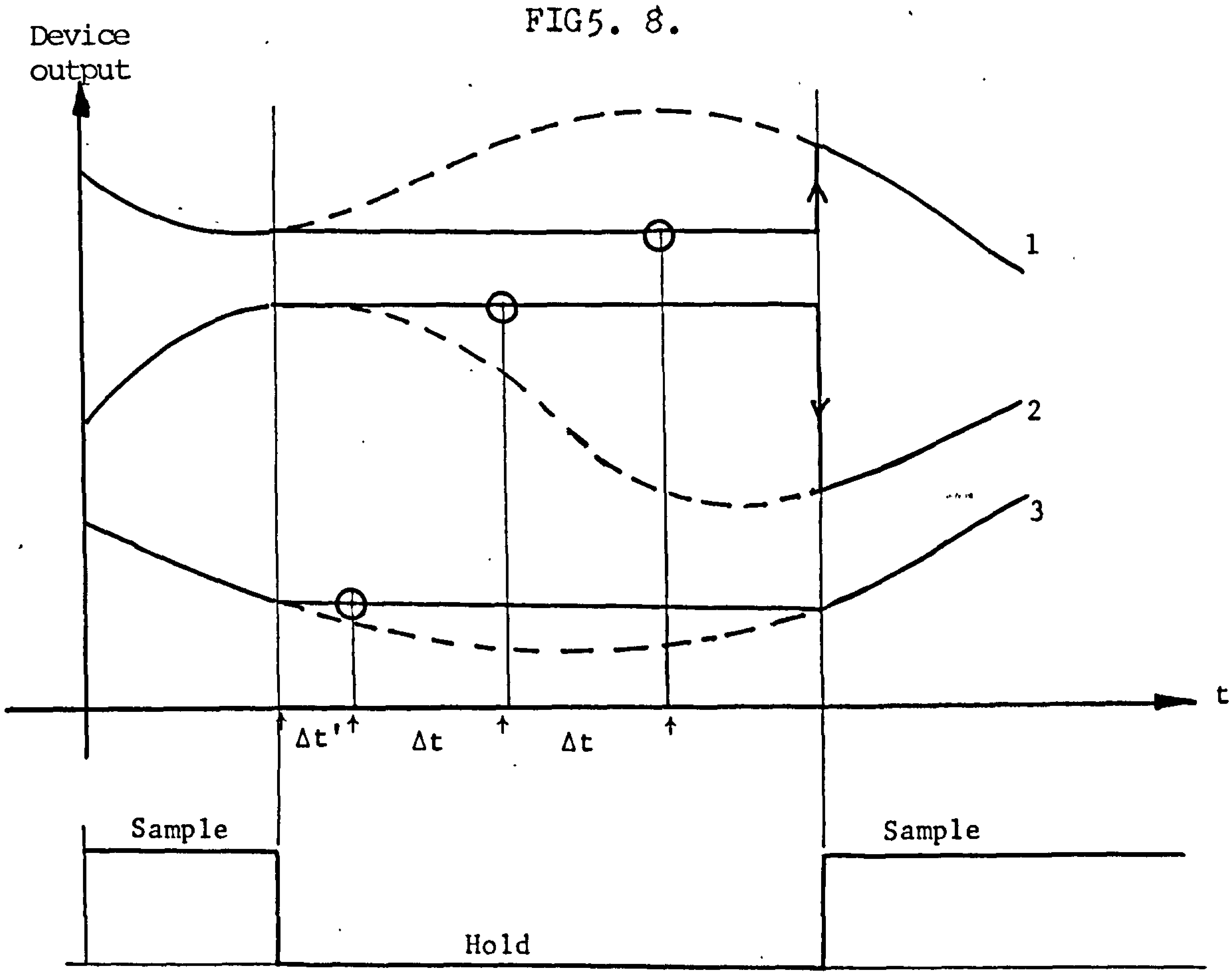
Circuit diagram for three channel filter

FIG5. 7.



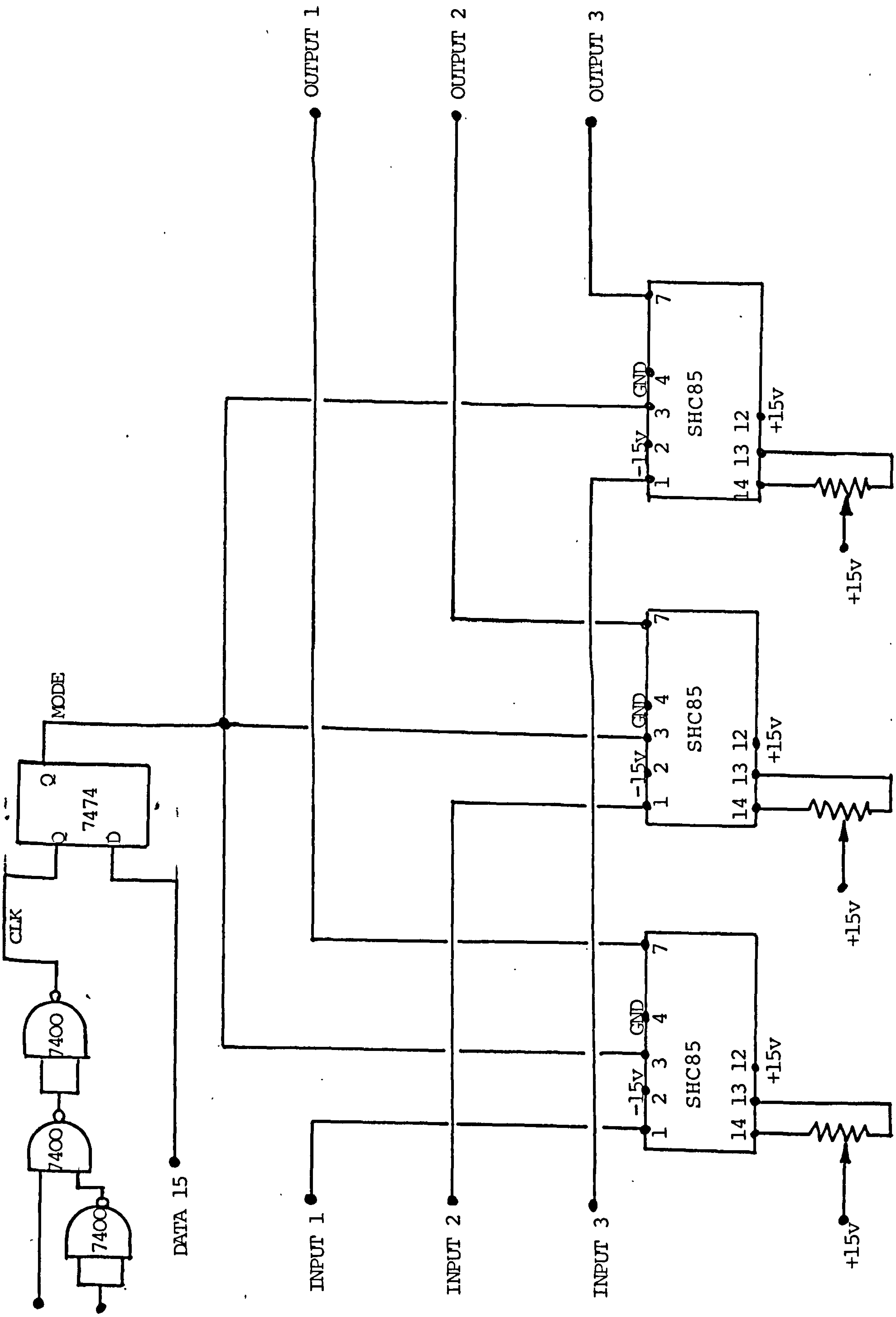
Errors due to serial sampling.

FIG5. 8.



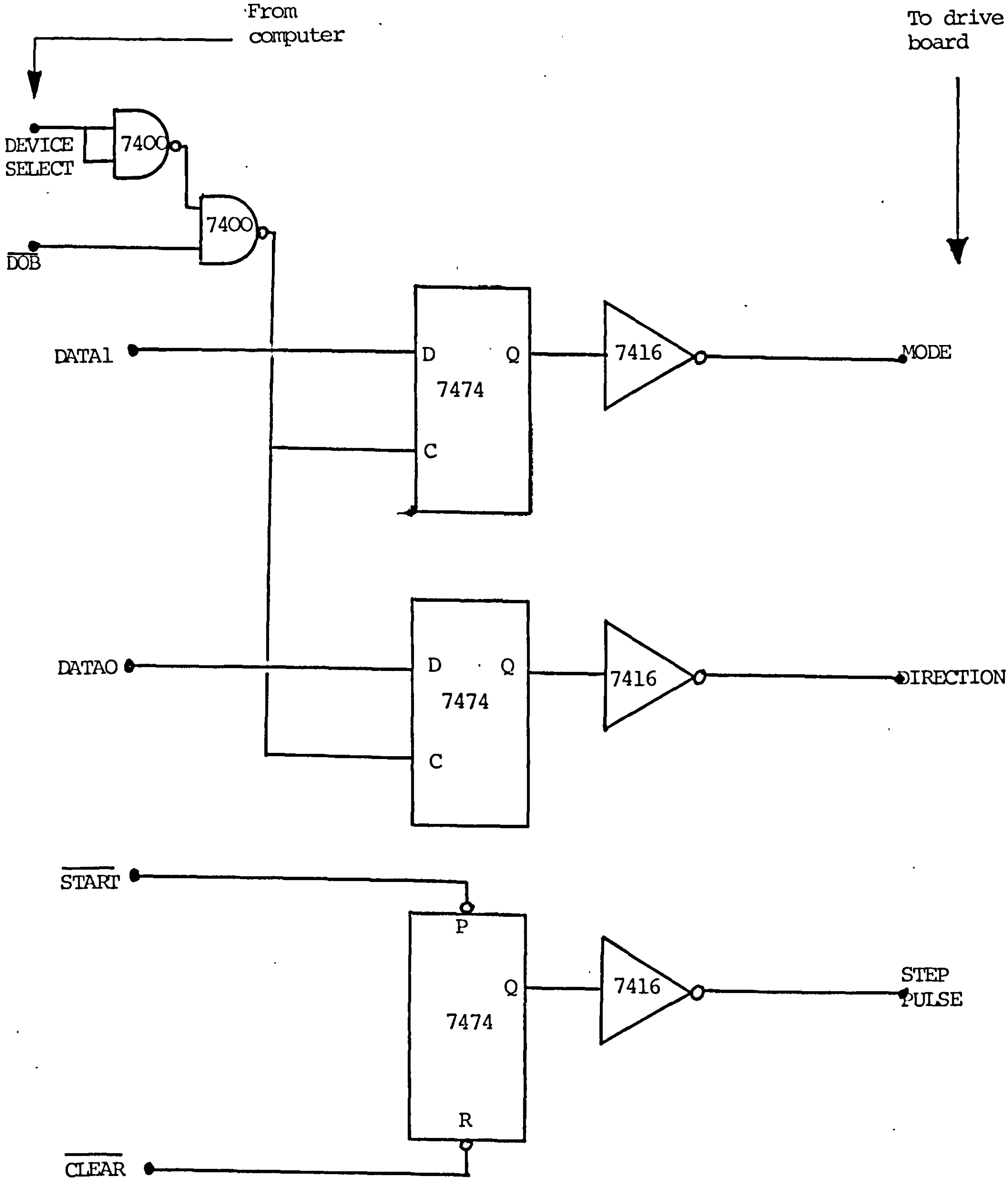
Effects of sample/hold devices.

FIG5. 9.



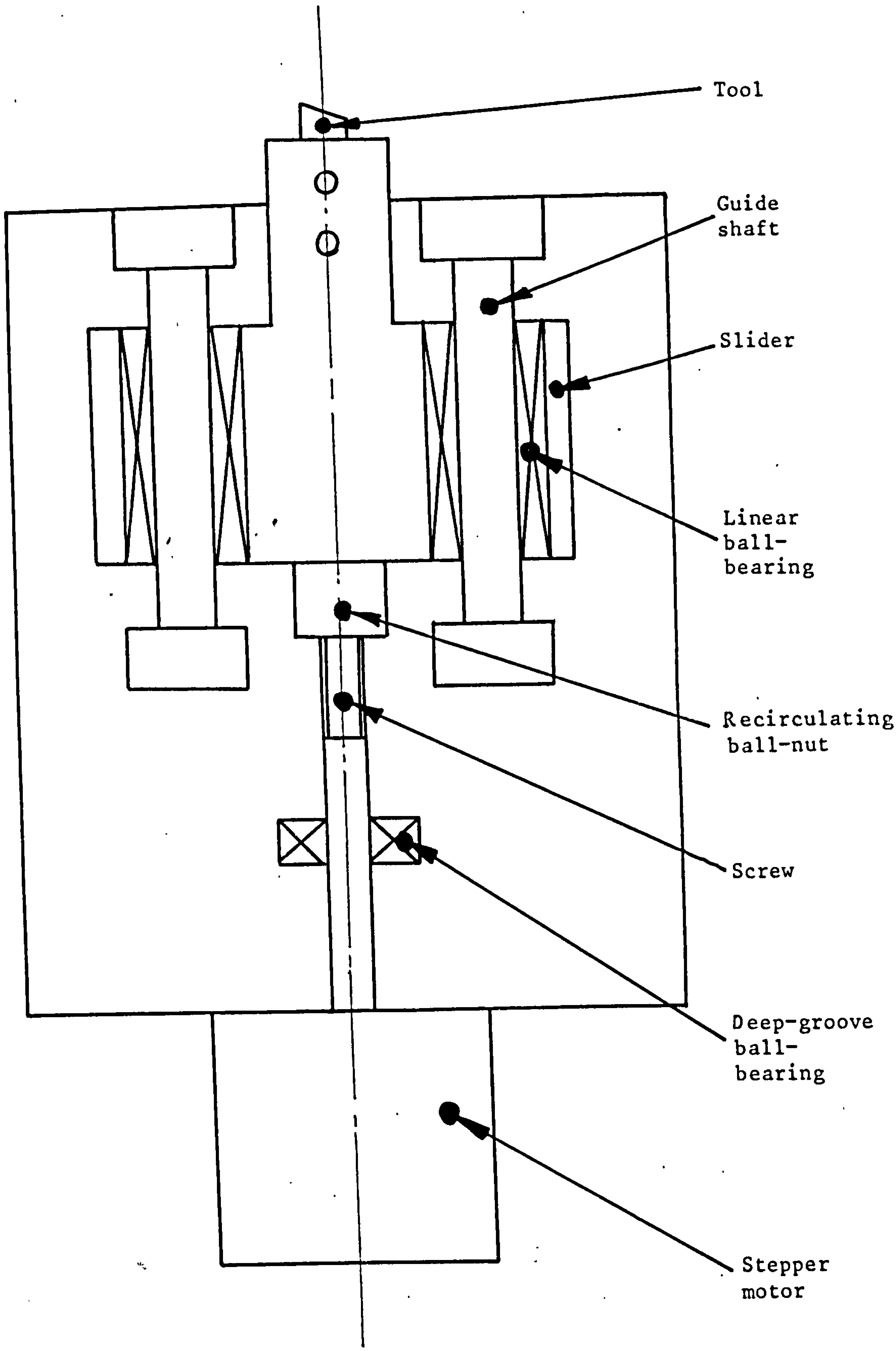
Circuit design for three channel sample/hold device

FIG5. 10.



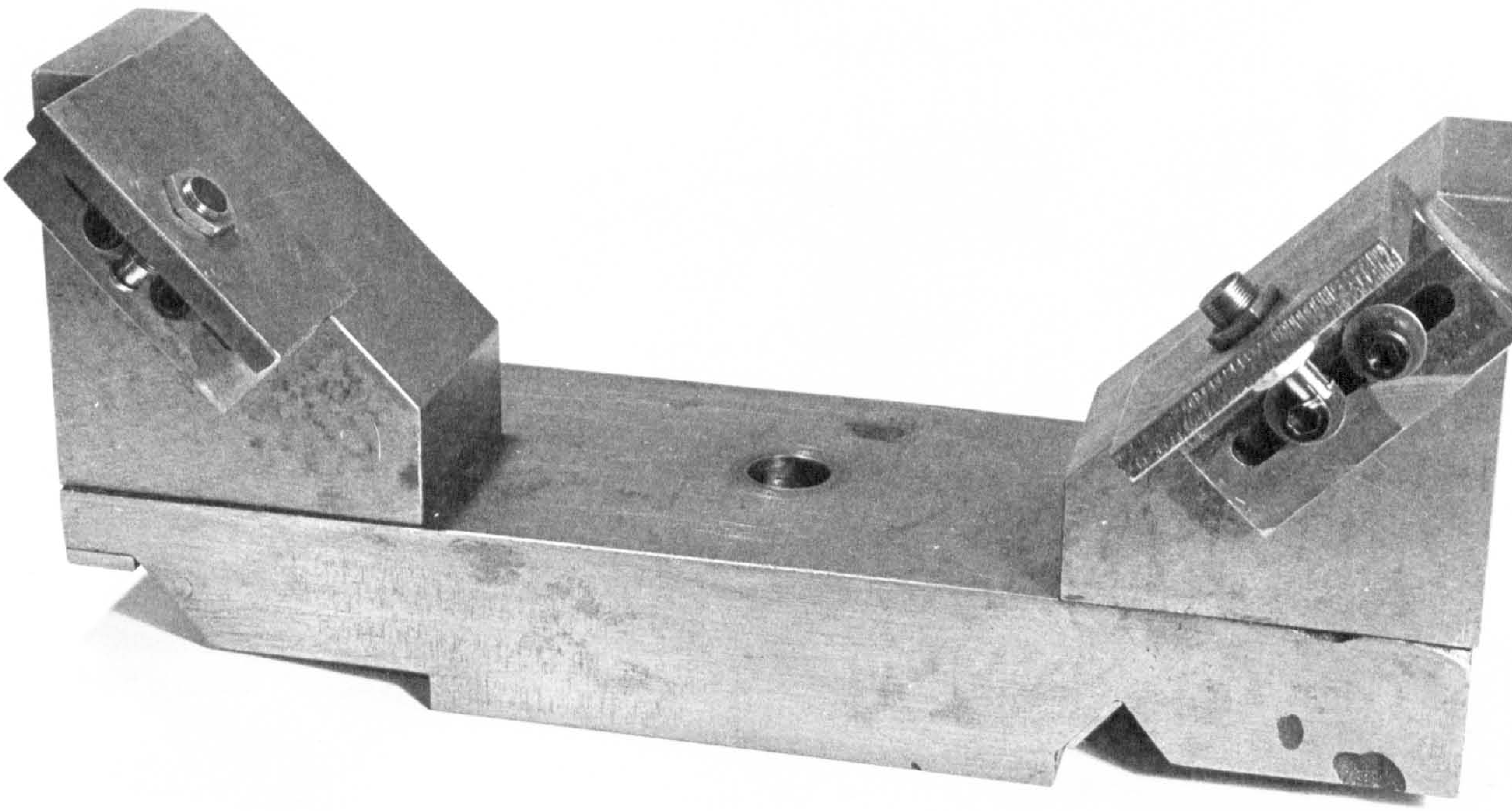
Circuit design for stepping motor interface

FIG5. 11.



Proposed tool positioner-A.

FIG5. 12.



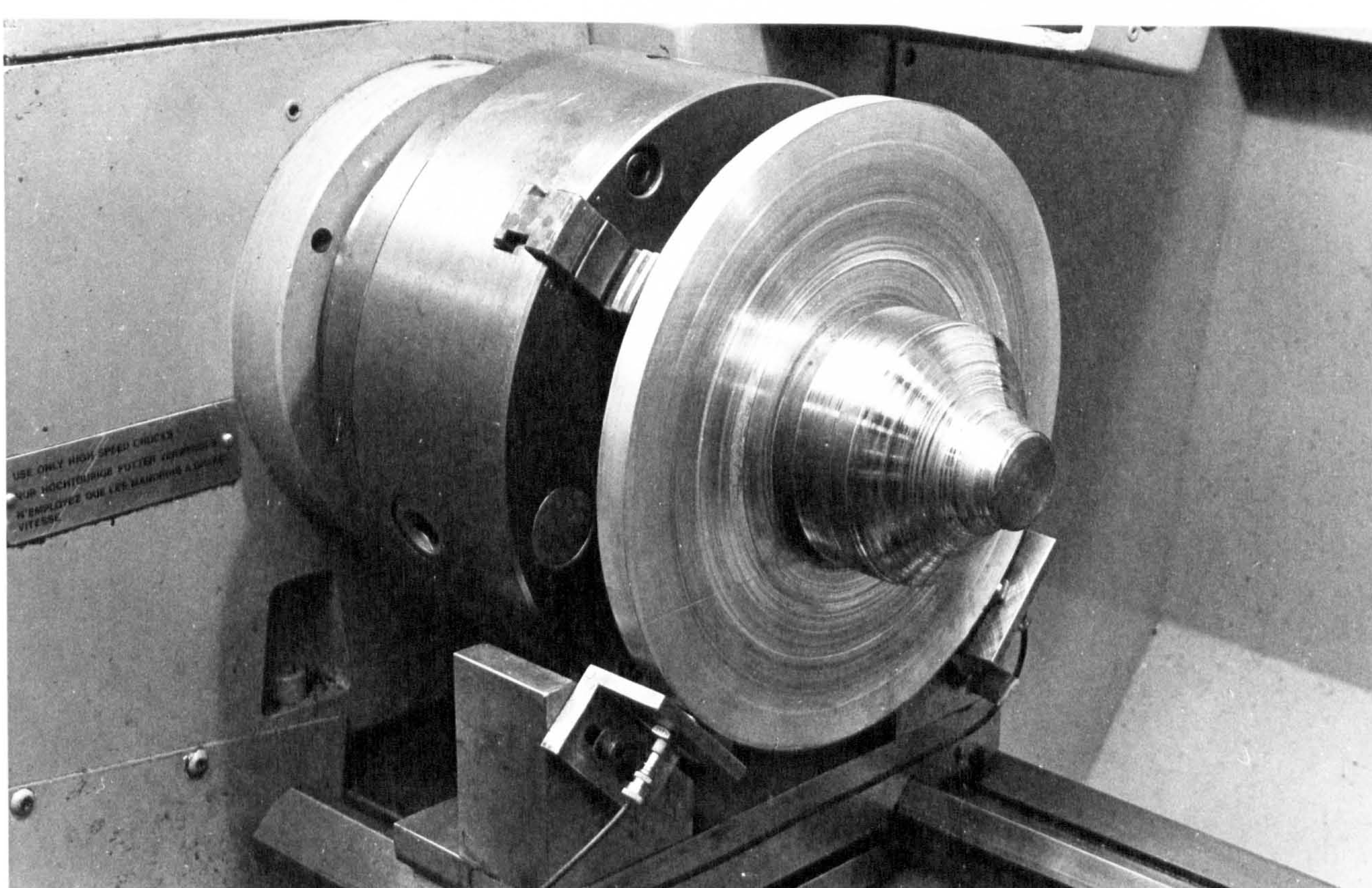


PLATE5. 1.

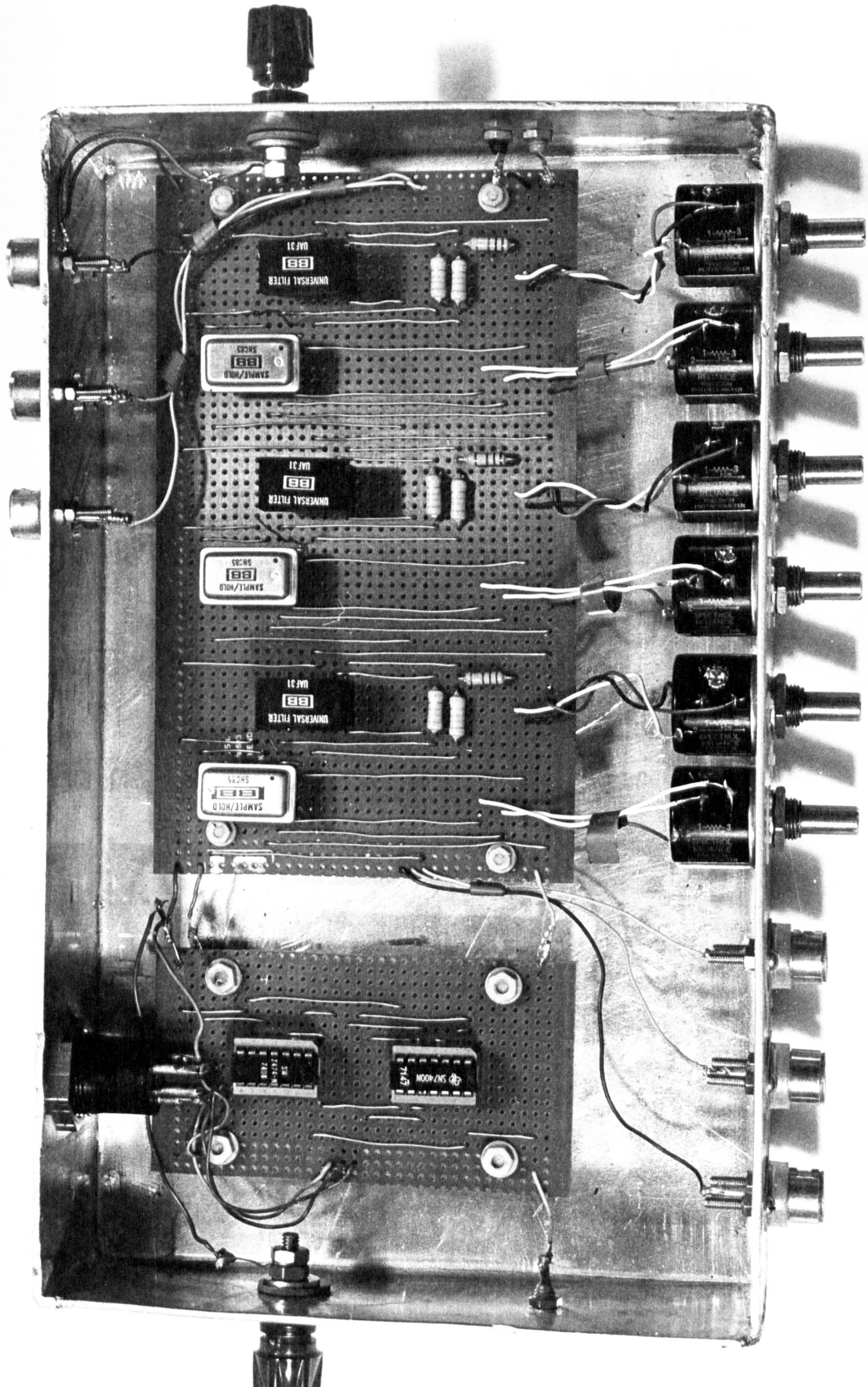
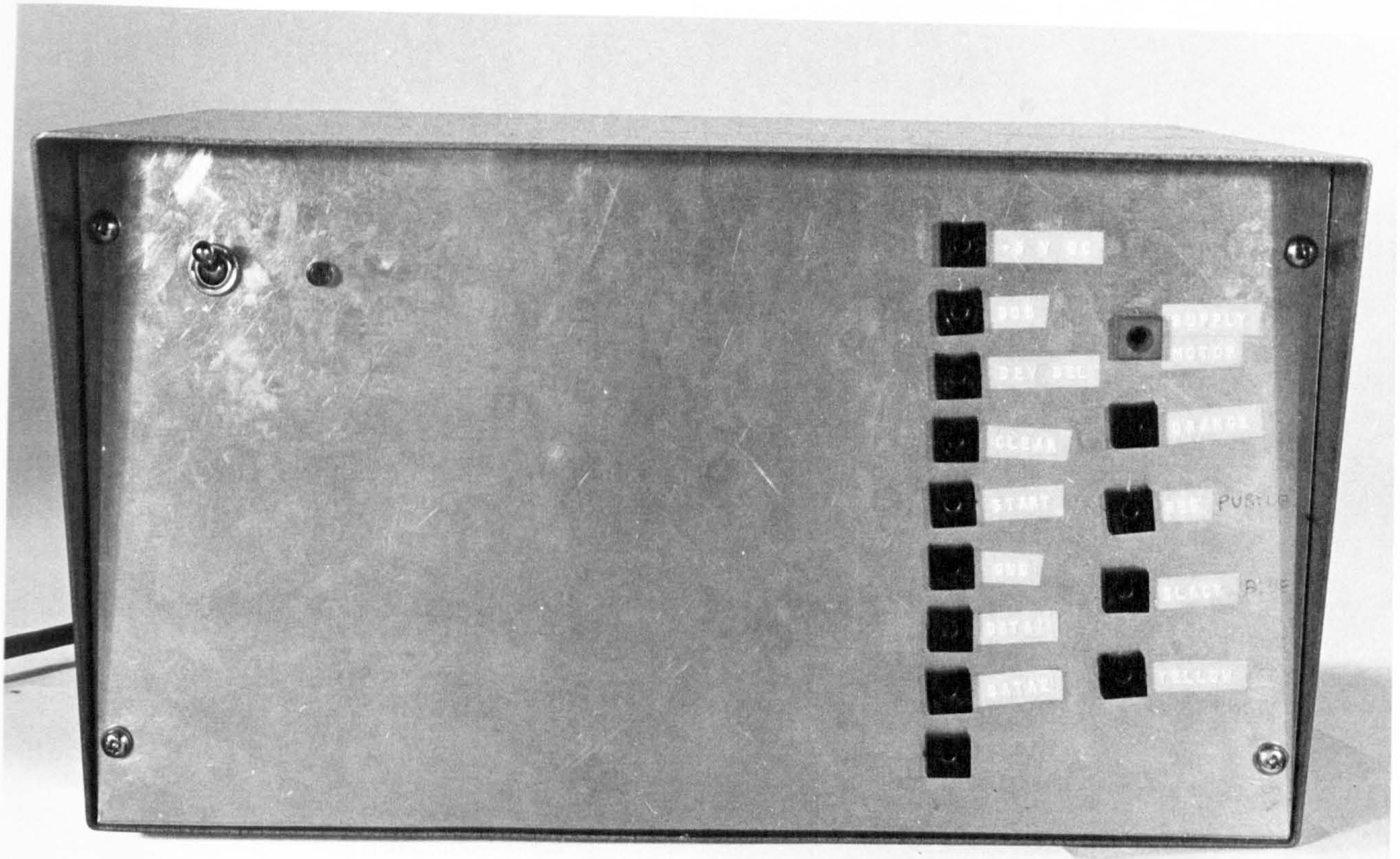


PLATE5. 2.



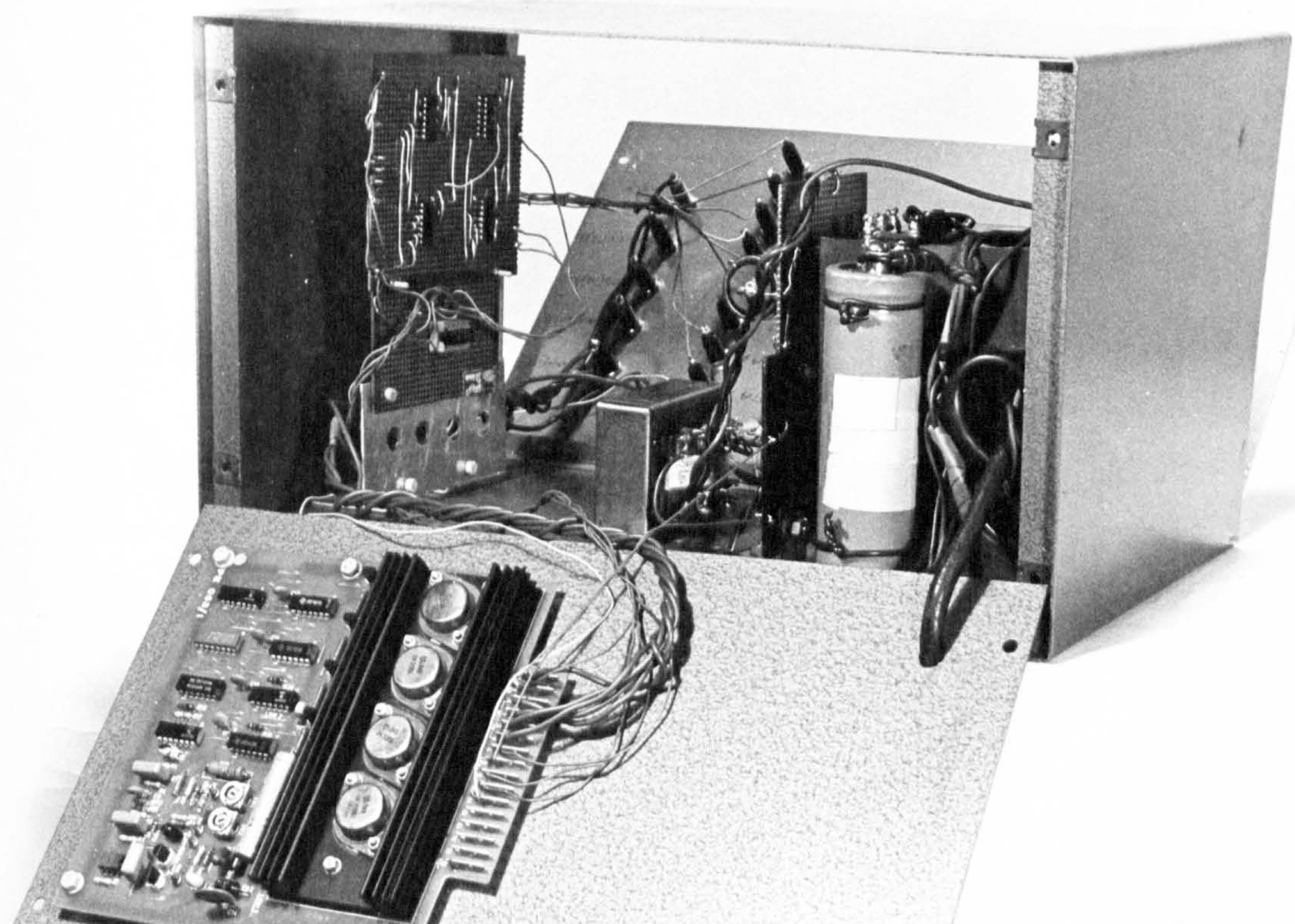
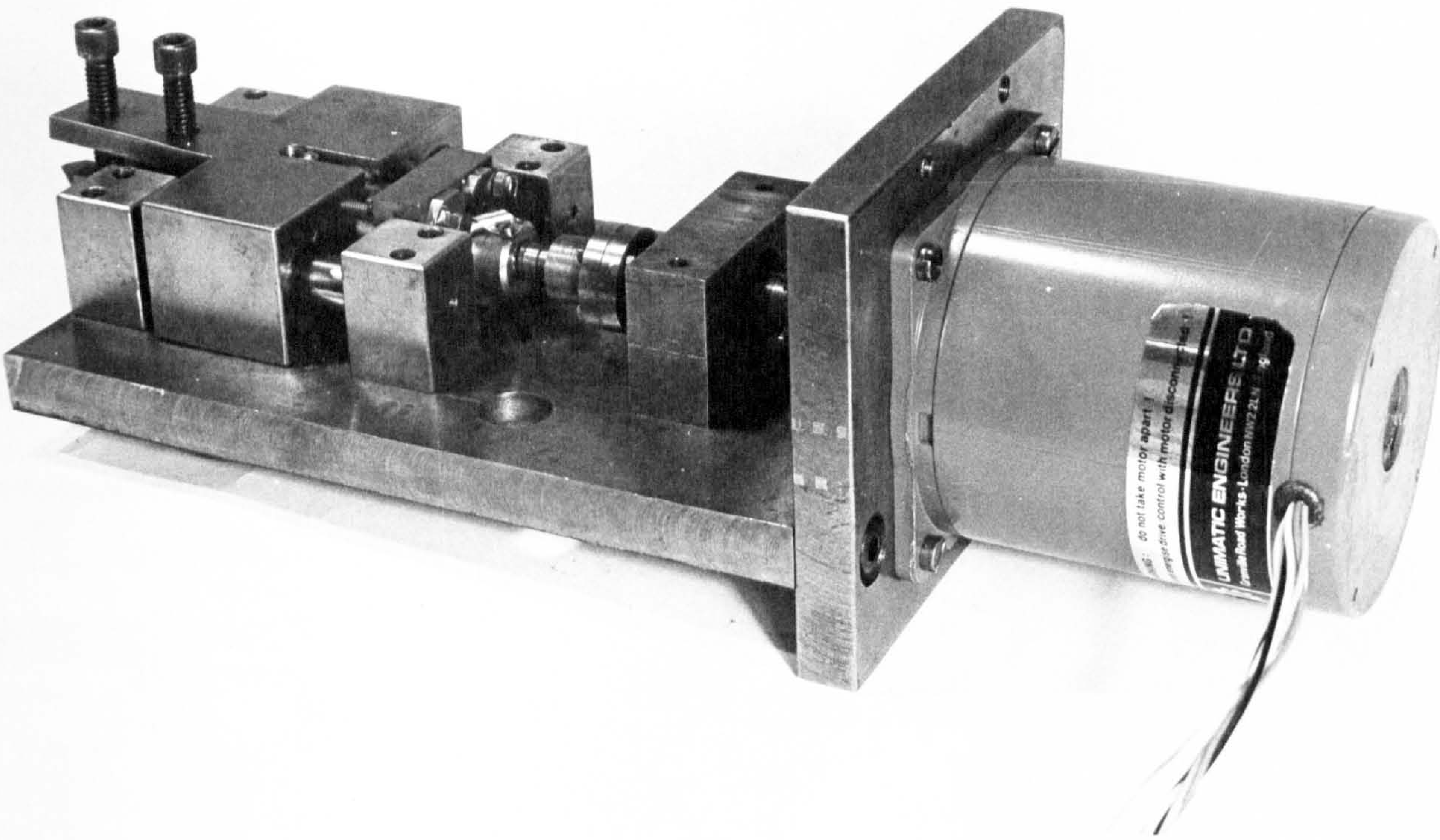


PLATE5. 3.

PLATE5. 4.



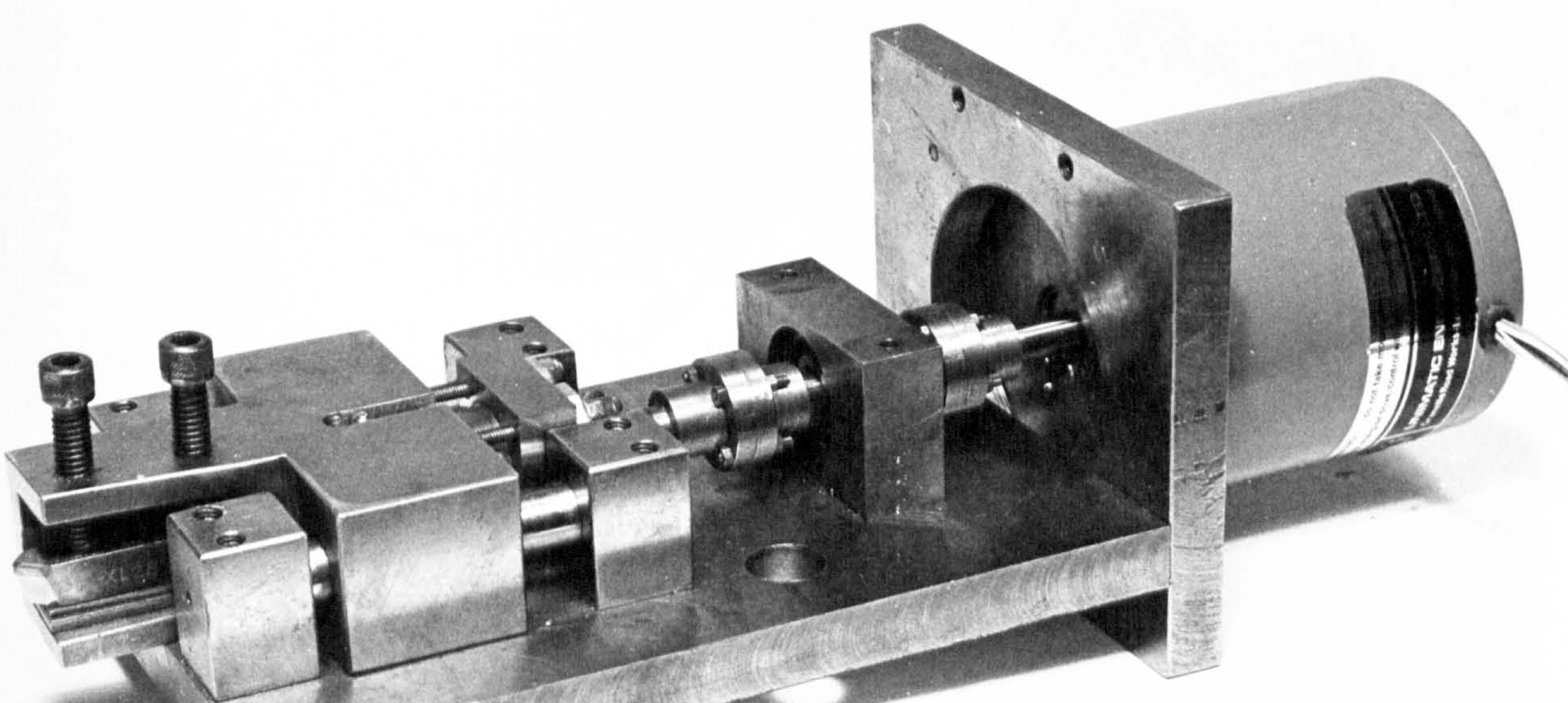


PLATE5. 5.

PLATE5. 6.

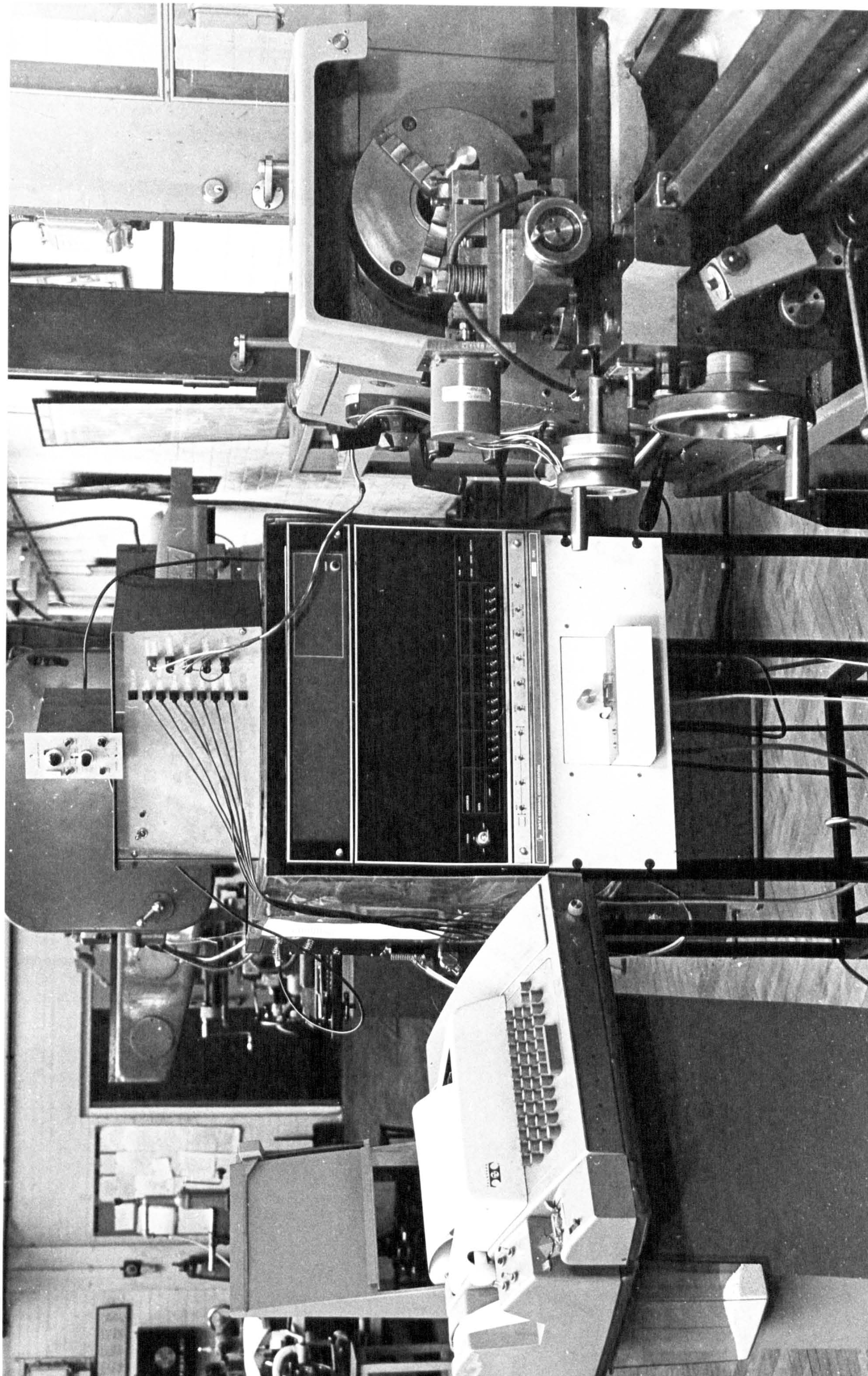


PLATE5. 7.

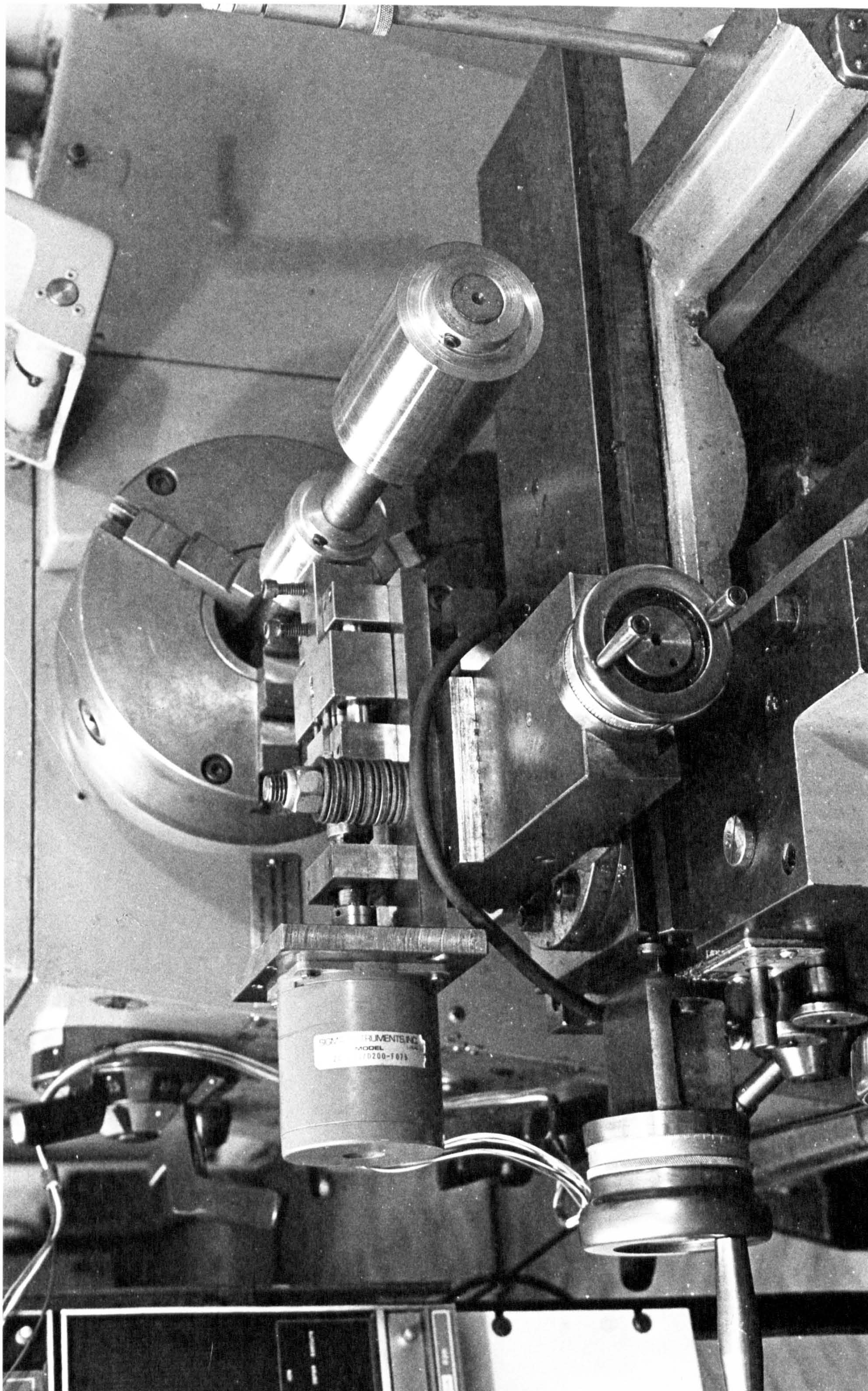


PLATE5. 8.

6. COMPUTER NUMERICAL CONTROLLED TURNING.

6. 1. Introduction.

Although the tool positioner described in Chapter 5 is designed for small amplitude motion (1 to 5 thou), it has a maximum displacement of about 1 inch. This capability is utilised in the simple C.N.C. turning system presented in this chapter. The system enables complex, axi-symmetric components to be produced directly from equations specifying it's shape.

6. 2. System design and implementation.

The basic system consists of a lathe, tool positioner and minicomputer. A schematic diagram of the machining geometry is shown in FIG6. 1. The axial displacement (l) is generated automatically by the feed of the lathe saddle. The depth of cut (d) is controlled by the minicomputer driving the tool positioner. These two variables are related by an equation which specifies the shape of the component. This has the general form:-

$$d = f(l) \qquad 6.1$$

In the case of the prototype system, the axial position (x) is calculated by the equation:-

$$l = f.r.t \qquad 6.2$$

Where f and r are the feedrate (inches/rev.) and speed (r.p.m.), and t is the time (mins.) from start of cutting. Prior to the start of machining, the axial position and depth of cut are set to known references by means of the saddle and slide positioners. These are chosen depending on the overall dimensions of the component to be machined. Once machining commences the minicomputer calculates the axial position at descrete time intervals (equation 6. 2.) and the corresponding depth of cut (equation 6. 1.). The required number of steps and direction are then output to the tool positioner. A flowchart of the control programme is given in APPENDIX A and the main computer programme in APPENDIX B.

At present the shape equation is implemented as a pair of subroutines. One inputs the parameters of the shape equation from the teletype, and the other performs the calculation of the depth of cut. Different basic shapes are represented by different pairs of subroutines. This method is used for development only and will be replaced by an equation interpreter which will input the complete shape equation from the teletype.

The main disadvantage in calculating the axial position is the errors which are introduced by inaccuracies in the lathe speed and feed. This problem may be overcome by direct measurement of the axial position. However this increases the complexity and expense of the system.

The major differences between the system described here and conventional numerical lathes are as follows :

-- it is equation driven, not 'point - to - point'.
-- existing lathes can be easily modified by 'adding-on' the tool positioner and minicomputer.
-- it is relatively cheap.

At present the main expense is the minicomputer. It is forseen that this could be replaced by a microcomputer with considerable cost savings. The tool positioner also needs some modification to give greater tool travel and workpiece clearance. A proposed design is shown in FIG6. 2. Work is in progress to develop a two axis version of the system. This will be capable of producing a more complex range of components with greater accuracy and repeatibility.

6. 3. Examples of components produced by the system.

Two basic applications of the C.N.C. turning system are presented in this section. PLATE6. 1 shows a typical machining set-up and some of the components produced by the system.

The component on the left has a shape equation of the form:-

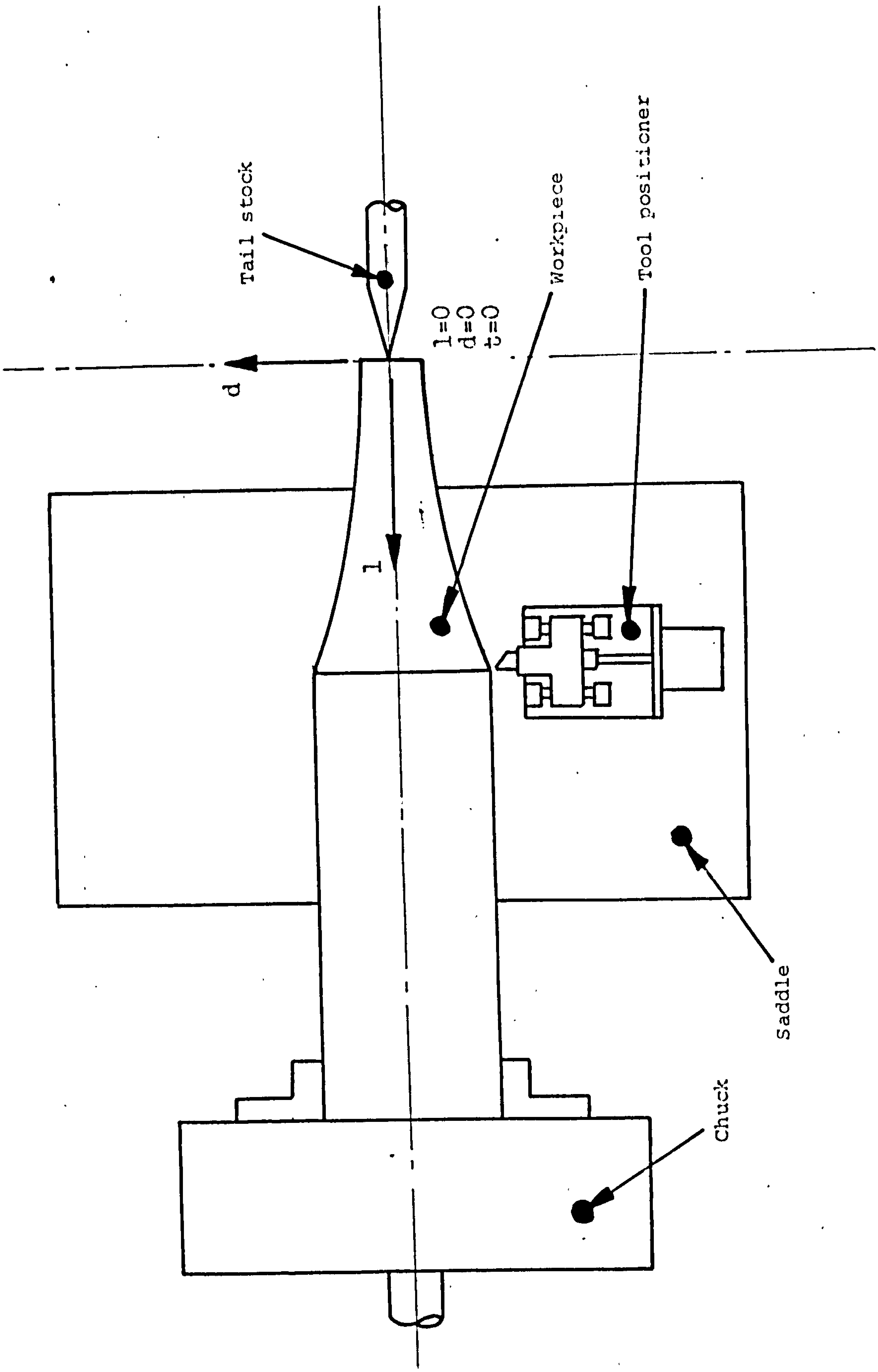
$$d = \begin{cases} m_1 + m_2 . l : & 0 < l < \sqrt{\dfrac{m_3 - m_1}{m_2}} \quad \text{—— 6.3a} \\[2ex] m_3 : & \sqrt{\dfrac{m_3 - m_1}{m_2}} < l < \dfrac{m_4}{m_3 - m_5} \quad \text{—— 6.3b} \\[2ex] \dfrac{m_4}{l} - m_5 : & \dfrac{m_5}{m_3 - m_5} < l \quad \text{—— 6.3c} \end{cases}$$

The other two components have the same basic shape equation:-

$$d = \begin{cases} n_1 : & 0 < l < n_3/3 \quad \text{—— 6.4a} \\ n_2\sqrt{n_3^2 - (n_3 - l)^2} : & n_3/3 \leqslant l \leqslant n_3 \quad \text{—— 6.4b} \\ n_3 : & n_3 < l < n_4 \quad \text{—— 6.4c} \\ n_3 - n_5(l - n_4) : & n_4 \leqslant l \leqslant n_6 \quad \text{—— 6.4d} \\ n_3 - n_5(n_6 - n_4) - n_7(l - n_6) : & n_6 \leqslant l \leqslant n_6 - [n_8 - n_3 + n_5(n_6 - n_4)]/n_7 \quad \text{—— 6.4e} \\ n_8 : & n_6 - \dfrac{n_8 - n_3 + n_5(n_6 - n_4)}{n_7} < l < n_9 \quad \text{—— 6.4f} \\[2ex] n_8 + n_9 . l^2 : & n_9 \leqslant l \leqslant \sqrt{\dfrac{n_9 - n_8}{n_{10}}} \quad \text{—— 6.4g} \\[2ex] n_{11} : & n_{11} < l \quad \text{—— 6.4h} \end{cases}$$

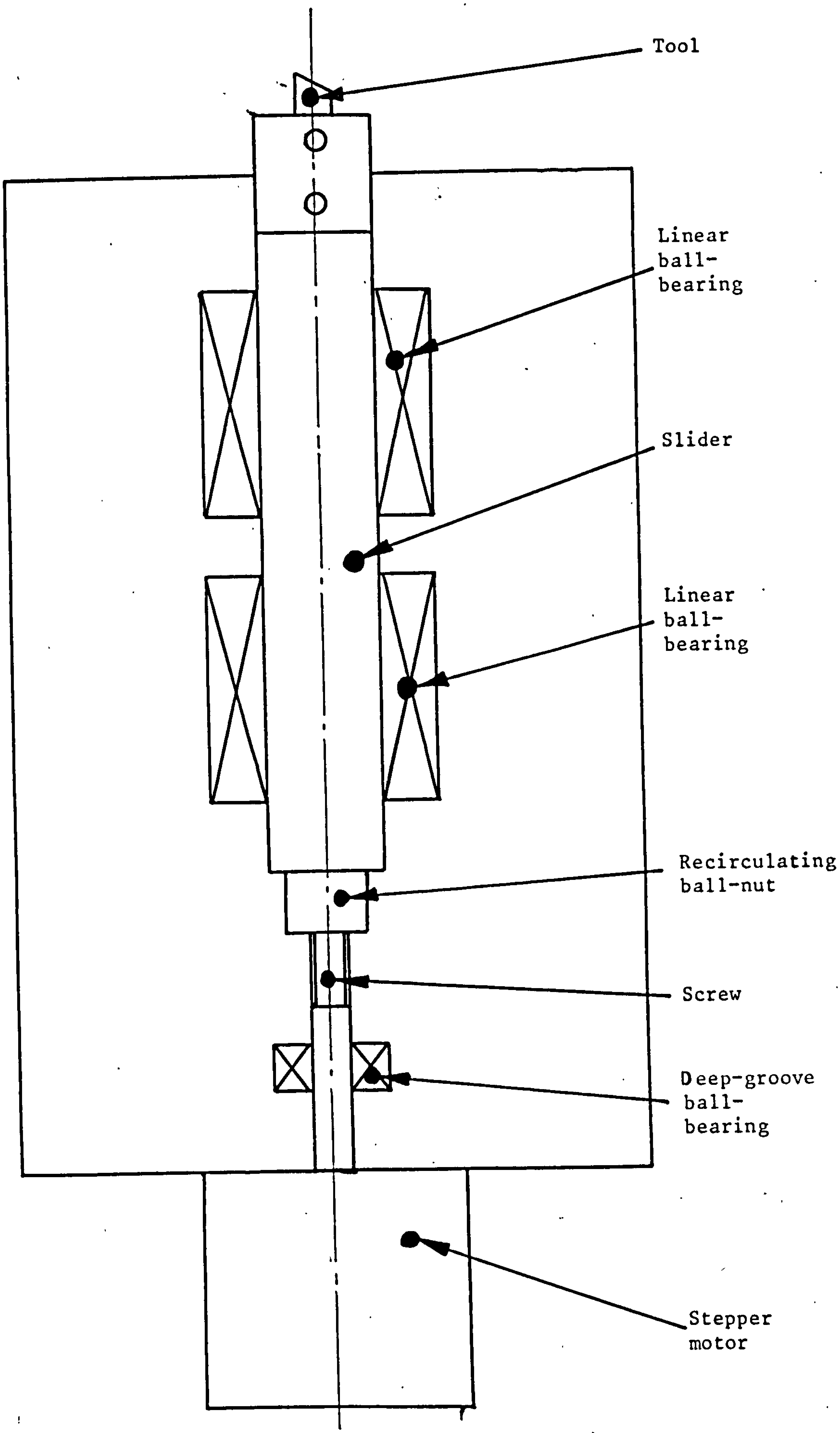
It was found while using the experimental system that two main problem areas exist. Firstly, when high rates of change of cutting depth are required, the tool positioner cannot keep pace. Secondly, the shape of the cutting tool must be carefully chosen for the shape of component to be machined.

There is much work to be done to create an acceptable manufacturing system, however the capabilities of the concept are clearly demonstrated.



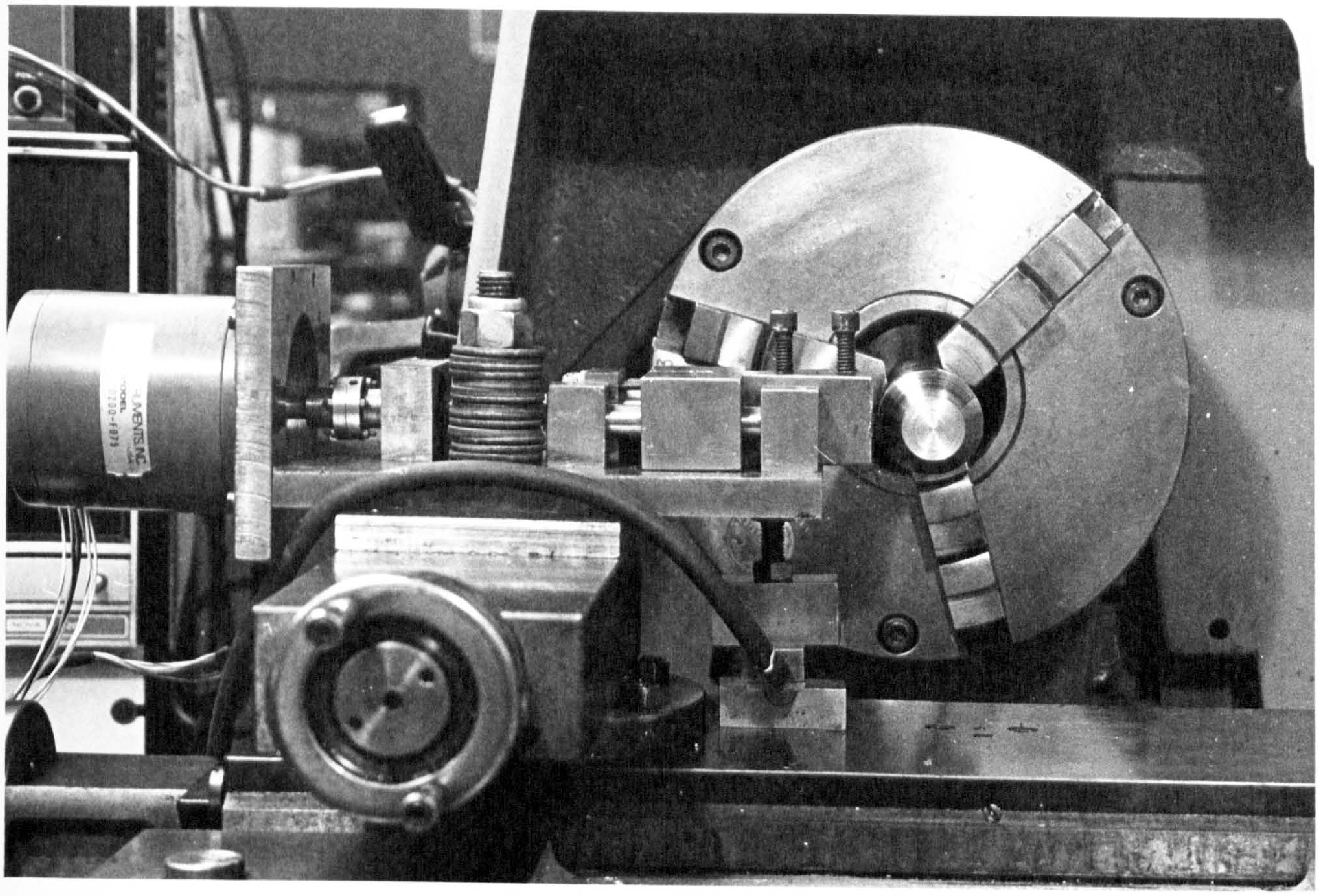
C.N.C. Machining.

FIG6. 1.



Proposed tool positioner-B.

FIG6..2



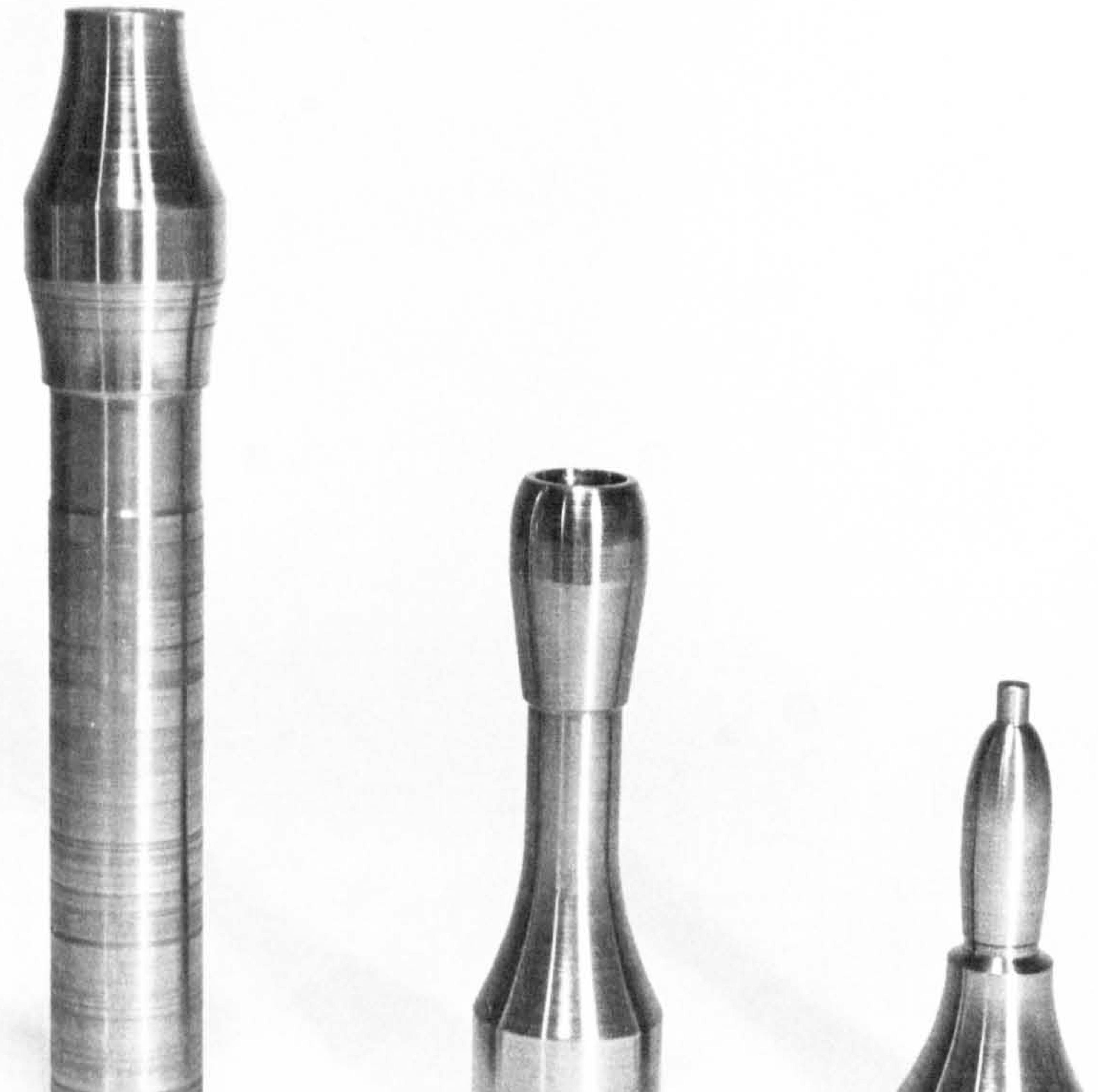


PLATE6. 1.

7. EXPERIMENTAL WORK.

7. 1. Introduction.

The experimental work performed during this research project falls into three main catagories, these being:

-- the investigation of the machine-workpiece dynamics
-- the validation of the chatter controller
-- the testing of the chatter suppression method

A description of the experimental procedures is presented in four sections. The first gives details of the instrumentation and calibration, the other three describe the catagories outlined above.

All the apparatus used throughout the experimental work is described in Chapter 5.

Results of the various experiments are also included in this Chapter, and are discussed in detail in Chapter 8.

7. 2. Instrumentation set-up and calibration.

In order that the signals monitored during the experimental work are accurately related to the physical variables being measured, the instrumentation system must be carefully set-up and calibrated. This is carried out to determine the following relationships:

-- voltage output to physical variable
-- digital representation to physical variable

Regular checks are also necessary throughout the testing to prevent errors due to drift and physical interference.

All calibration is performed 'in-situ' by applying known inputs to the transducers and measuring the output voltage and the digital representation.

7. 2. 1. Setting-up the filter and sample-and-hold unit.

Before calibration is performed the filters and sample-and-hold amplifiers must be adjusted to eliminate any D.C. offset. This is achieved by grounding the inputs to the devices and adjusting the 'trim-pots' so that the outputs are zero.

Regular checking of this unit is also necessary to correct for long term drift. This proceduce is the same as that for initial set-up.

7. 2. 2. Calibration of the force measurement system.

Prior to calibration of this system, the load cells are pre-loaded to ensure they always operate within their linear range. For the vertical axis this is achieved by expanding a screw jack, and for the horizontal axis by thightening the ballscrew clamping bolts. The amount of pre-load is gradually increased until the output signal shows no sign of 'flattening' even under the most severe cutting conditions.

The charge amplifiers are then set to the required sensitivity.

-- 20 pc/lb. for the horizontal axis

-- 5 pc/lb. for the vertical axis

and the time constant set to long. Cutting operations are then performed for a range of cutting conditions and the amplifier gains adjusted so that the output voltage never exceeds 4 volts. This allows a 1 volt safety margin before the A-D converter overloads.

The calibration is performed by applying a series of known loads to the tool tip and monitoring the outputs. This is done in a load-up/load-down manner, the output voltage and digital representation being noted at each load. Vertical and horizontal calibrations are performed independantly. Checks are also made to determine the cross-talk between the two axes. So as to minimise the effects of measurement noise and observation error, several calibration runs are performed and the scaling factors calculated for the averaged reading.

Calibration curves for the vertical and horizontal axes are shown in FIG7. 1. and FIG7. 2. respectively. Cross-talk between the axes is negligible at the loading levels encountered during the tests.

During all calibration and test runs, the charge amplifiers must be reset prior to use. This prevents erroneous readings being obtained due to amplifier drift. A warm-up period of about 30 minutes should be allowed with this equipment.

7. 2. 3. Calibration of the displacement measurement system.

Before the displacement measurement system can be calibrated, the reference disk must be accurately centred. This is ensured by machining the disk 'in-situ' and then smoothing the surface with fine emery paper. The transducer mountings are then adjusted so that their axes are at 45° to the vertical and pass through the disk centre (see FIG5. 4.). Next, the initial gaps between the transducers and the disk are set to 10 thousandths-of-an-inch. This is achieved by adjusting the clamping nuts and checking the gaps with a feeler gauge. A 10 'thou' gap is used as it provides the required combination of sensitivity, linearity and clearance.

The lathe is then run under non-cutting conditions and the oscillators and F.M.units adjusted (see reference 43) to give maximum output signals. If the reference disk is not correctly centred, as indicated by a sinusoidal signal, the setting-up procedure must be repeated.

Calibration of the system is now performed. This is done by varying the gap between the transducer and the disk and recording the corresponding output voltage and digital representation. The gap is varied by means of the transducer clamping nuts, and measured with a feeler gauge. Calibration curves for the two axes are given in FIG7. 3. and FIG7. 4.

The displacement measurement system requires a warm-up period of about 30 minutes. Care is also required to ensure that all cables are kept clear of the rotating parts. The disk must be checked for concentricity before all tests, and re-trued if necessary.

7. 3. Tests on the machine-workpiece structure.

Three types of test are performed to determine the nature of the machine-workpiece dynamics. These are :

-- cutting tests
-- impulse responce tests
-- on-line system identification

Where recording of the cutting force or workpiece displacement is required, an ultra-violet oscillograph is used.

7. 3. 1. Cutting tests.

Cutting operations are carried out for a variety of cutting conditions, including chattering, and the cutting force and workpiece displacement are monitored. A brief outline of the experimental procedure is given below:

-- set-up the U.V. oscillograph
-- allow the instrumentation to warm-up
-- calibrate the instrumentation (see section 7. 2.)
-- set-up the workpiece and cutting tool
-- select the lathe speed and feedrate
-- set depth of cut
-- start lathe
-- start U.V. oscillograph
-- commence cutting operation
-- record trace for about 10 to 20 seconds
-- stop cutting then U.V. oscillograph

Some representative examples of cutting force and workpiece displacement traces are presented in FIG7. 5. to FIG7. 19. The cutting parameters associated with each example are included on the figure.

7. 3. 2. Impulse response tests.

Impulse response tests are performed on both the machine, and with various types of workpiece clamped in the chuck. In the case of the 'machine-only' tests the displacement transducers are arranged to monitor the chuck surface. Although this configuration cannot be used with the lathe running, static tests are possible. When a workpiece is in use, a reference disk is used (see FIG5. 4. and PLATE5. 1.). This enables tests with the lathe both running and stationary.

The impulse is generated by striking either the chuck or workpiece with a soft mallet. This rather crude method is found to give a sharp, clean impulse. The experimental procedure is as follows:

-- set-up the U.V. oscillograph
-- set-up the workpiece and reference disk (if required)

-- allow instrumentation to warm-up
-- calibrate the displacement instrumentation (see section 7.2.3)
-- start the lathe (if required running)
-- start the U.V. oscillograph
-- deliver impulse(s)
-- stop the U.V. oscillograph

Some typical responses are given in FIG7. 20. and FIG7. 21. Details of the conditions for each test are included on the respective figures.

7. 3. 3. On-line system identification tests.

The method described in section 4.3. is used to determine the transfer functions:

-- relating the horizontal force to the horizontal workpiece displacement
-- relating the vertical force to the horizontal workpiece displacement

Both are assumed to be second-order, and the identification method estimates the 'best' parameters (see section 4. 3.) for these functions. The tests are not extended to include the vertical displacement as this is thought to be of only minor importance in chatter instability.

In order to prove the implementation of the method, and evaluate its performance, tests are performed on known second-order systems. Once proven, the method is used to examine the machine-workpiece structure.

7. 3. 3. 1. Method evaluation.

An analogue computer is used to model a second-order system, the system parameters being varied by means of potentiometers. These parameters are set to several known values and the system excited by an input signal. Three type of input signal are used:

-- pseudo random binary sequence
-- square wave
-- sine wave

The input and corresponding output are monitored by the minicomputer and the 'best' estimates for the parameters are calculated and output to the teletype.

A schematic diagram of the experimental arrangement is given in FIG7. 22. with the analogue model detailed in FIG7. 23. Flowcharts for the identification programme are presented in APPENDIX A. 6. and listings in APPENDIX B. 7.

The analogue computer is an EAI PACE TR-48, details of which are given in reference 50.

The experimental procedure is as follows:

-- switch on electronic equipment and allow a 30 minute warm-up period
-- set the signal generator to the required signal
-- select frequency and amplitude for signal
-- select the model parameters by adjusting the respective potentiometers
-- set the analogue computer to 'run' (see reference 50)
-- start the identification programme and input the programme constants via the teletype (see APPENDIX B.)

The identification programme then proceeds to estimate the system parameters.

It is found from these tests that a sample frequency of approximately 10 times the input signal frequency gave the most accurate results. The sample size (number of samples per run) was varied without noticable effect.

Results of several runs are given in FIG7. 24. and FIG7. 25. The variables associated with each test are included on the respective figures.

7. 3. 3. 2. Machine-workpiece identification tests.

The results of the tests described in sections 7. 3. 1. and 7. 3. 2. are used to select the required filter cut-off frequency and sampling frequency. These being such that the sampling frequency is about 10 times the dominant frequency in the workpiece displacement signal, and the filter cut-off frequency half the sampling frequency.

The experimental rig used throughout the tests is shown in PLATE5. 6. It is similar to the arrangement used during the validation tests, except that the analogue computer is replaced by the lathe and instrumentation. The experimental procedure is as follows:

-- warm-up electronic apparatus
-- set-up and calibrate instrumentation (see section 7. 2.)
-- set-up workpiece and cutting tool
-- select lathe speed and feedrate
-- select and set depth of cut
-- start the identification programme and input the set points and scaling factors for the instrumentation, and other runtime constants (see APPENDIX B.)
-- start the lathe and commence cutting

Estimates of the machine-workpiece parameter estimates are output to the teletype. Tests are conducted for a range of cutting conditions ,including chattering. A summary of the results is given in FIG7. 26.

7. 4. Tool positioner tests.

The dynamic performance of the tool positioner is investigated by observing it's response to known inputs. Two types of input are used:

-- single step, forward then reverse
-- sine wave, various frequencies and amplitudes

These are used to determine the 'stop/start' and 'tracking' capabilities, from which the overall performance limitations can be inferred.

7. 4. 1. Forward/reverse response.

For these tests the tool positioner is repeatedly driven one step forward then one step reverse.

The tool positioner is rigidly clamped to a mounting plate and an inductive displacement transducer is positioned to monitor the axial motion of the tool. A aluminium bar with a square end is used as a dummy tool, and an initial gap of 10 'thou' is set between the tool end and the transducer. The measurement system is set-up and calibrated as described in section 7. 2.

A test programme is used to drive the positioner in a forward/reverse motion. The displacement is recorded on a U. V. oscillograph for drive frequencies between 5 and 100 Hz. Some typical results are shown in FIG7. 27 to FIG7. 32.

7. 4. 2. Frequency/amplitude tests.

Using the same experimental arrangement as described in the previous section, the positioner is driven to 'track' a signal from a signal generator. The initial gap between the tool and the transducer is set to approximately 50 'thou'. This ensures sufficient clearance for large amplitude displacements and gives a linear range of about 80 'thou'. Sine waves are used for the majority of the tests although square waves and triangular waves are also tried.

A computer programme is used to sample the input signal and calculate and output the required control pulses to the stepping motor.

Input signals with frequencies between 5 and 50 Hz. are used, with various amplitudes. Results of a representative group of tests are given in FIG7. 27 to FIG7. 32.

The results of these tests are used to determine the limiting response of the tool positioner. They are used in the selection of a machine-workpiece configuration for use in the chatter suppression tests.

7. 5. Chatter suppression tests.

In order to determine the effect of the suppression method in a workshop environment, various cutting operations are performed both with and without the controller. The effect of switching the controller 'on-then-off' during cutting is also observed. Prior to the cutting tests, the chatter suppressor is tested to validate the implementation.

7. 5. 1. Chatter suppressor validation.

Using the complete chatter suppressor (model,controller and positioner), the response to known inputs is observed. A second-order model with a natural frequency of 1 Hz. and a damping factor of 0.1 is used so that the suppressor response is easily seen. The experimental arrangement is the same as that described in section 7. 4. 1, with the inclusion of a force transducer. Step and sine wave forces are applied to the transducer and the tool positioner movement is monitored. Similar tests are performed with the suppressor installed on the lathe. In this case, the input force is applied to the tool tip.

For both groups of tests, the observed step and frequency response is compared to the expected second-order responses. Correct implementation is inferred by agreement between the observed and expected responses.

In order to determine the limits on the overall performance of the chatter suppressor a series of tests is performed where the natural frequency of the model and the sine wave input are gradually increased. The natural frequency always being about 30% above the input frequency. It is found that the suppressor has a limiting response of 3 steps (1 'thou') at a frequency of 30 Hz. This is determined by the positioner which is found to be an order of magnitude slower than the computation time of the model and controller.

7. 5. 2. Effects of the chatter suppressor.

Using the results of the suppressor validation tests, a workpiece is chosen so that the chatter conditions are within the limits of the suppressor performance. As a general rule, the chatter frequency (approximately equal to the natural frequency) must be about 20% less than the maximum useable frequency of the suppressor. Thus a machine-workpiece configuration is chosen to have a chatter frequency of about 24 Hz. It is found from the structural tests (see section 7. 3.) that the damping factor is 0. 2 and the gain is 12,500 lbf/in.

The experimental arrangement is shown in FIG7. 33, PLATE5. 7 and PLATE5. 8. The model is set up to have nominal parameters equal to the experimentally determine machine-workpiece parameters. Throughout the tests, the tool positioner is operated with a third of a 'thou' step size. The sampling frequency is set to 250 Hz, with the filter cut-off frequency at 125 Hz.

Cutting tests are performed for a range of speeds, feedrates and depths of cut, both chattering and non-chattering situations being covered. For each set of cutting conditions, three test runs are performed:

-- without the suppressor

-- with the suppressor

-- with the suppressor switched 'off-then-on' during the run

The effectiveness is assessed by monitoring the cutting force, which is recorded on a U. V. oscillograph. The experimental procedure is as follows:

-- warm-up electronic equipment

-- set-up and calibrate instrumentation (see section 7. 2.)

-- set-up workpiece and cutting tool

-- select lathe speed, feedrate and depth of cut

-- start the suppression programme (if required) and input the model parameters, instrumentation set points and scaling factors and programme constants (see APPENDIX B.8)

-- start the cutting operation

-- start the U. V. oscillograph

The length of the test runs vary between 10 and 30 seconds, depending on the rate of chatter build-up.

It is found during the tests that the horizontal cutting force is not suitable as input to the chatter suppressor as it is effected by the tool positioner drive force. This is due to poor siting of the transducer. The vertical cutting force is free from this interference and is used for all the tests. A second-order model is still used as it is shown from the identification tests that an approximate second-order relationship exists between the vertical force and the horizontal displacement. Matching of the model to the machine-workpiece dynamics is done by 'trial-and-error' as the nominal parameters do not usually prove to be sufficiently accurate.

Although this is not presently acceptable as a practical technique, the problem may be overcome by developing further the on-line identification method. Several methods of improving the basic least squares technique are available (19,20,21,22,23). These both improve the accuracy and noise immunity of the method, and are used successfully in other practical applications.

Results of some representative tests are shown in FIG7. 34 to FIG7. 36. It is found that the matching of model and system parameters is very difficult to achieve and many unsuccessful attempts to suppress chatter are not presented.

7. 6. Review.

The experimental tests are performed in order to prove the system design and implementation, and evaluate the effectiveness of the suppression method. In this section, the results of all the individual tests are reviewed and the relevant achievements and problems are highlighted in the context of the overall system.

The instrumentation performs satisfactorily, although some problems are encountered during the chatter suppression tests. This is due to the tool positioner drive force being transmitted to the transducer, which should ideally be placed at the tool tip. As this is not practical, one alternative would be to use strain gauges on the tool. Because of this problem, only the vertical cutting force is used during the chatter suppression tests.

All the tests to aid identification of the machine-workpiece dynamics provide useful results. The cutting tests give an insight into the overall behaviour of the system, especially during chattering. The impulse response tests are particularly useful in demonstrating the second-order nature of the machine-workpiece dynamics. Results from the on-line identification tests are found to be unreliable, with large variations in all the parameter estimates. However, some useful results are obtained, and these tend to support the results from the other tests.

The chatter suppressor is implemented correctly, although its performance is limited by the response of the tool positioner. This could be improved by re-designing the tool positioner so that the driven inertia is minimised. Also, a high speed stepping motor with a more sophisticated driver (6,7,43) could be used.

The effectiveness of the suppressor is demonstrated, but difficulties are encountered in matching the model to the machine-workpiece dynamics. This situation would be improved by using a more accurate and reliable identification method.

A more detailed discussion of the experimental results is given in the next chapter.

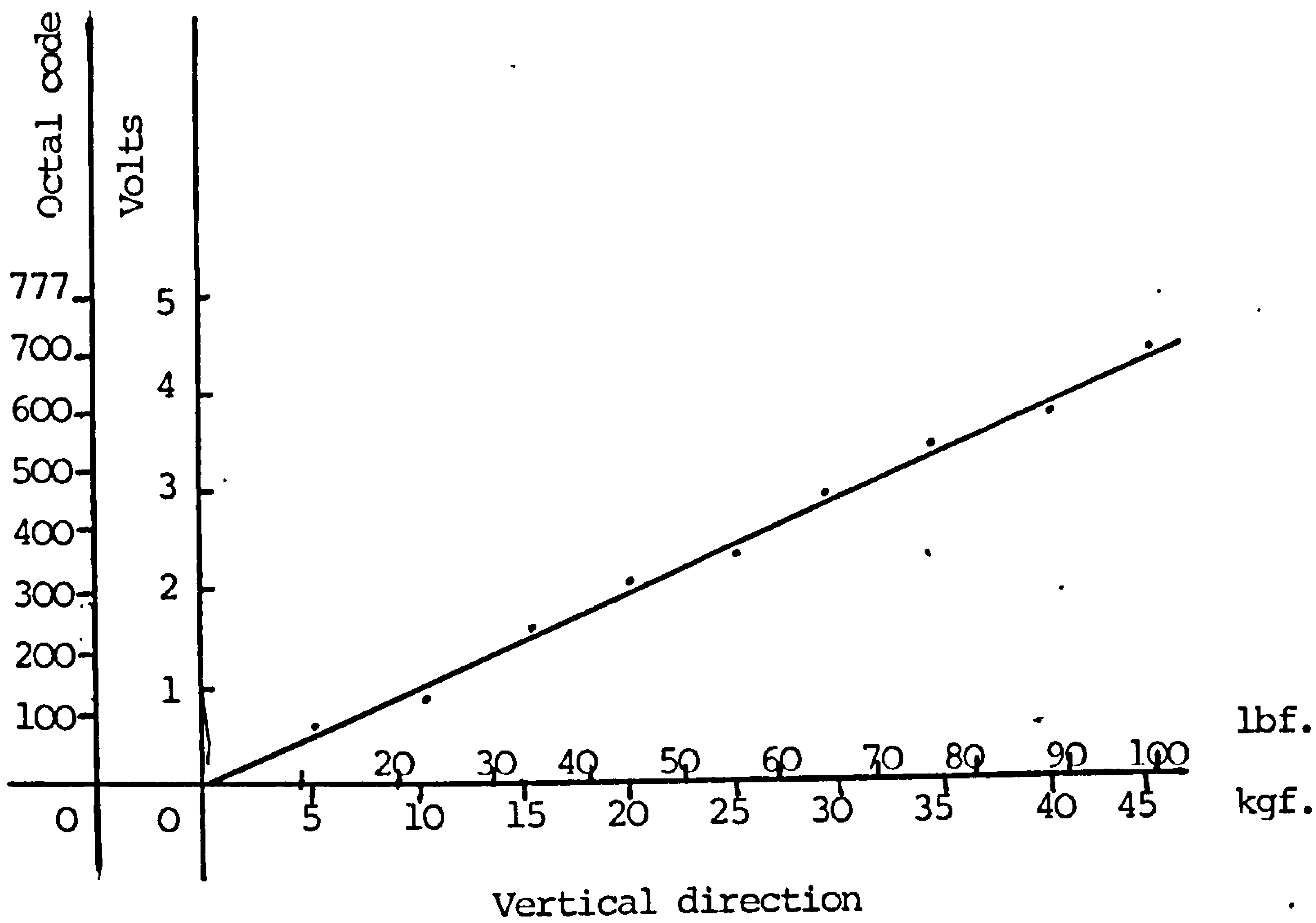
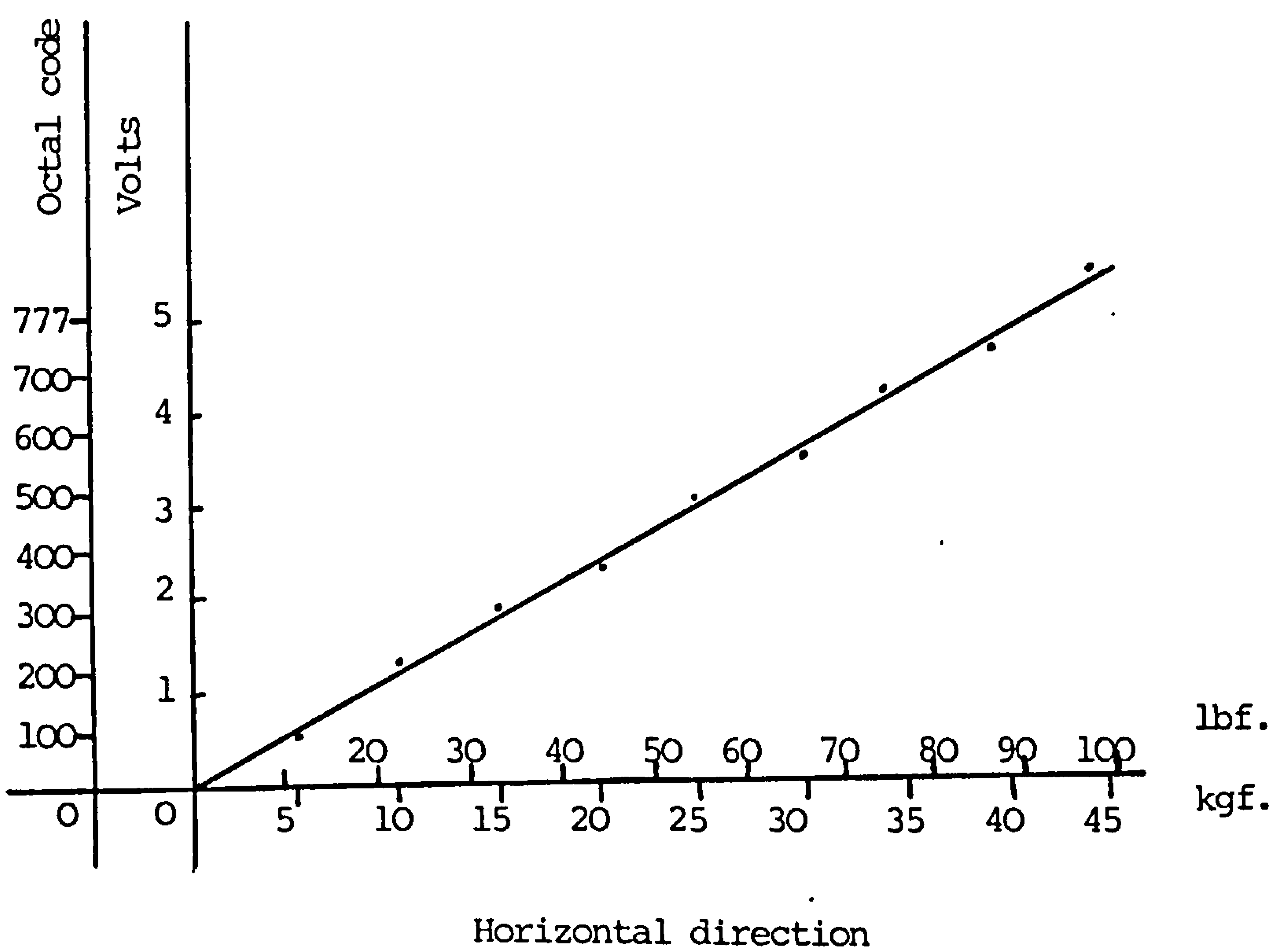


FIG7. 1.



Calibration curves for cutting force measurement system

FIG7. 2.

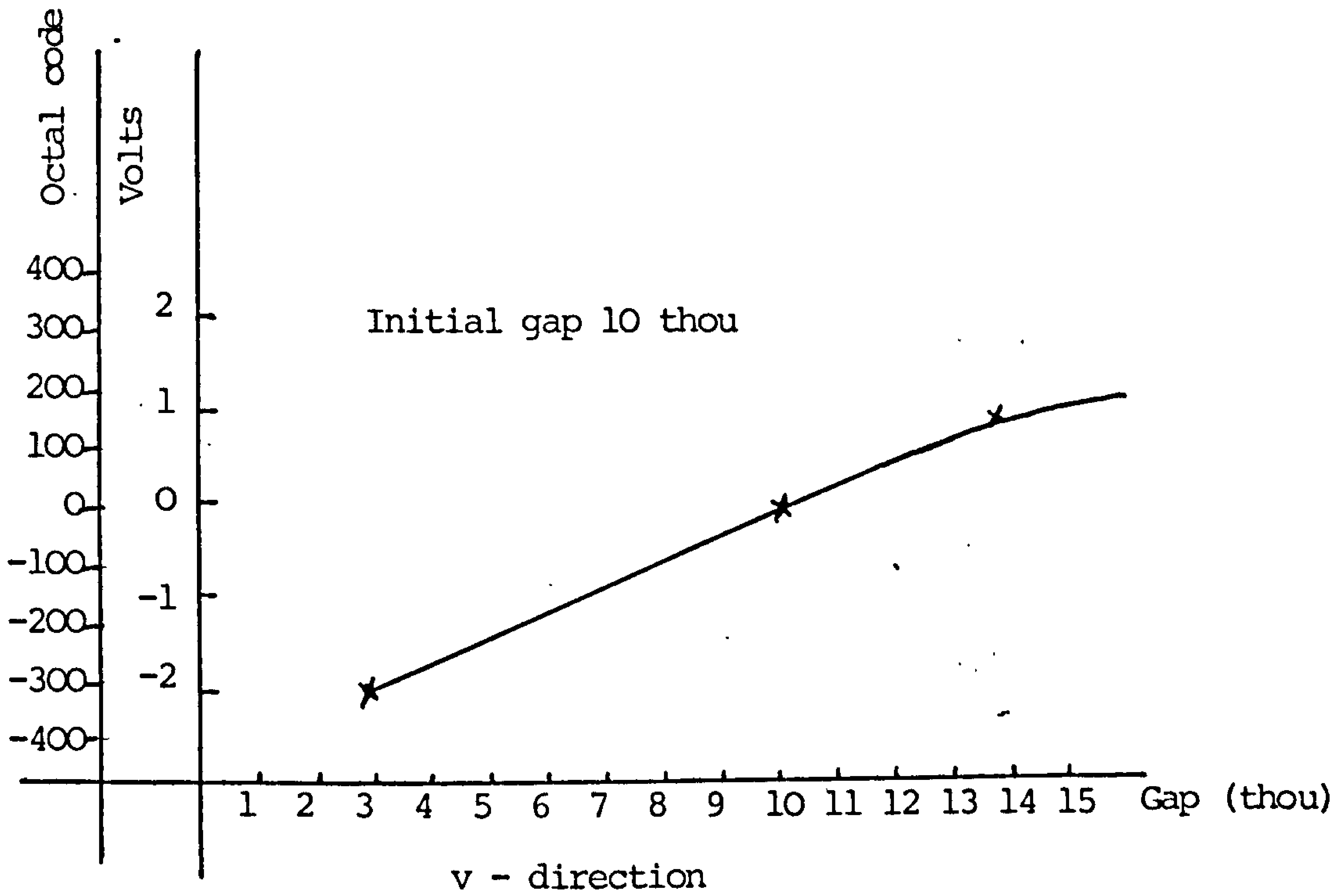
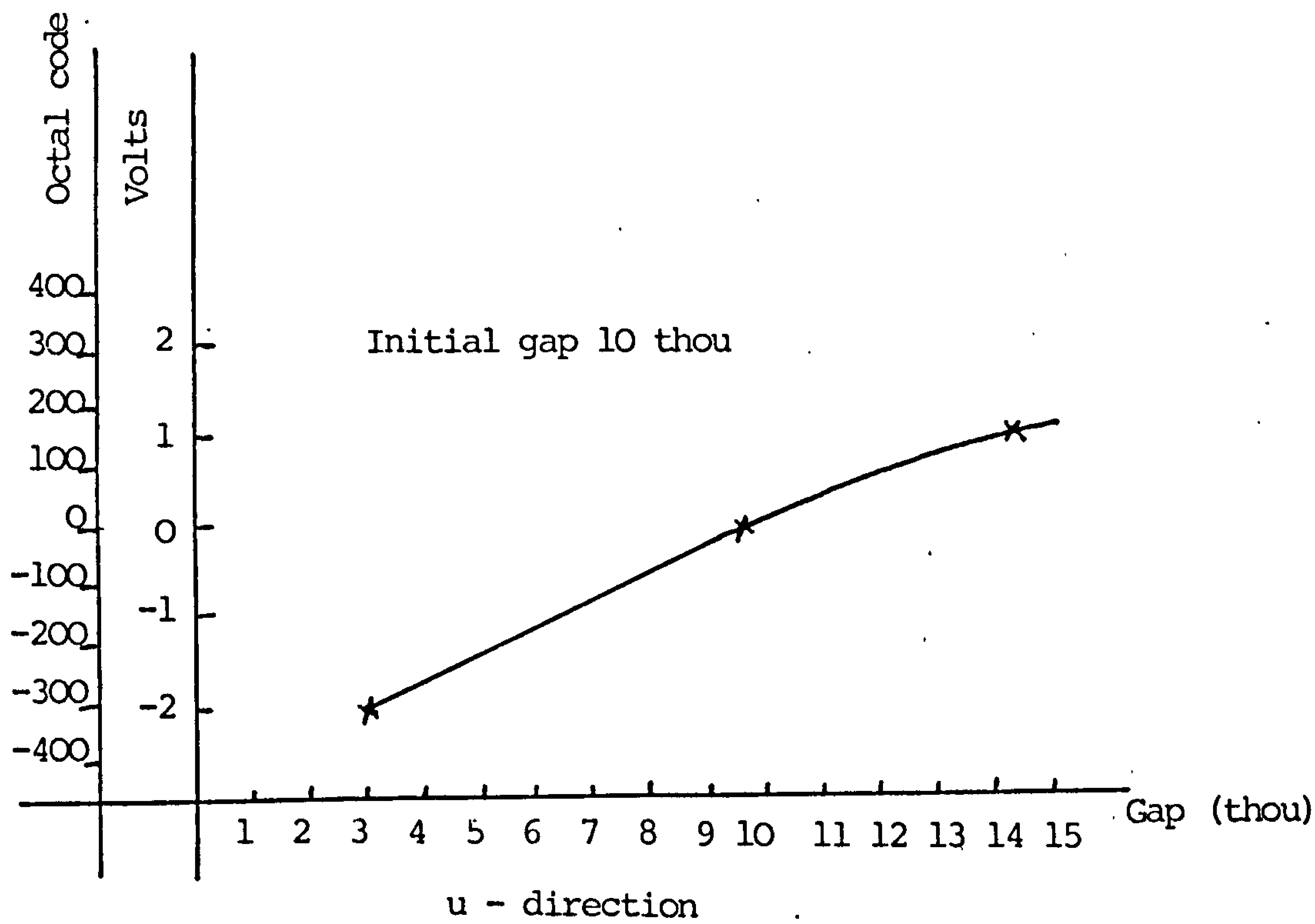
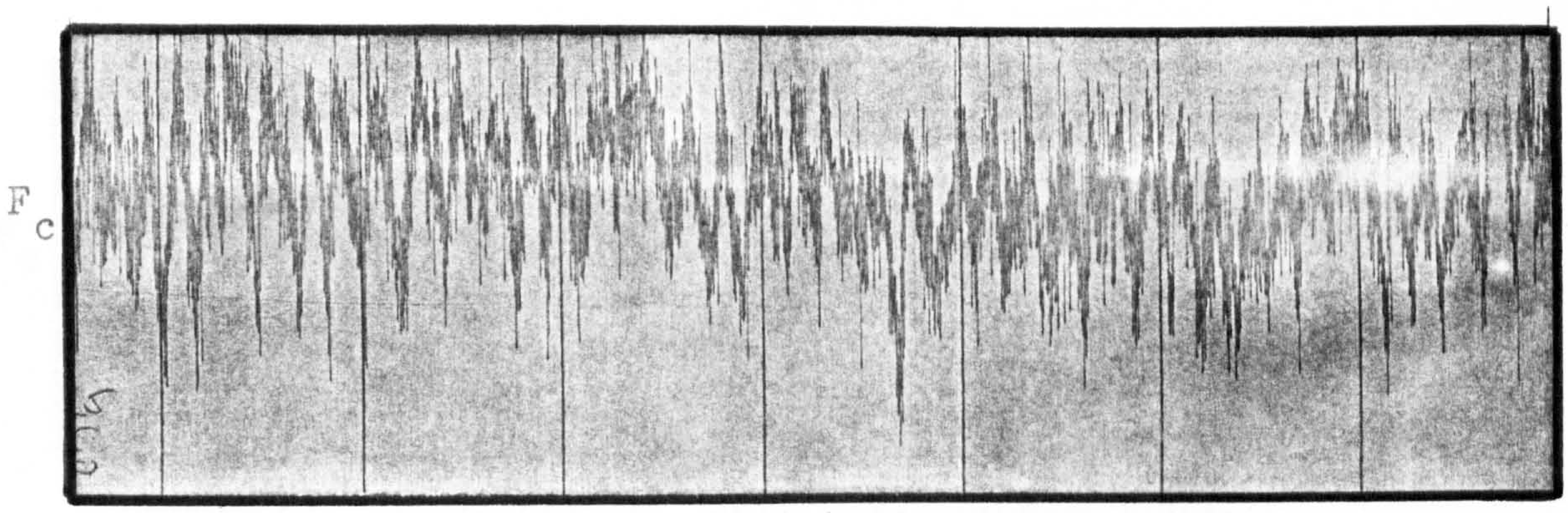


FIG7. 3.

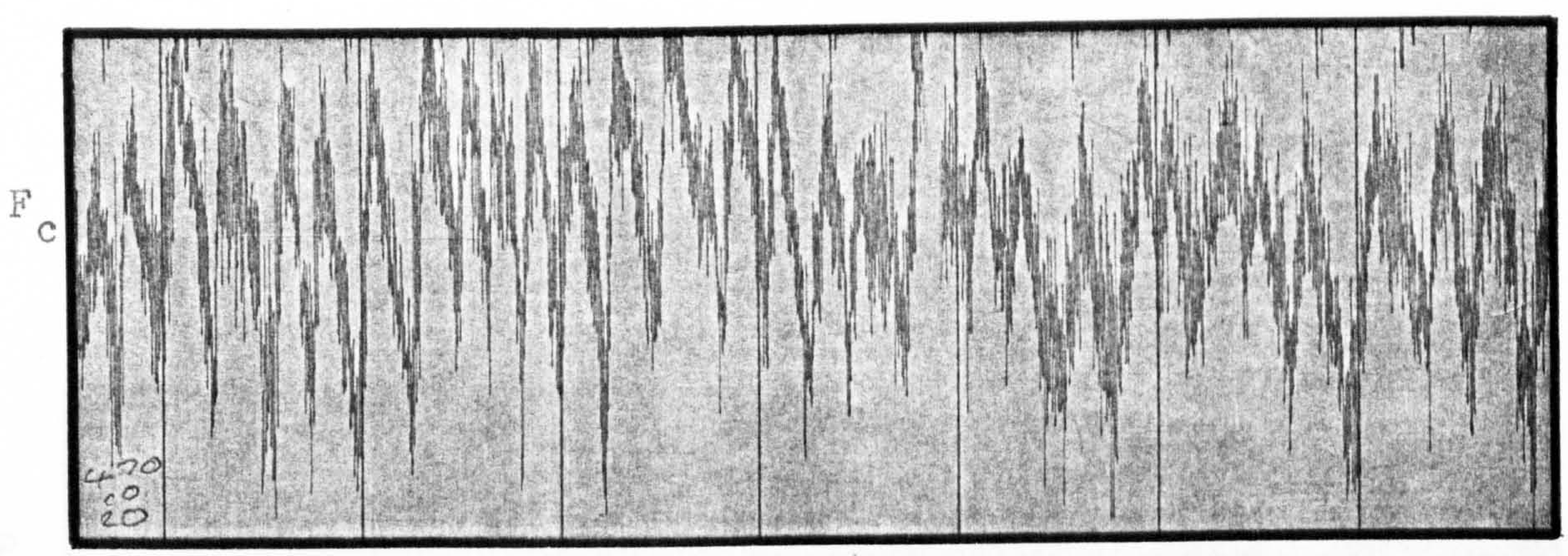


Calibration curves for displacement measurement system

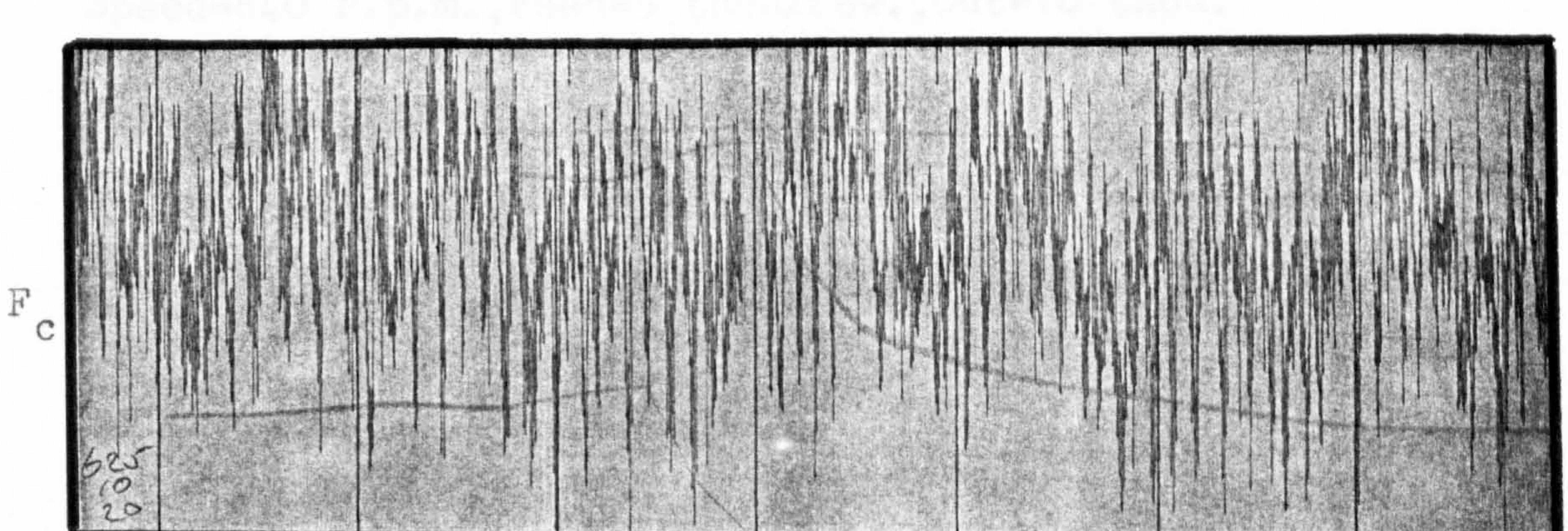
FIG7. 4.



Speed=625 r.p.m.,Feed=5 thou/rev.,Cut=20 thou.



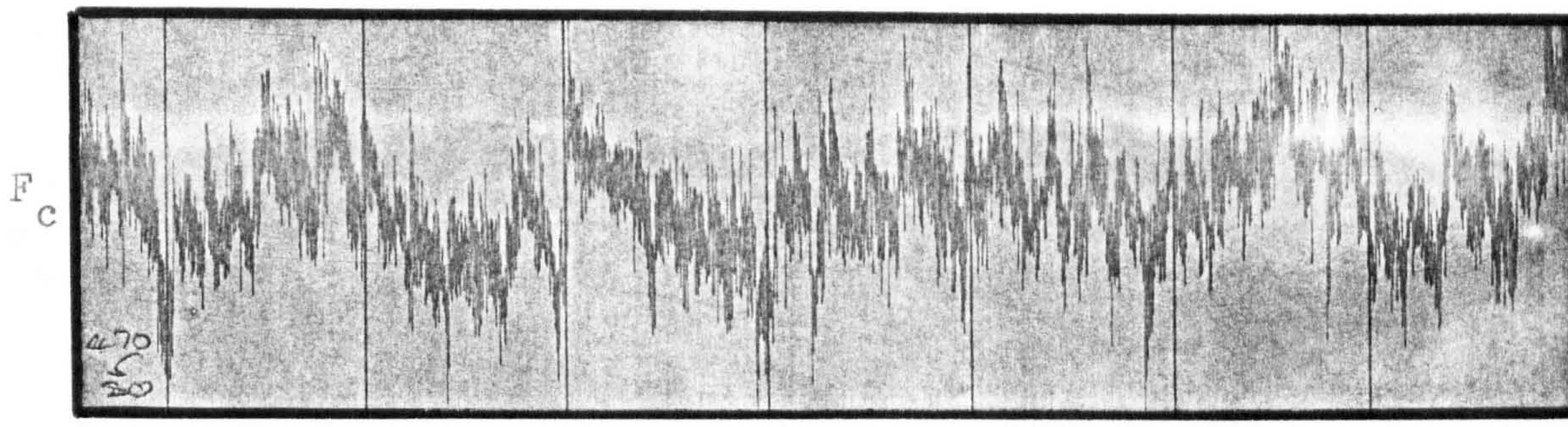
Speed=470 r.p.m.,Feed=10 thou/rev.,Cut=20 thou.



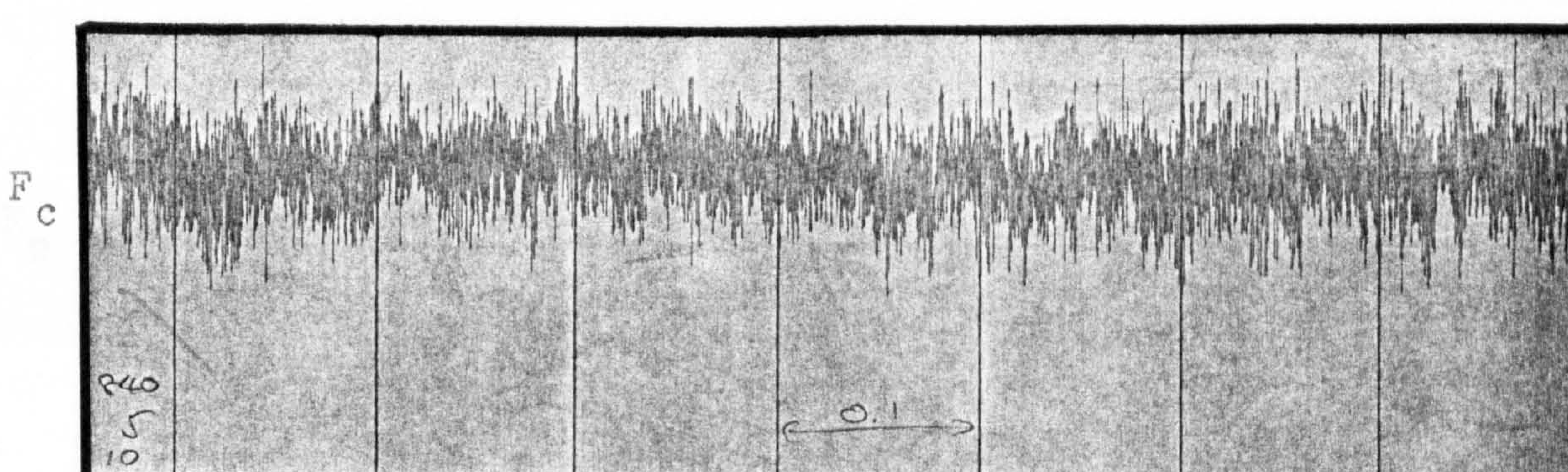
Speed=625 r.p.m.,Feed=10 thou/rev.,Cut=20 thou.

<u>Cutting force traces.</u>

FIG7. 5.



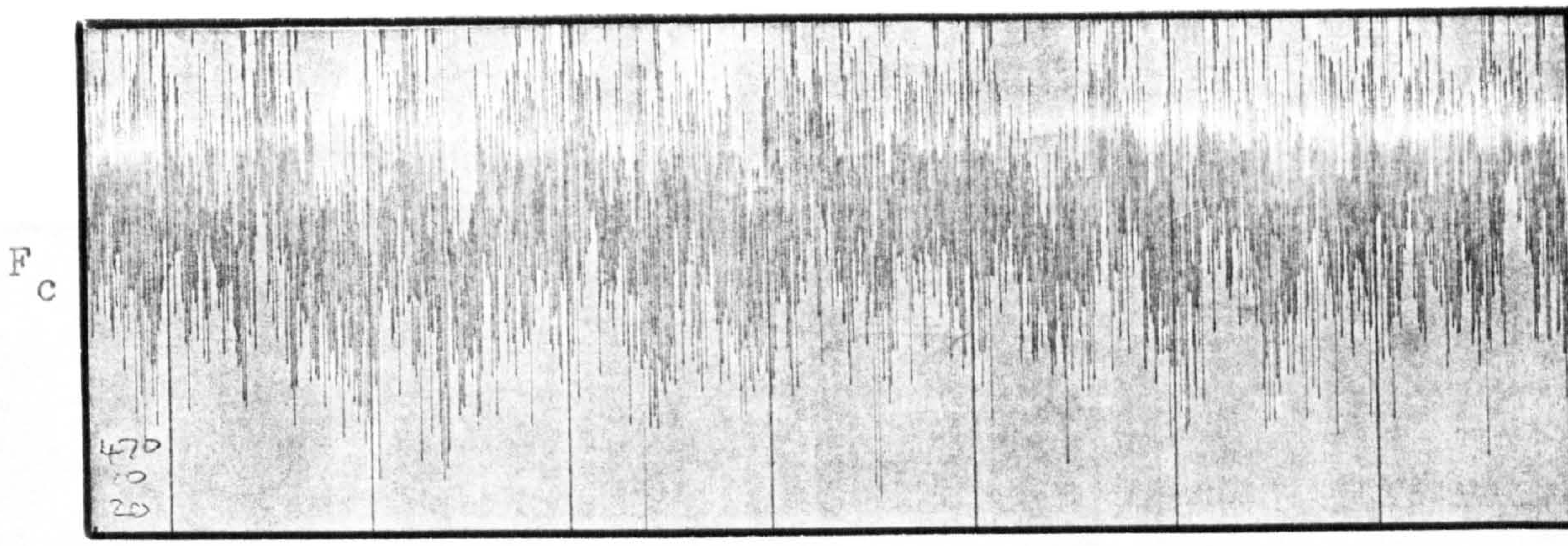
Speed=470 r.p.m.,Feed=5 thou/rev.,Cut=20 thou.



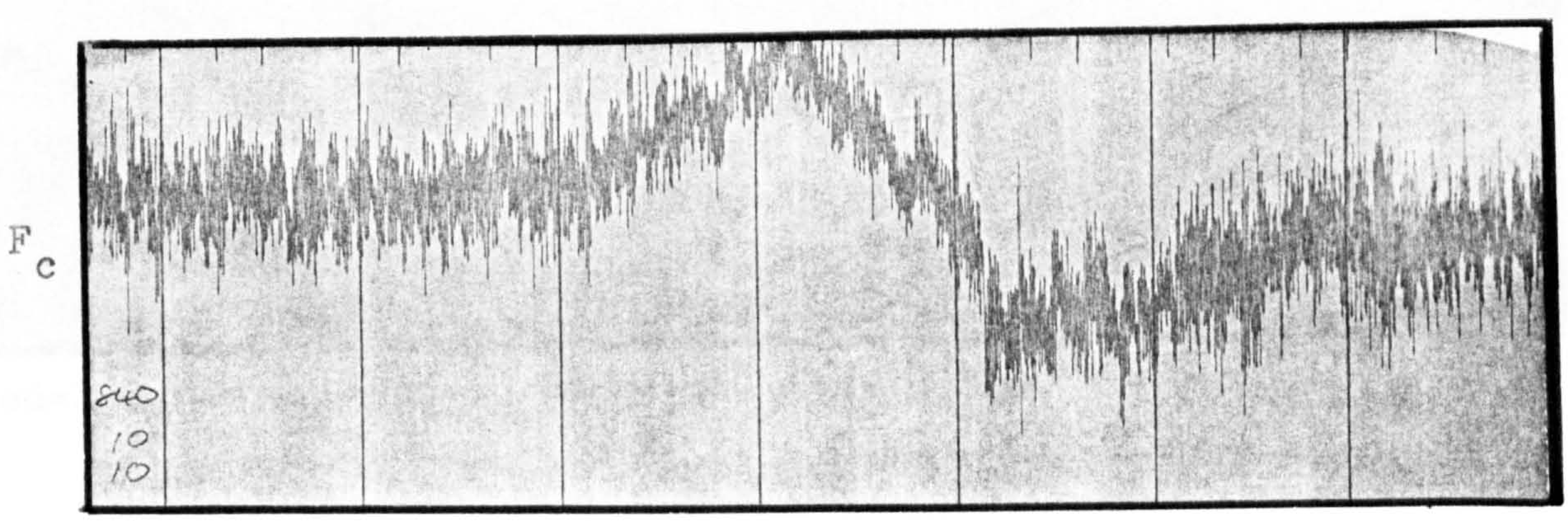
Speed=840 r.p.m.,Feed=5 thou/rev.,Cut=10 thou.

<u>Cutting force traces.</u>

FIG7. 6.



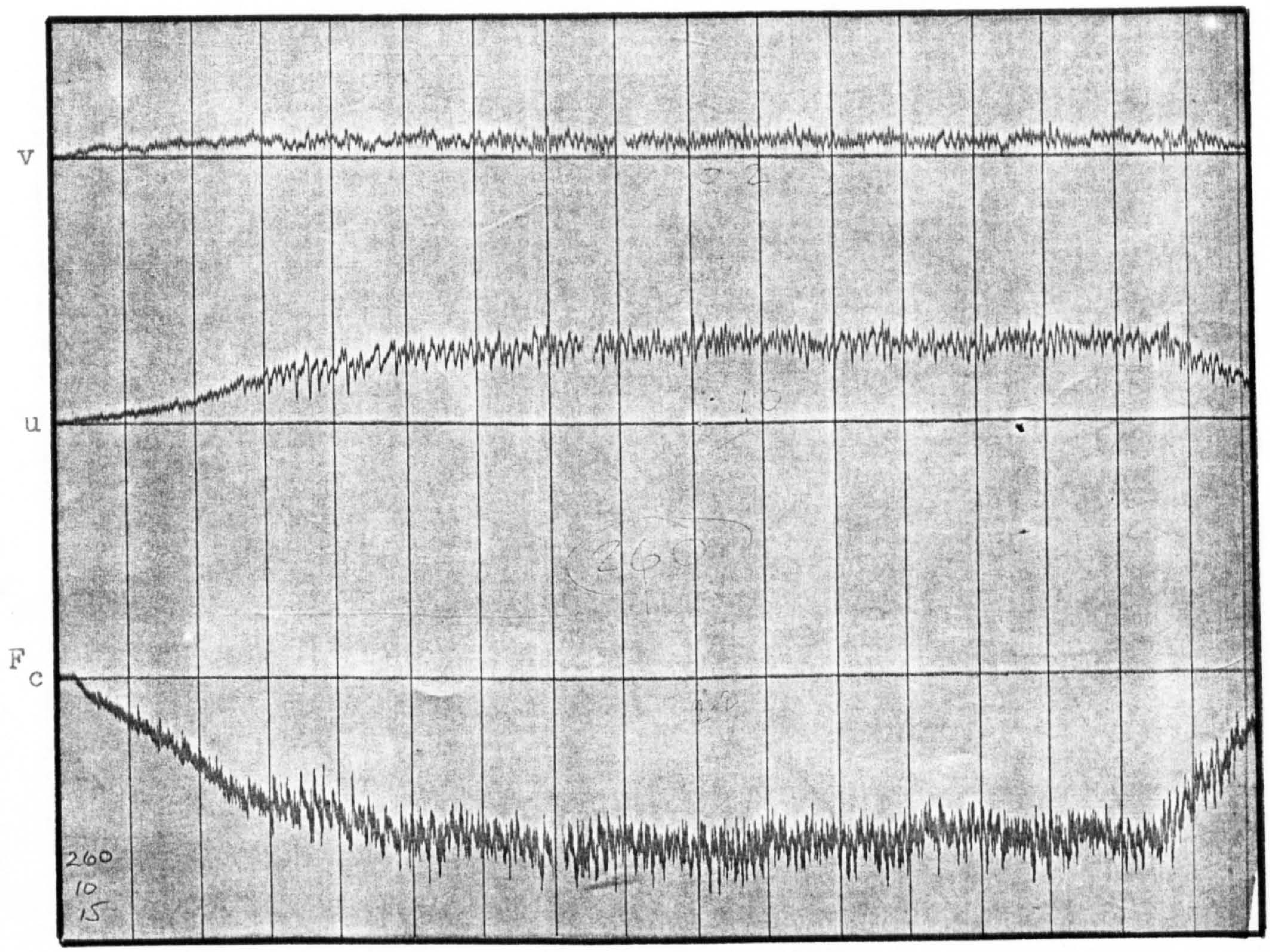
Speed=470 r.p.m.,Feed=10 thou/rev.,Cut=20 thou.



Speed=840 r.p.m.,Feed=10 thou/rev.,Cut=10 thou.

Cutting force traces.

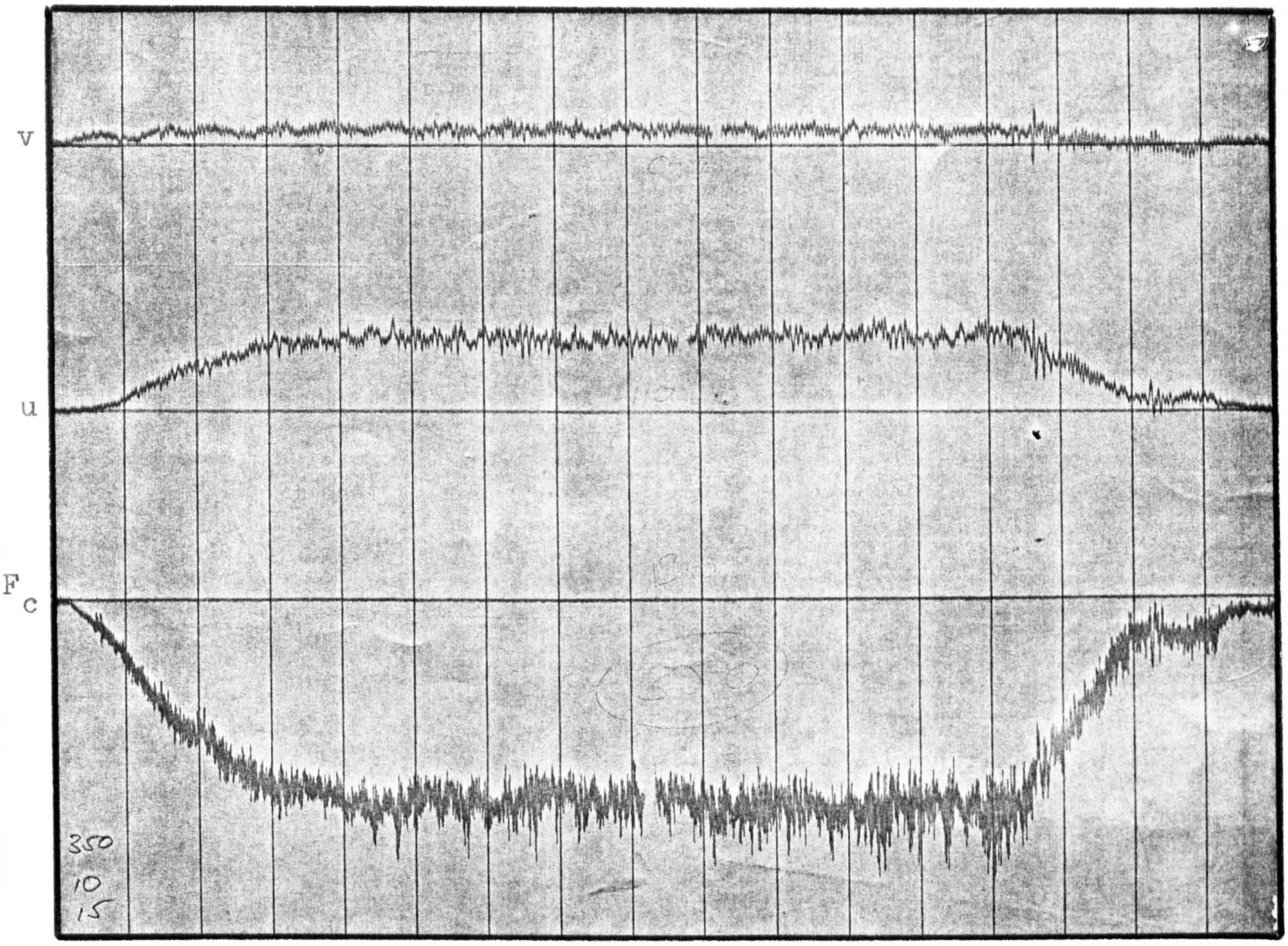
FIG7. 7.



Speed=260 r.p.m.,Feed=10 thou/rev.,Cut=15 thou.

Cutting force and workpiece displacement traces.

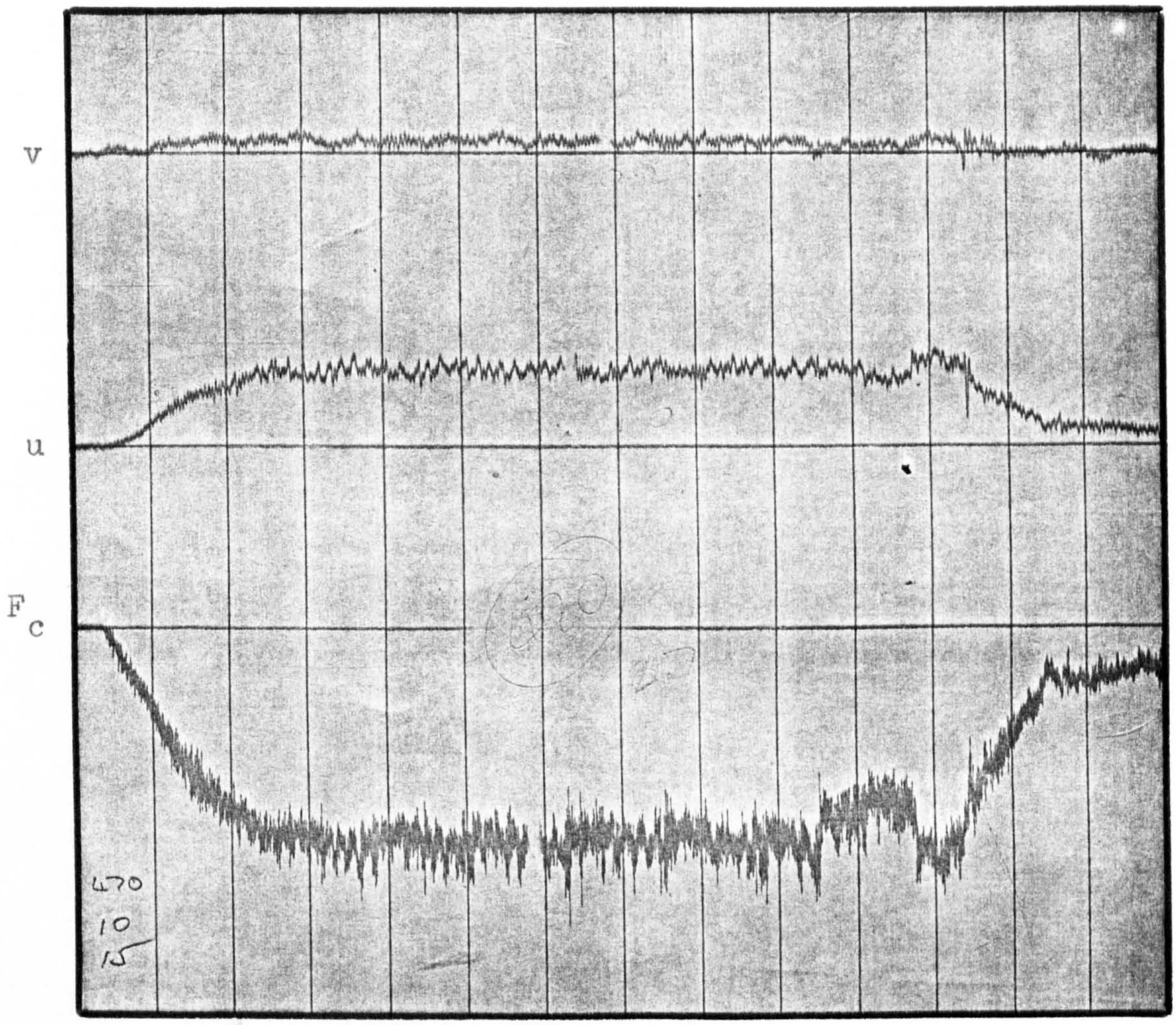
FIG7. 8.



Speed=350 r.p.m.,Feed=10 thou/rev.,Cut=15 thou.

Cutting force and workpiece displacement traces.

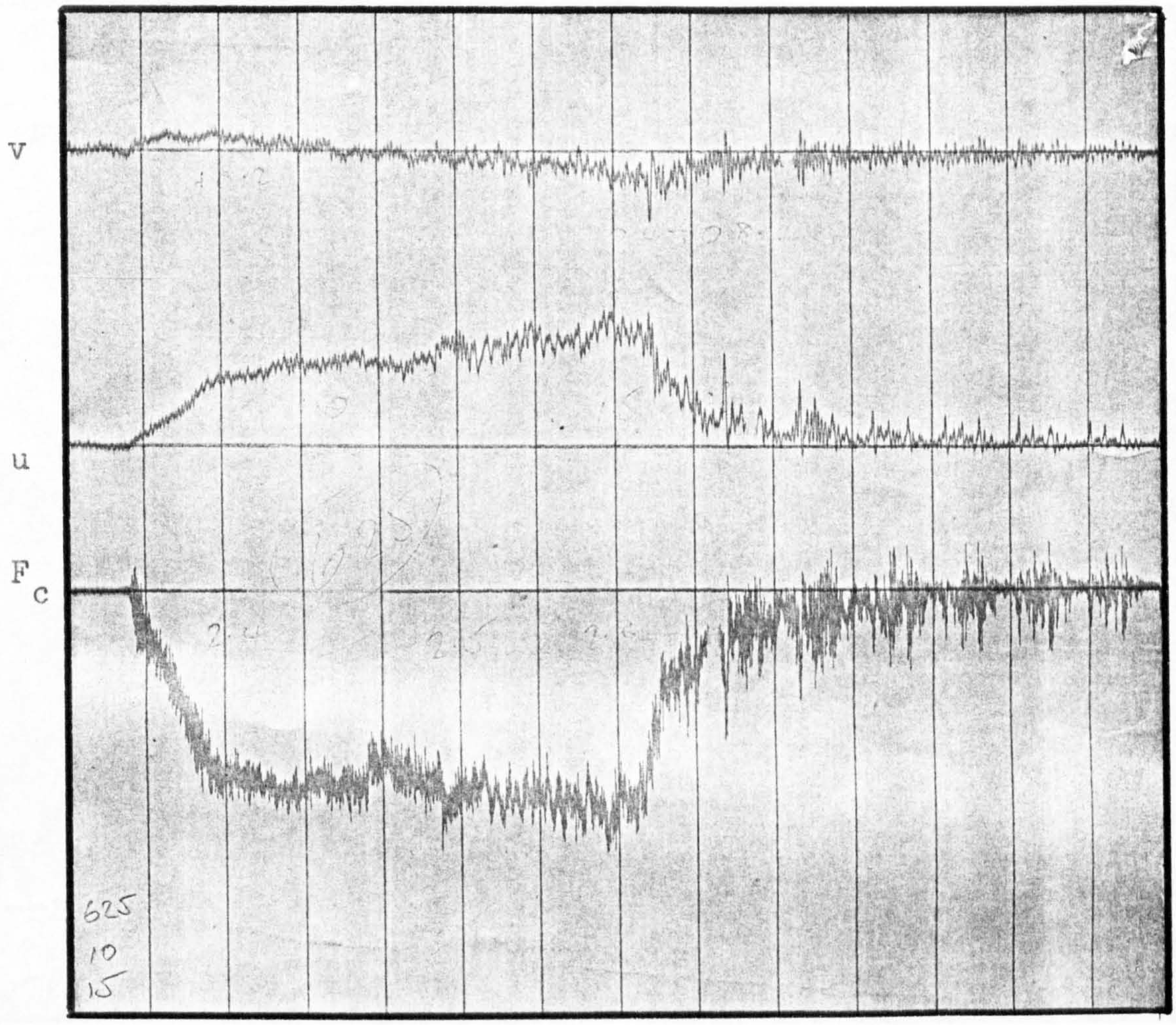
FIG7. 9.



Speed=470 r.p.m.,Feed=10 thou/rev.,Cut=15 thou.

Cutting force and workpiece displacement traces.

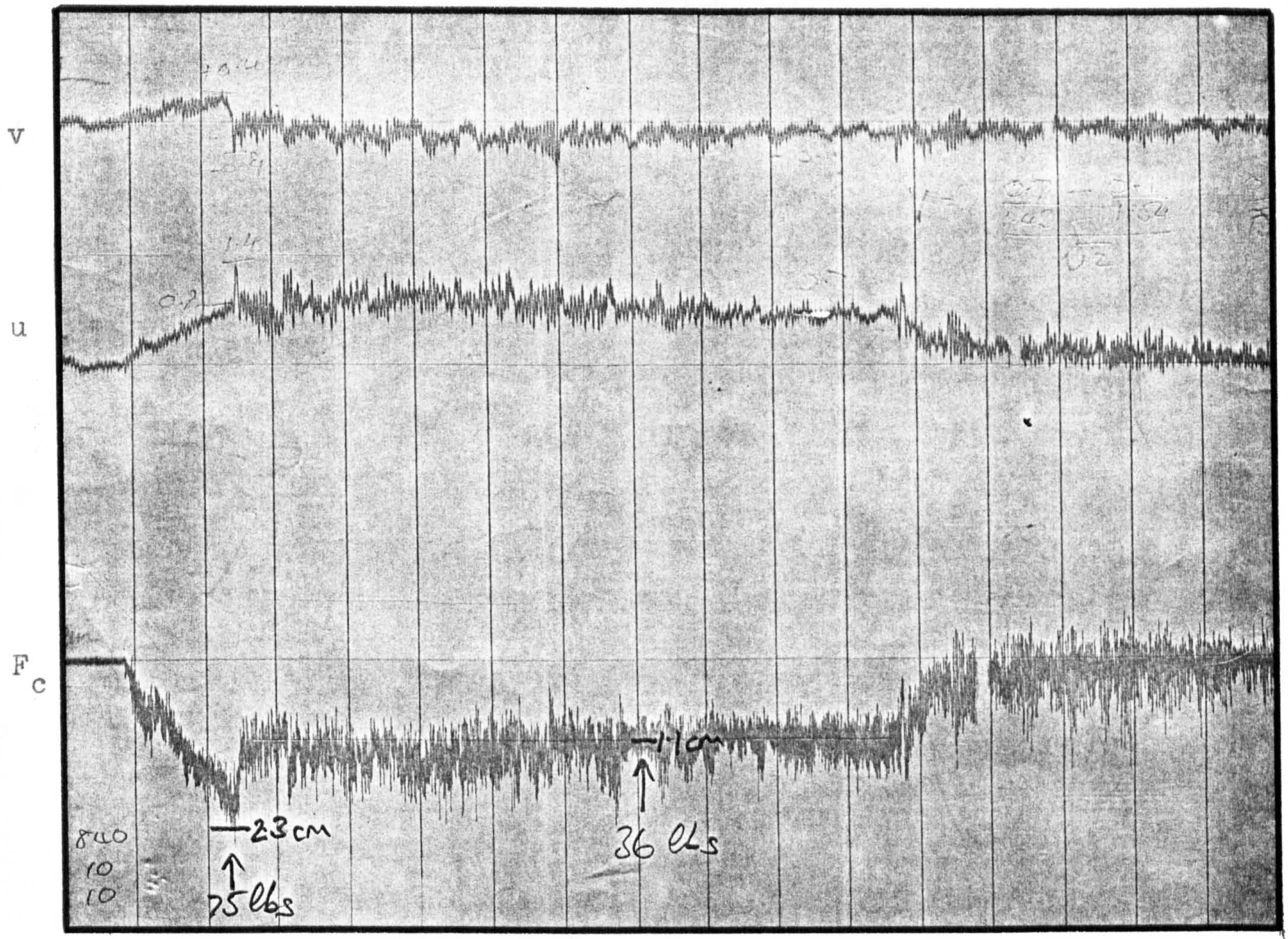
FIG7. 10.



Speed=625 r.p.m.,Feed=10 thou/rev.,Cut=15 thou.

Cutting force and workpiece displacement traces.

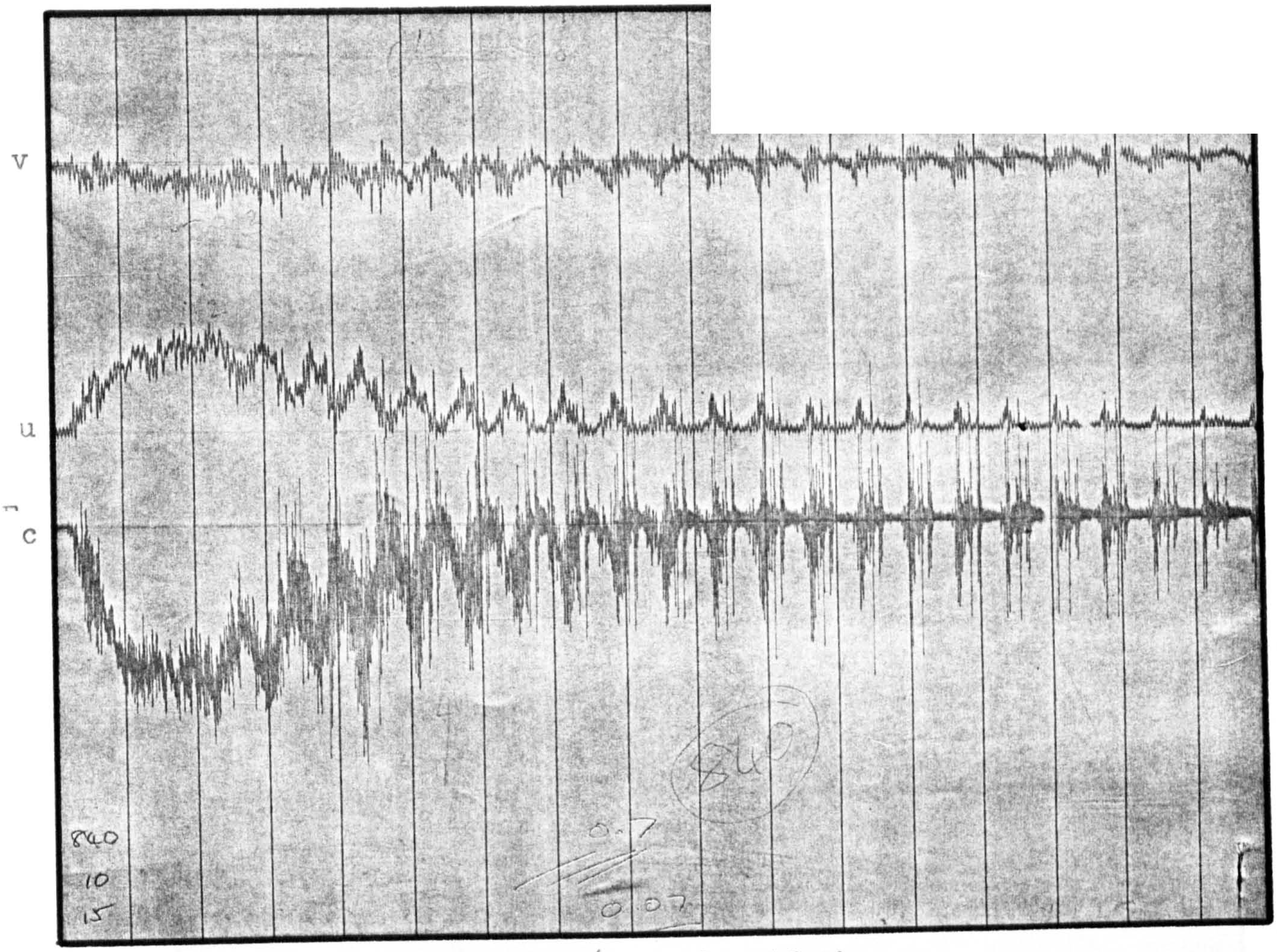
FIG7. 11.



Speed=840 r.p.m.,Feed=10 thou/rev.,Cut=10 thou.

<u>Cutting force and workpiece displacement traces.</u>

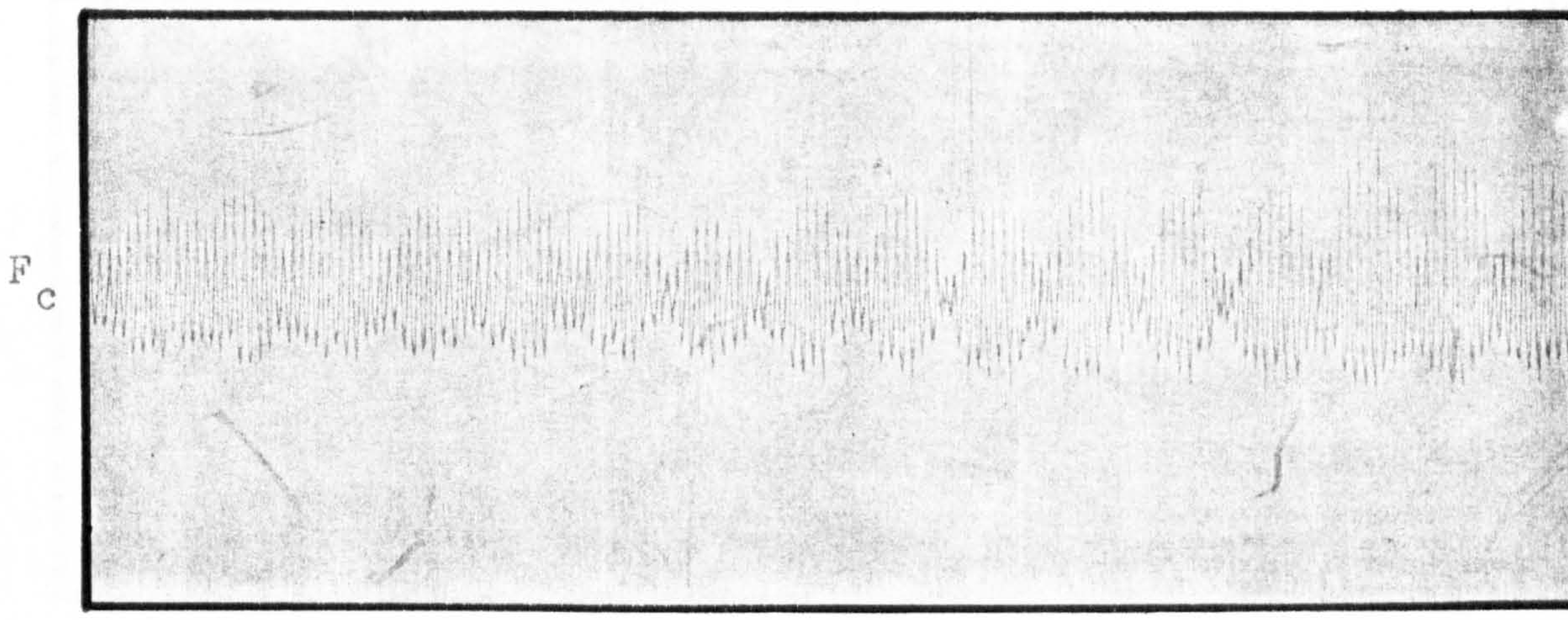
FIG7. 12.

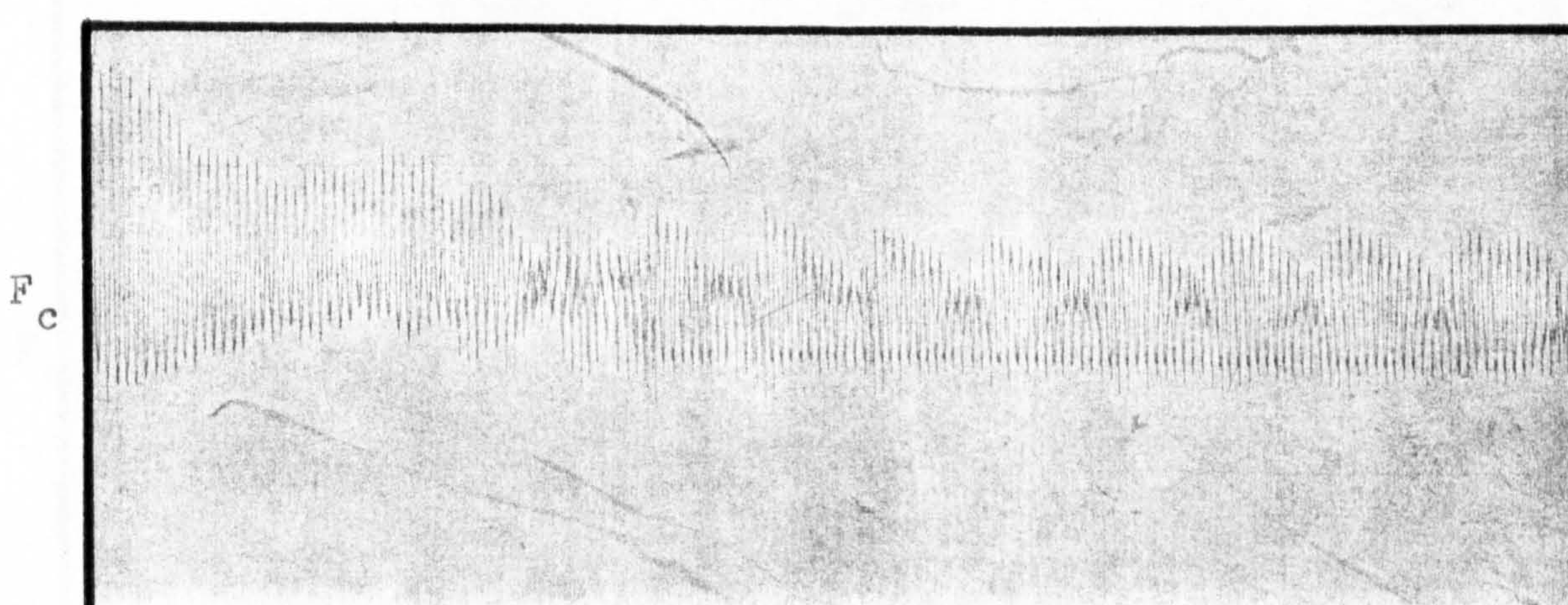


Speed=840 r.p.m.,Feed=10 thou/rev.,Cut=15 thou.

Cutting force and workpiece displacement traces.

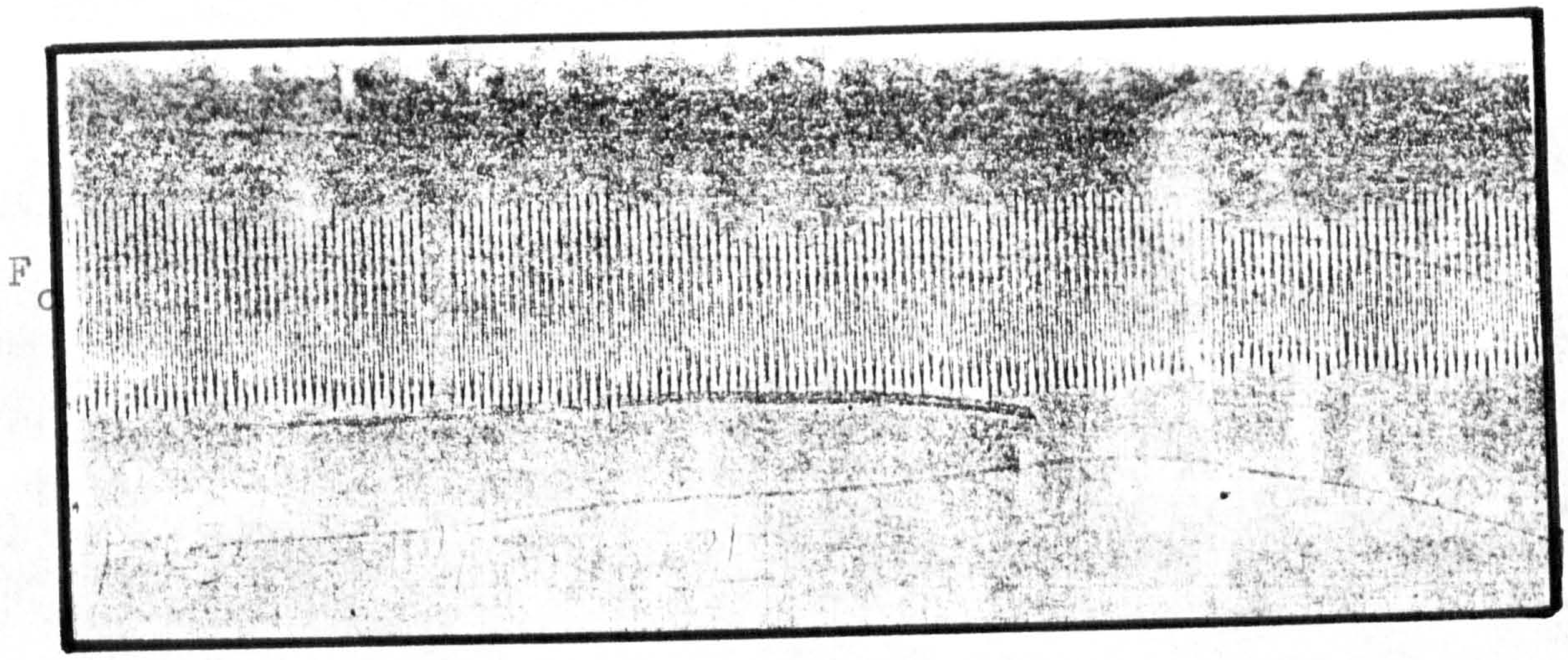
FIG7. 13.

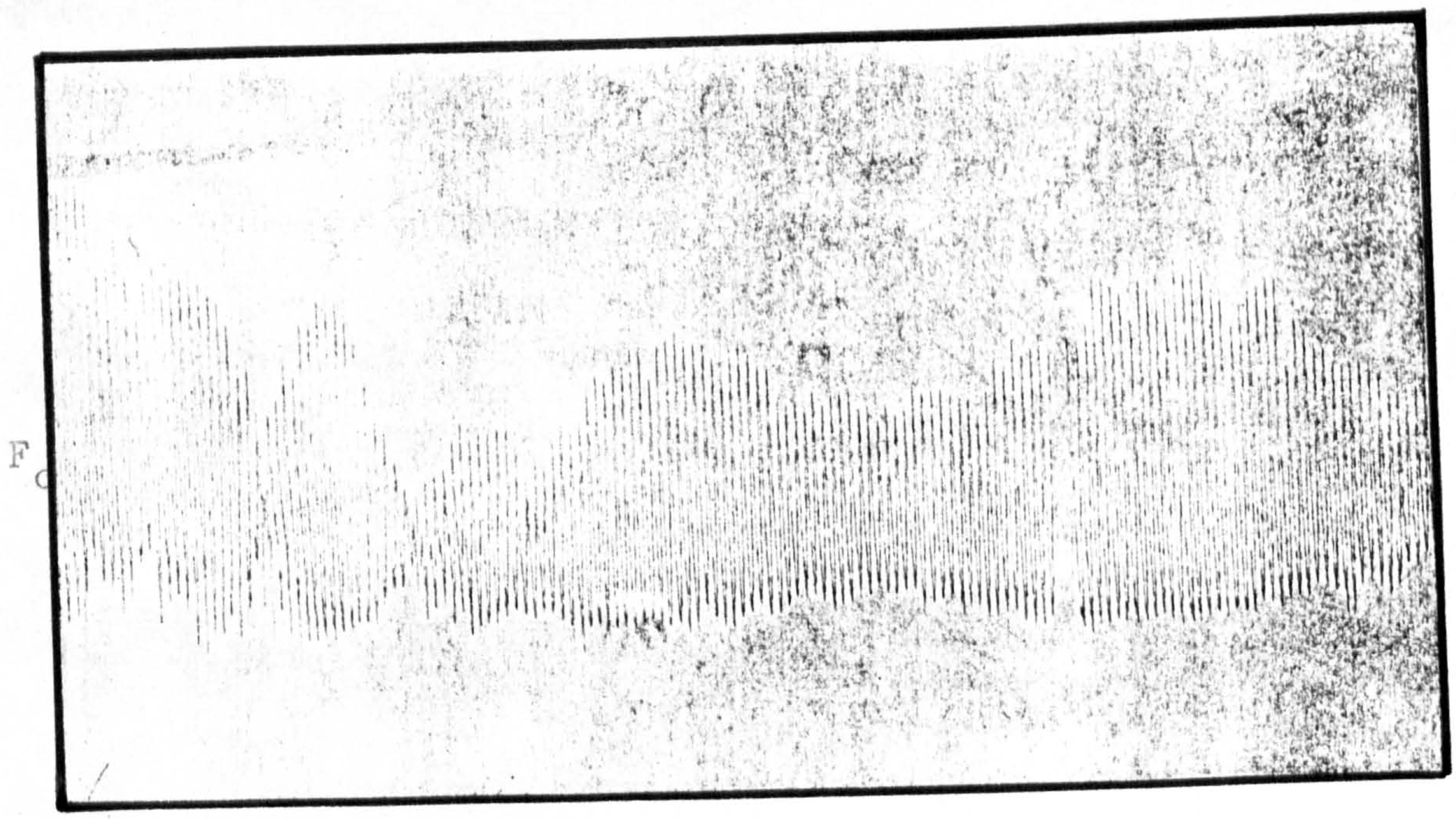




Cutting force traces - chattering,'beats'

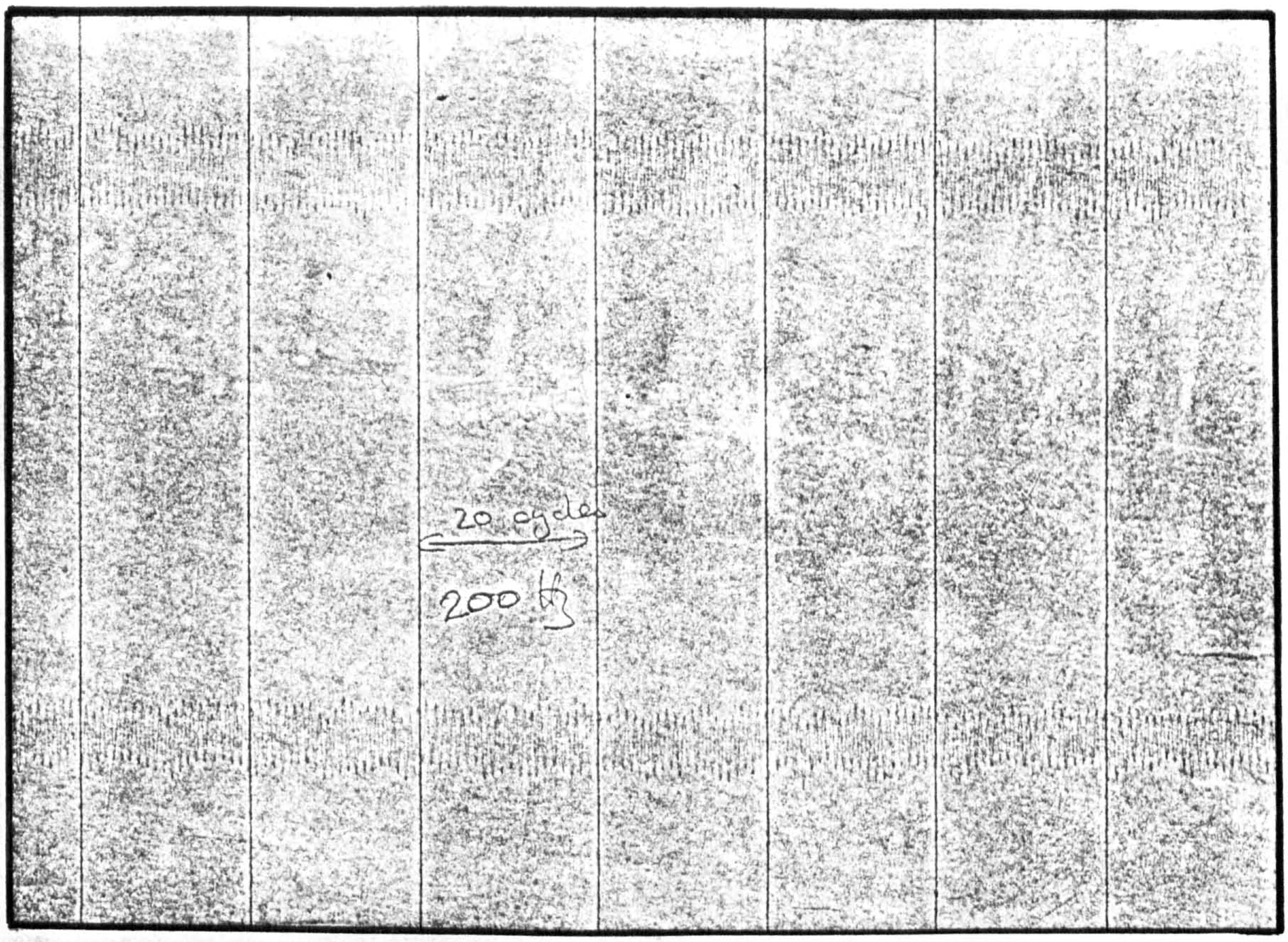
FIG7. 14.

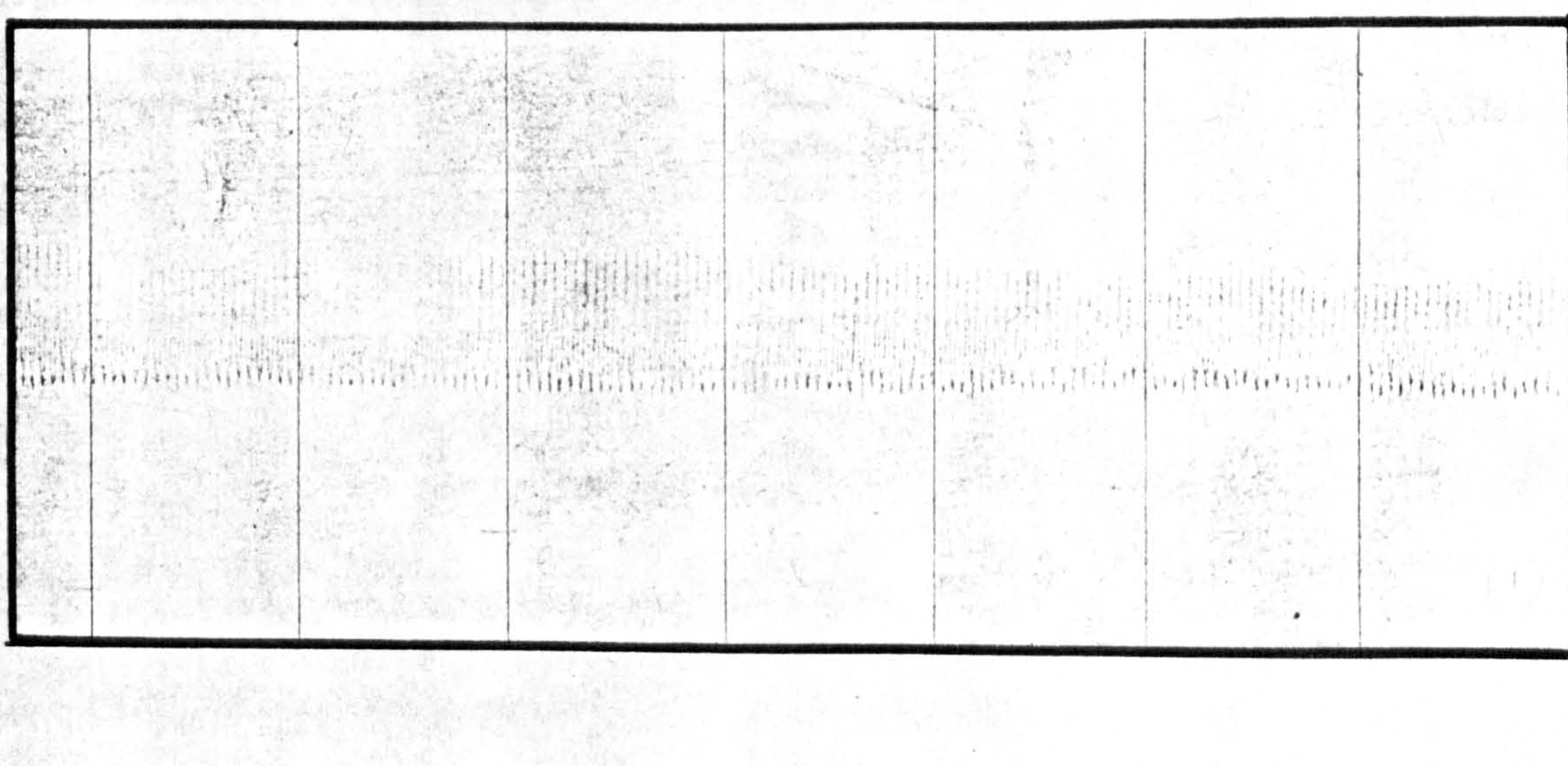




Cutting force traces - severe chattering.

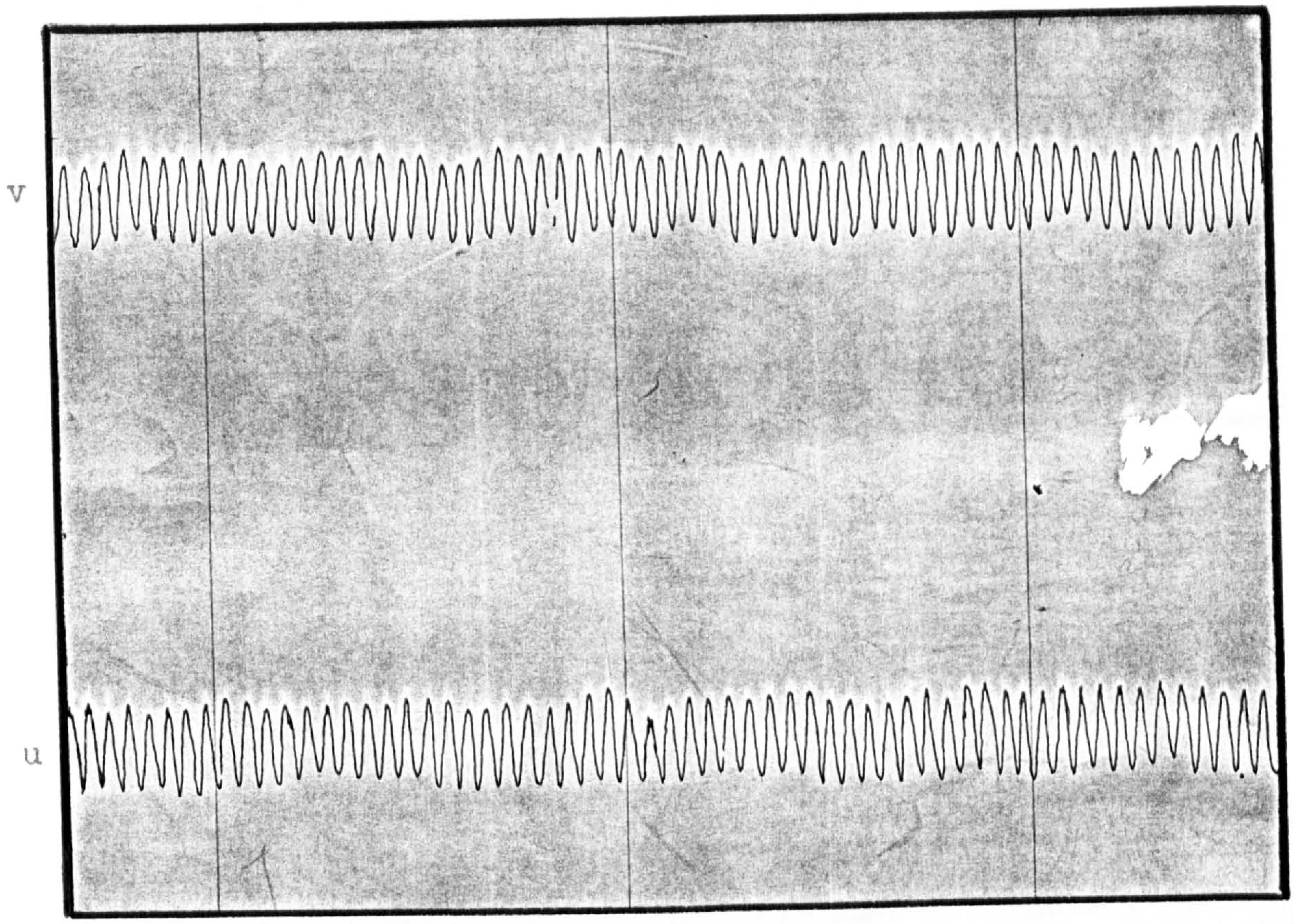
FIG7. 15.





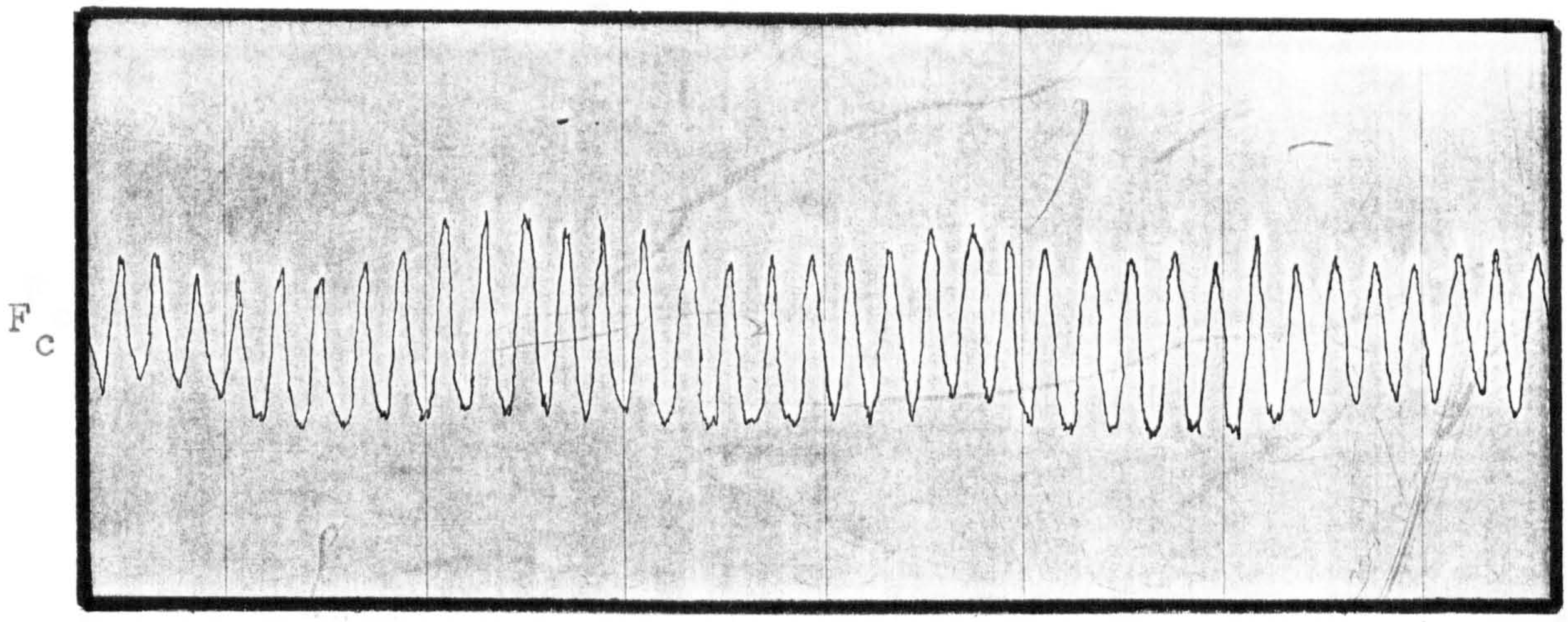
Cutting force and workpiece displacement traces - chatter

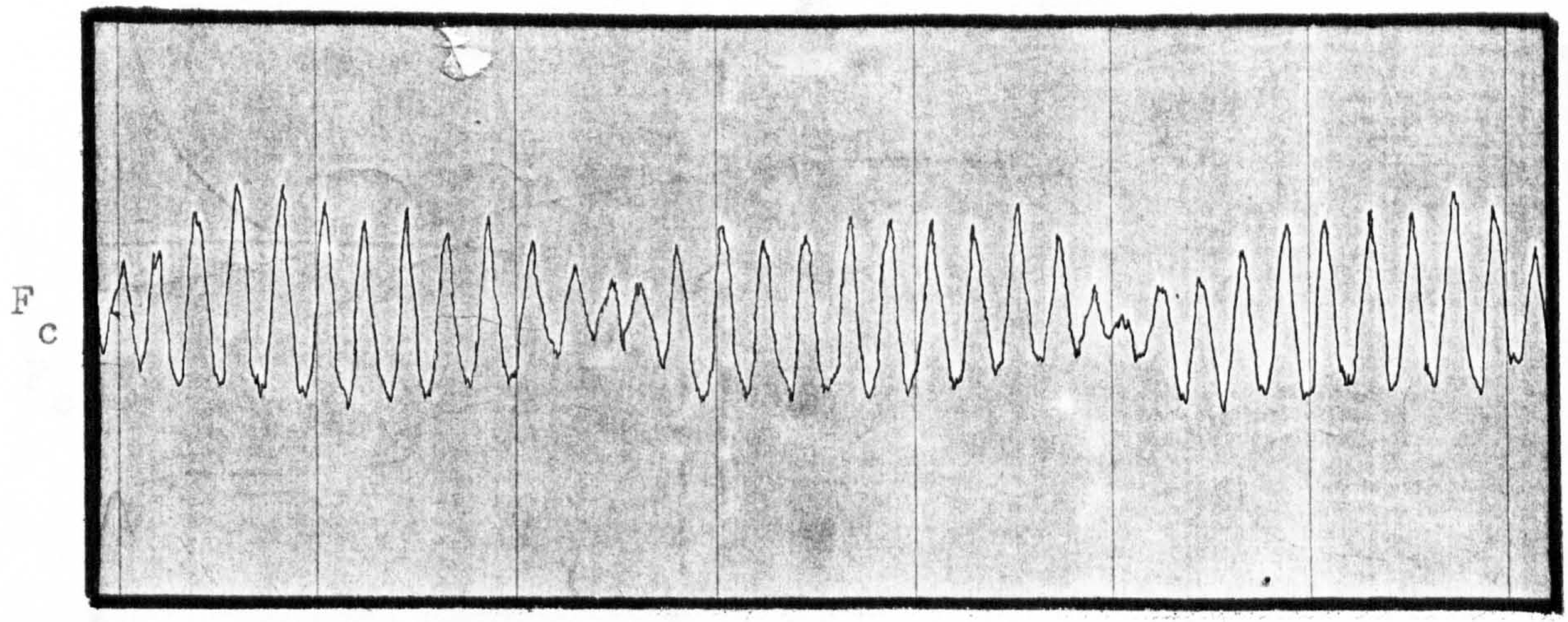
FIG7. 16.



Workpiece displacement traces - chattering.

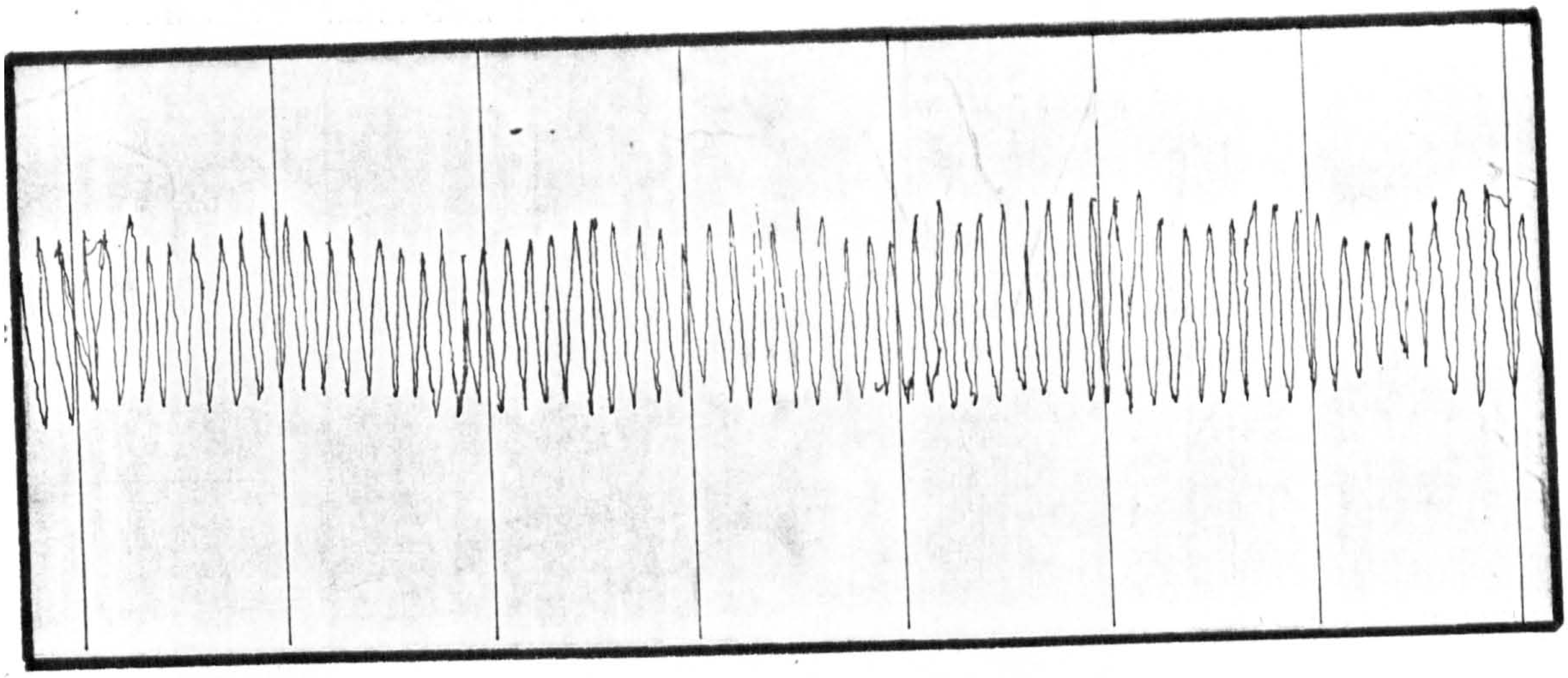
FIG7. 17.

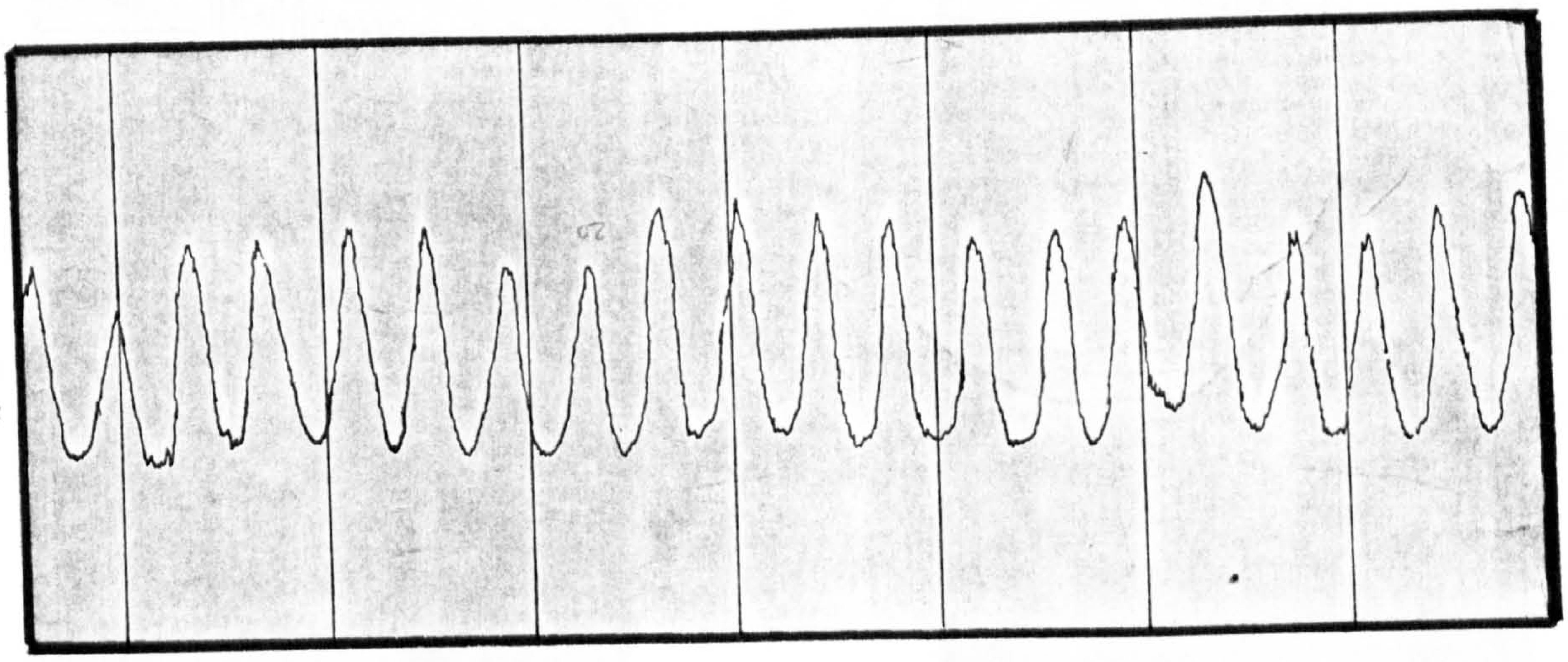




Cutting force traces - chattering, 'beats'

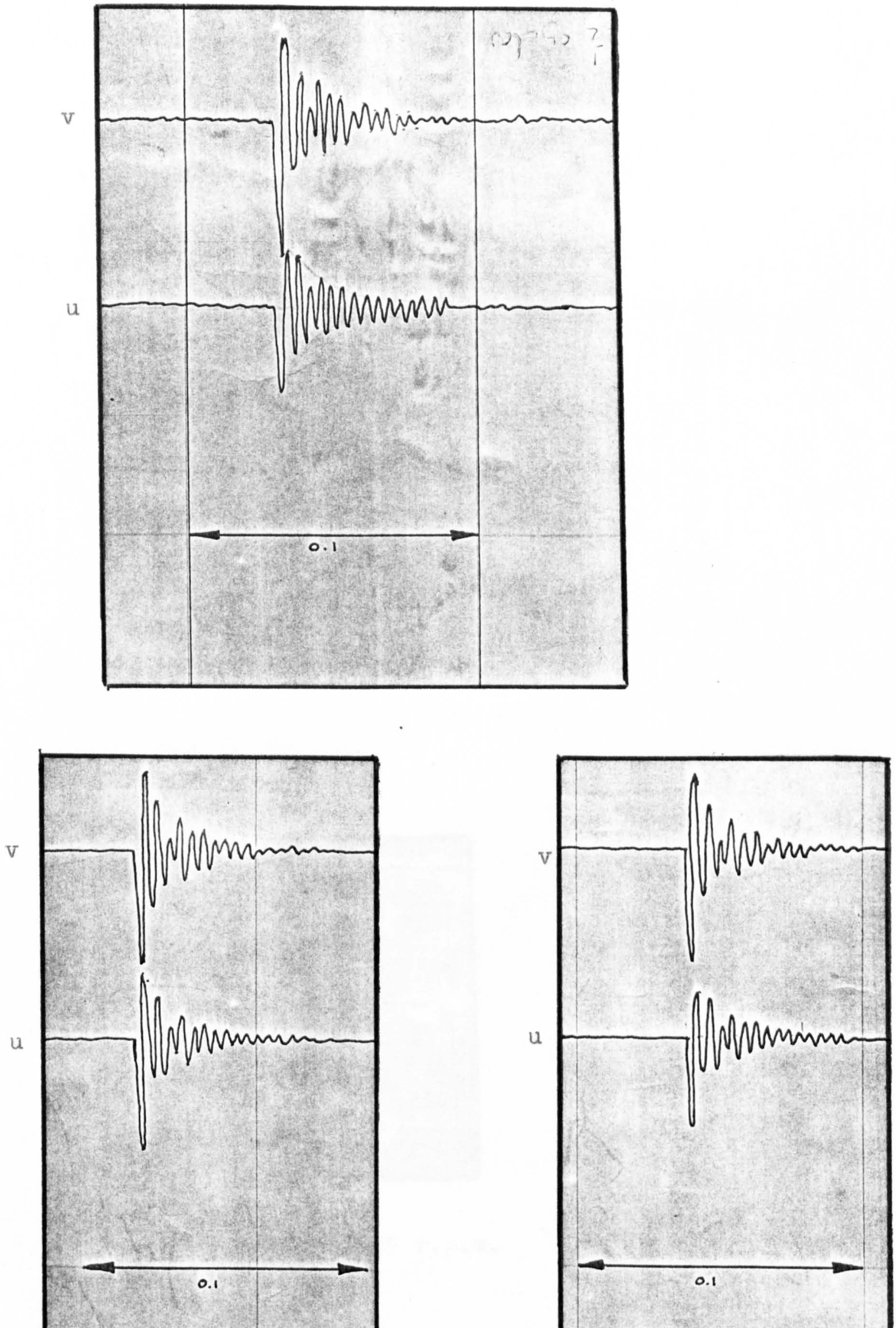
FIG7. 18.





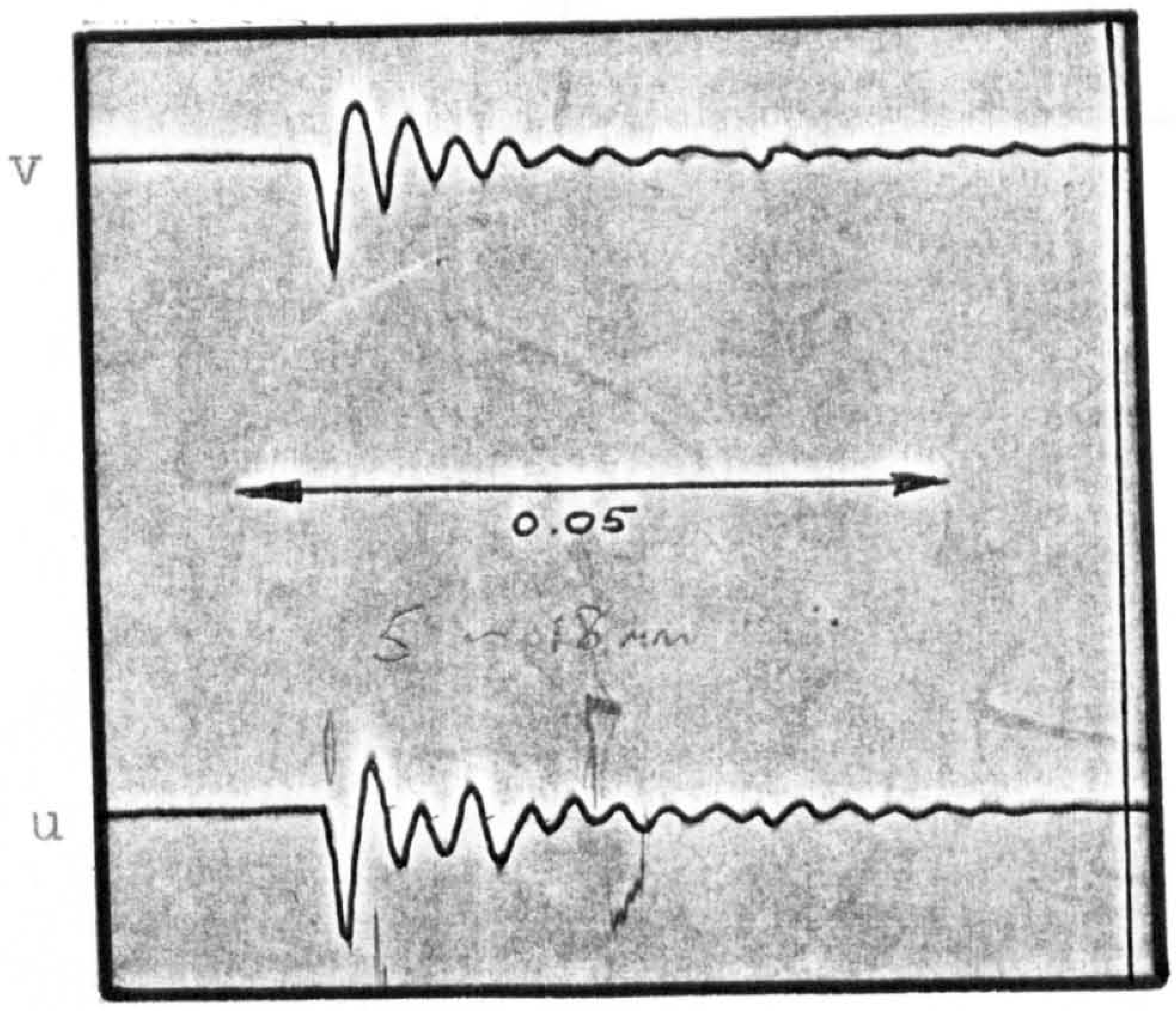
Cutting force traces - chattering.

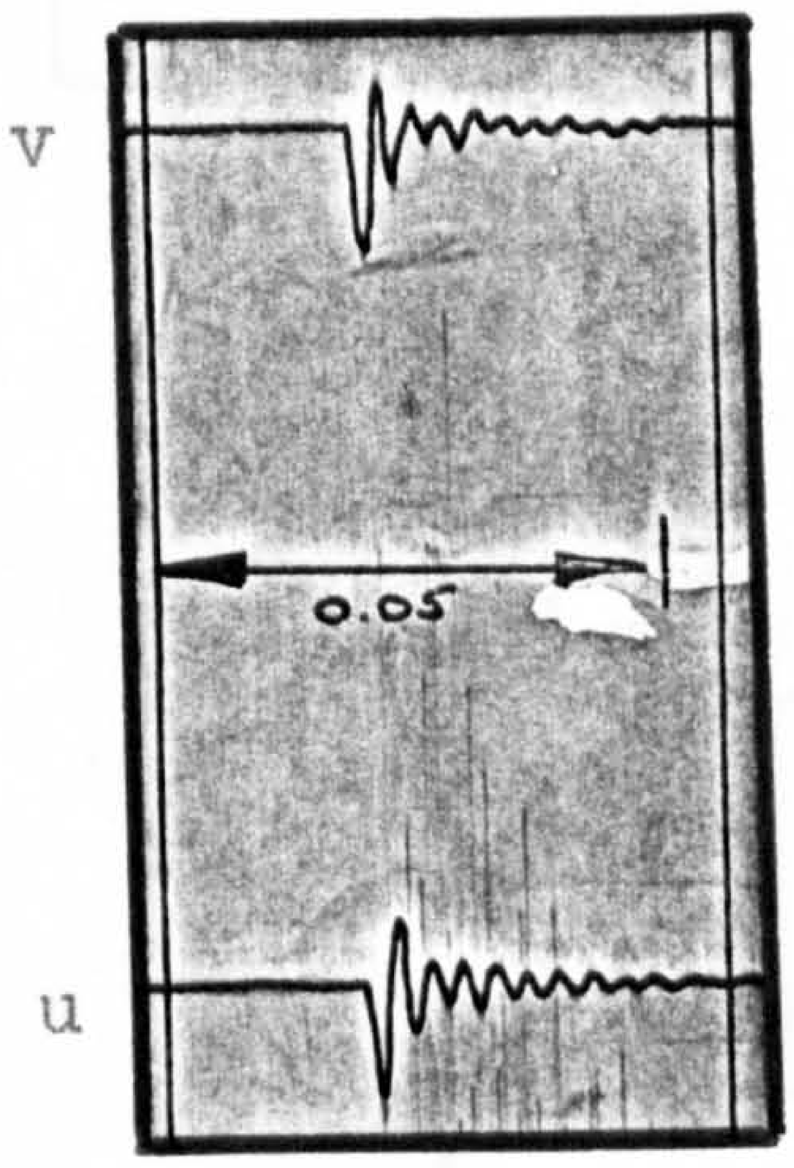
FIG7. 19.



Impulse responses - lathe stationary.

FIG7. 20.

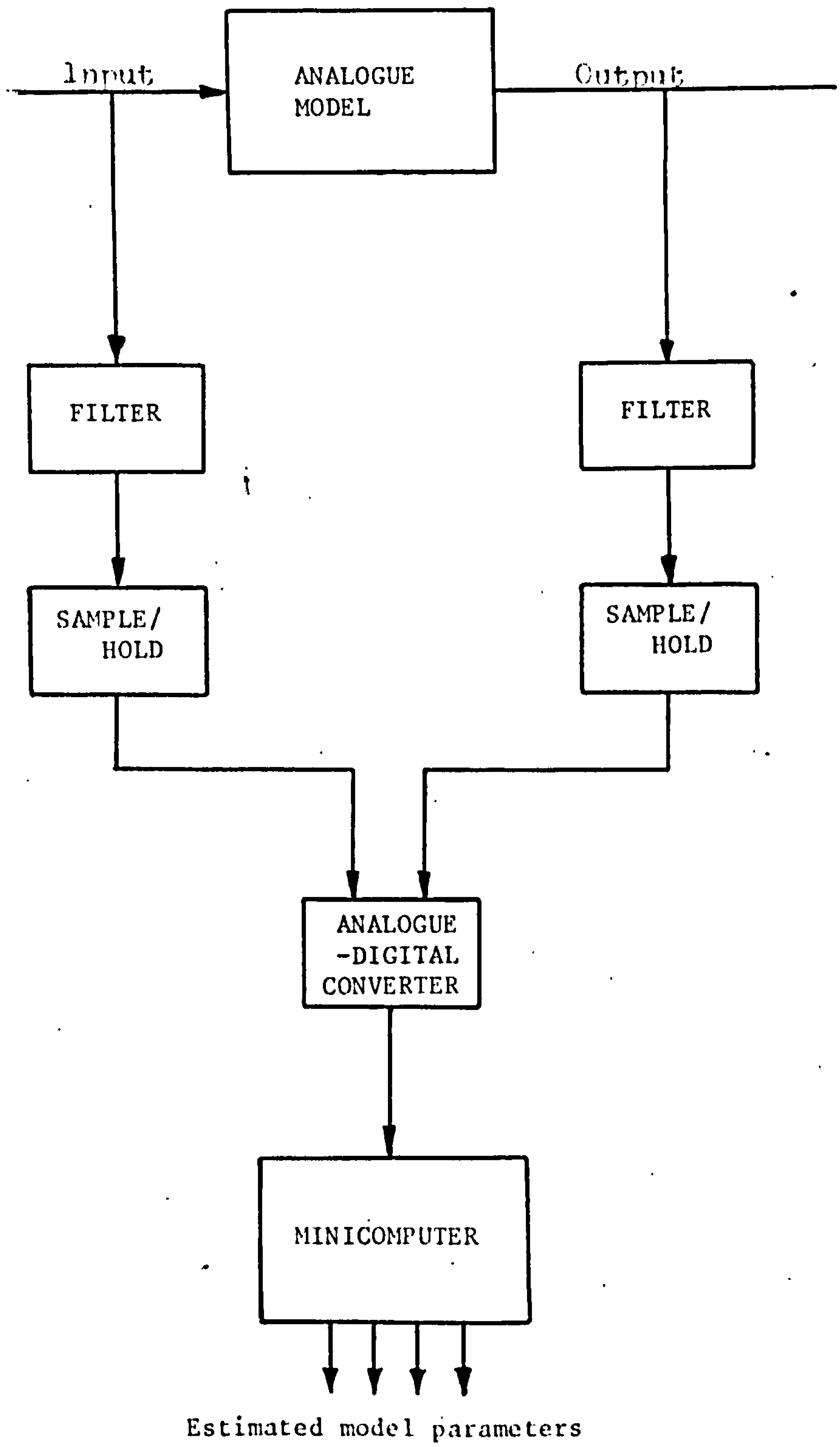




Speed = 625 r.p.m.

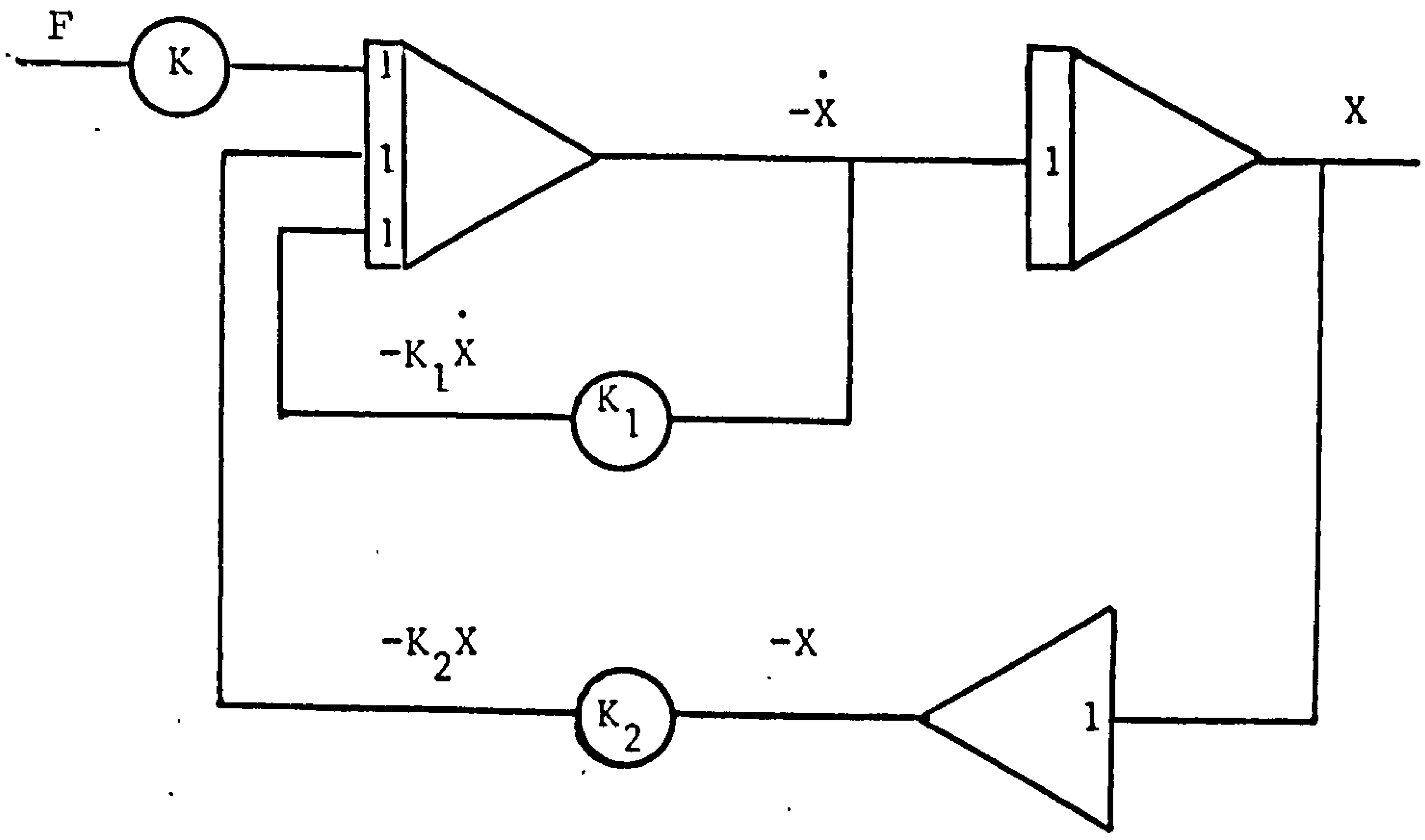
Impulse responses - lathe running.

FIG7. 21.



Schematic arrangement for testing identification method.

FIG7. 22.

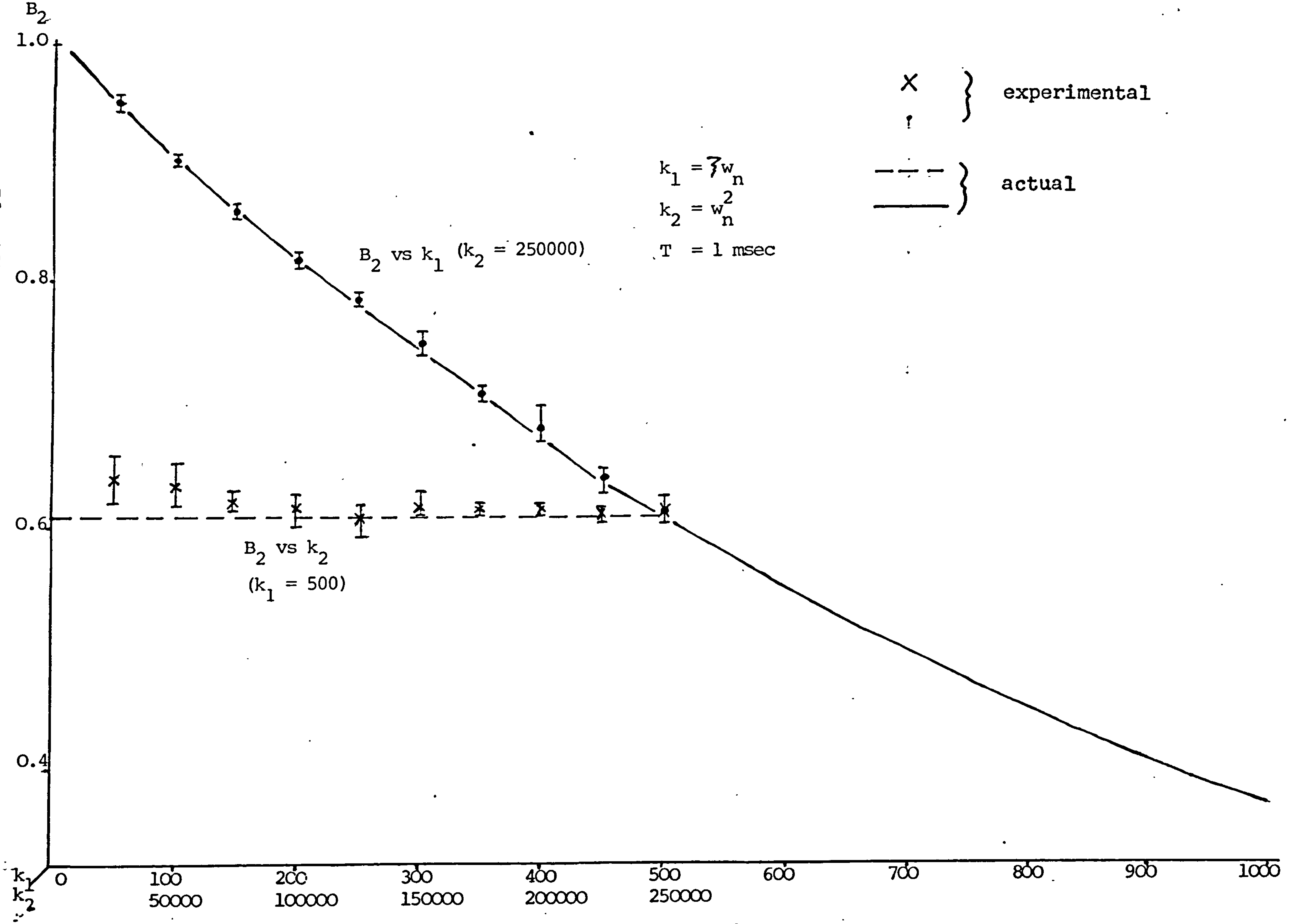


Analogue model used in identification tests.

FIG7. 23.

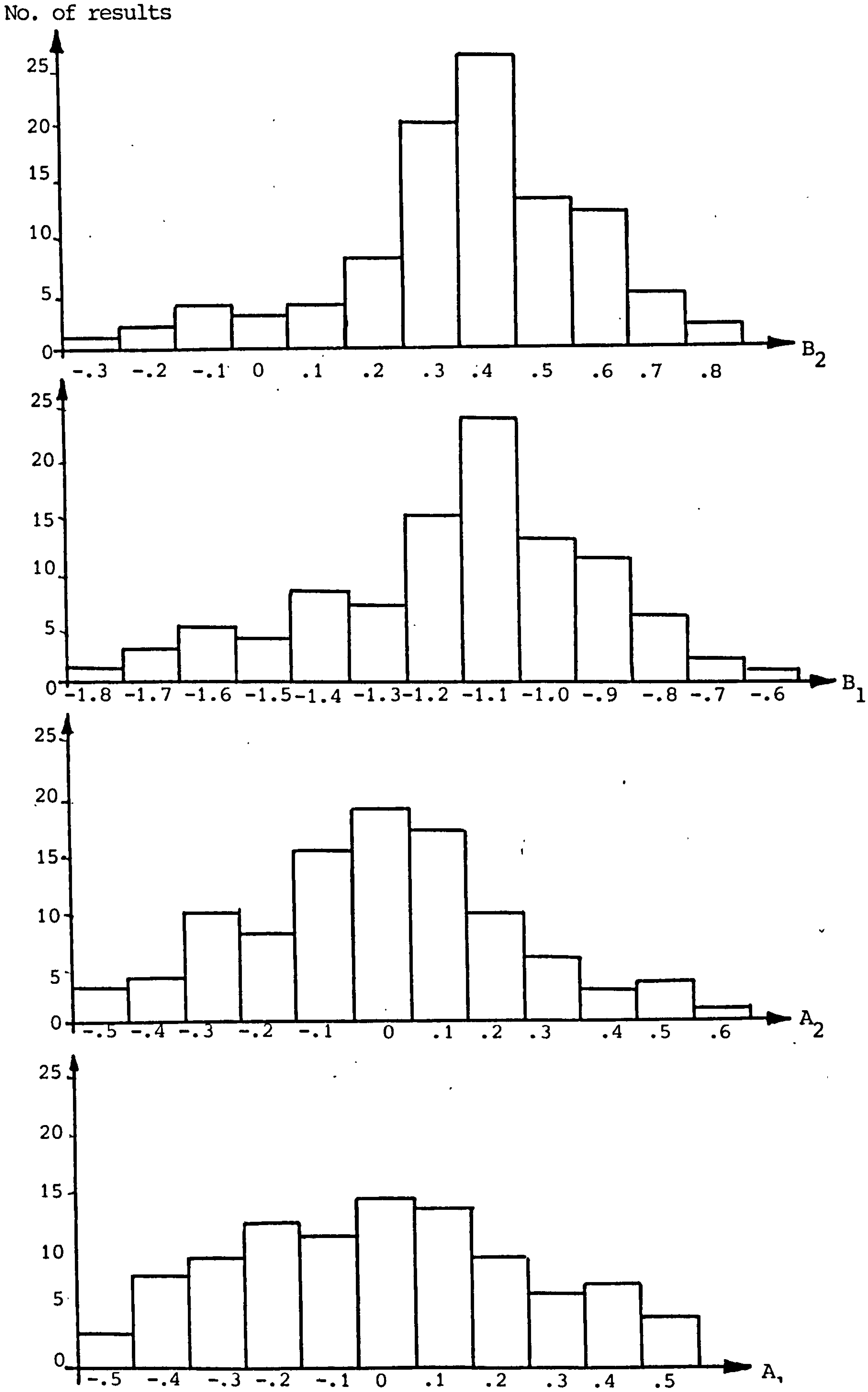
Identification method validation - B_1 vs k_1 and k_2

FIG7. 24.



Identification method validation - B_2 vs k_1 and k_2

FIG. 25.

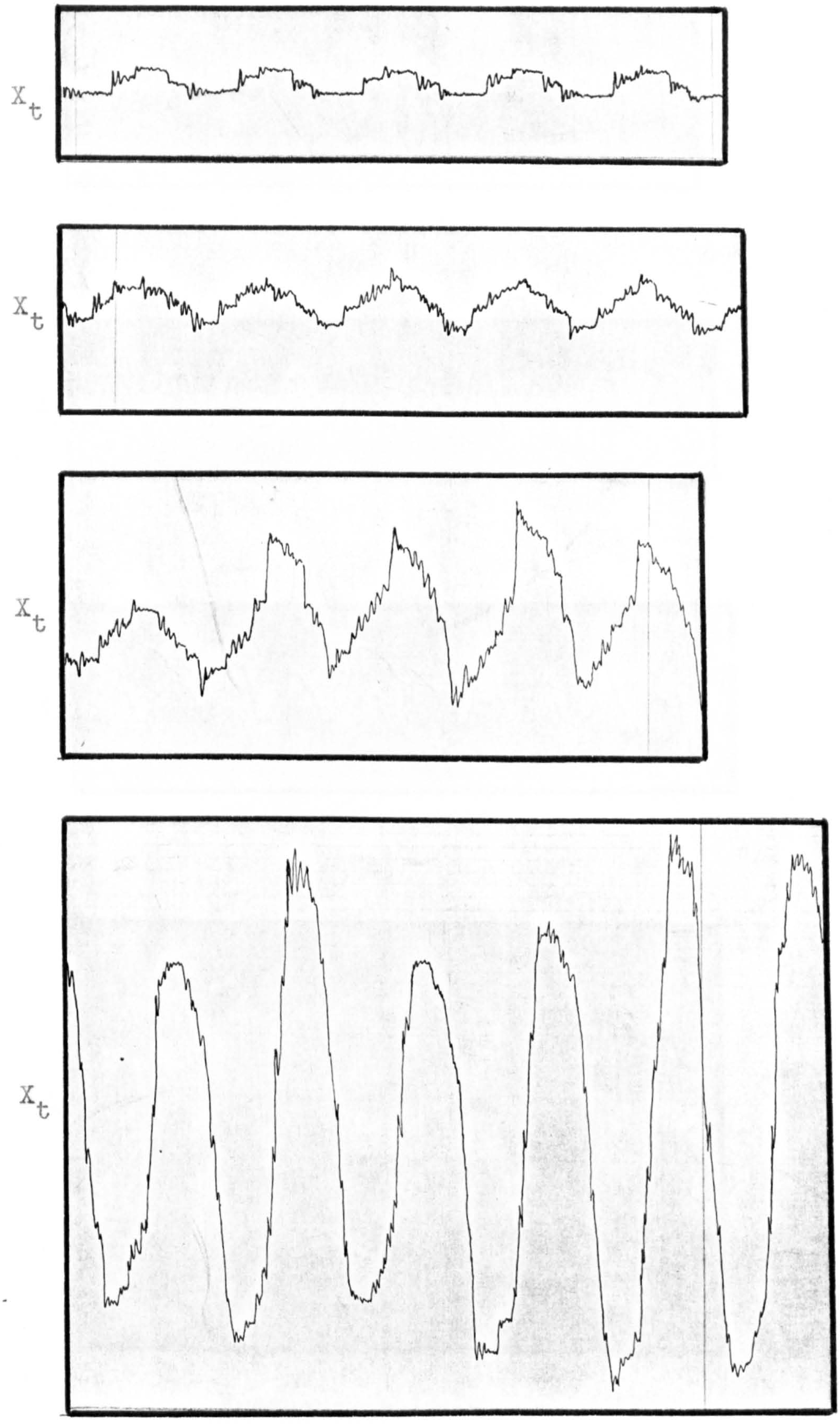


Sample period, T = 0.415 secs.

These give :- ζ = 0.7, w_n = 260, K = 860000.

Results from on-line identification of machine-workpiece structure.

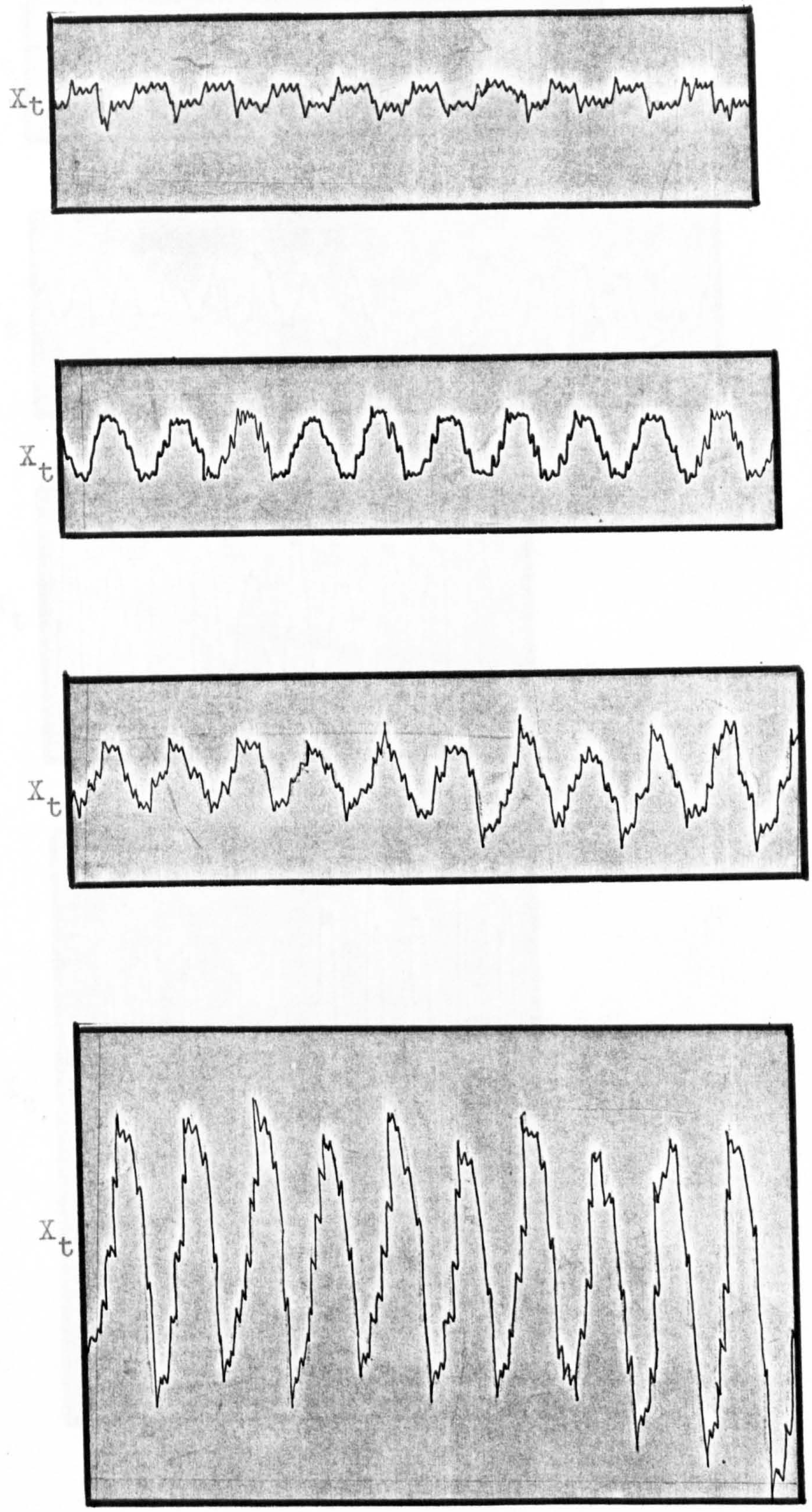
FIG7. 26.



Frequency = 5 Hz.

Tool positioner response.

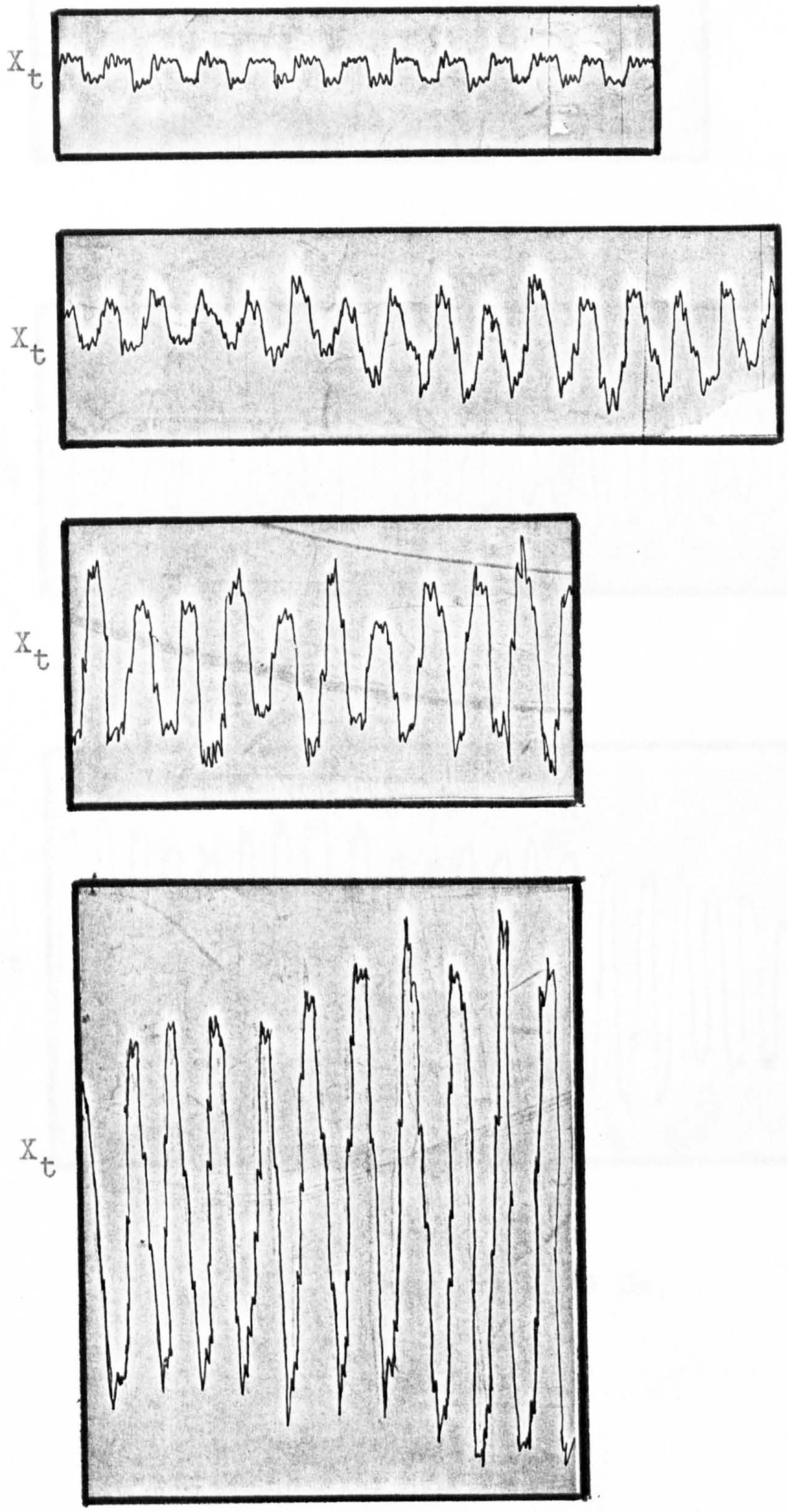
FIG7. 27.



Frequency = 10 Hz.

Tool positioner response.

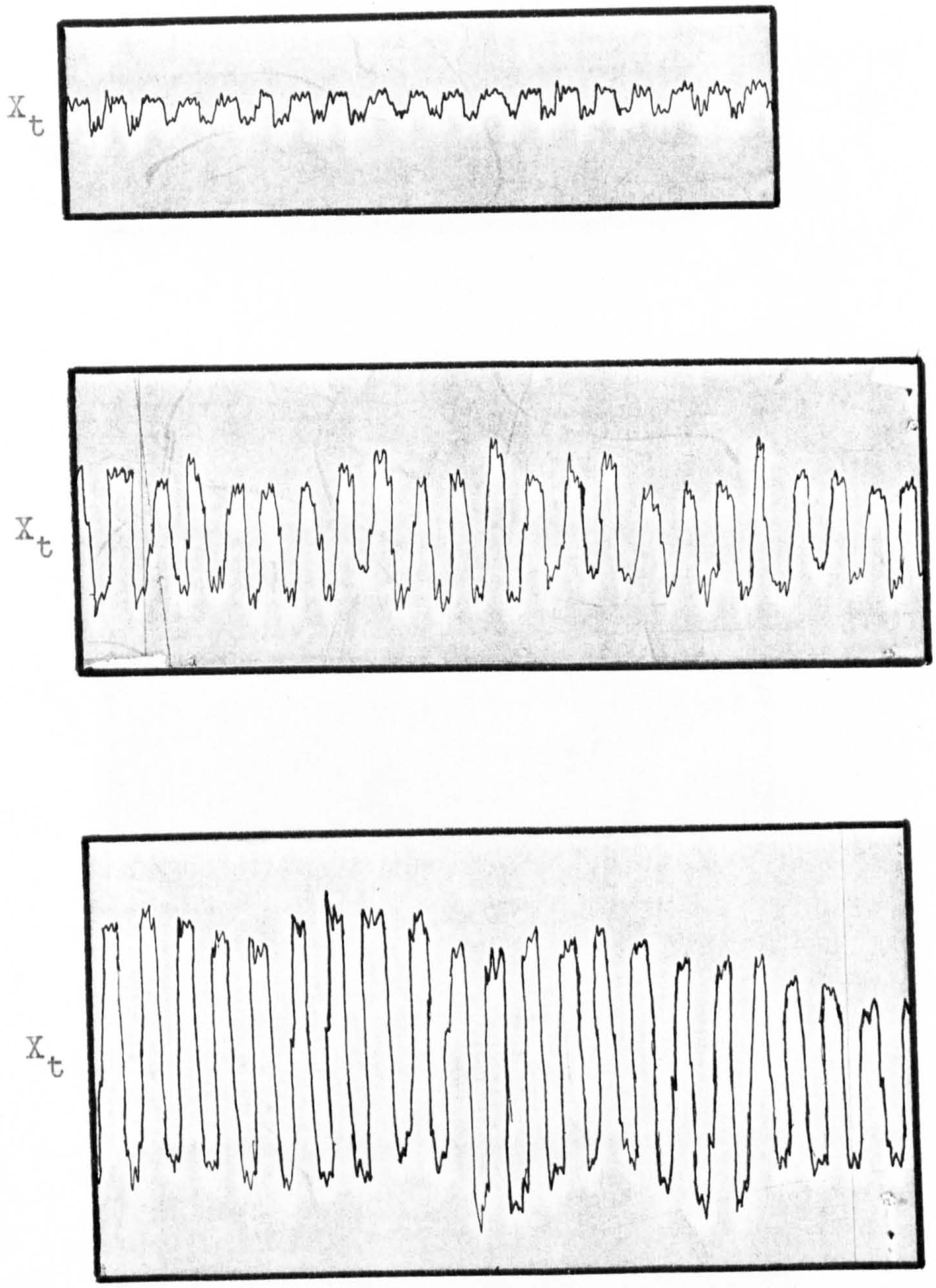
FIG7. 28.



Frequency = 15 Hz.

Tool positioner response.

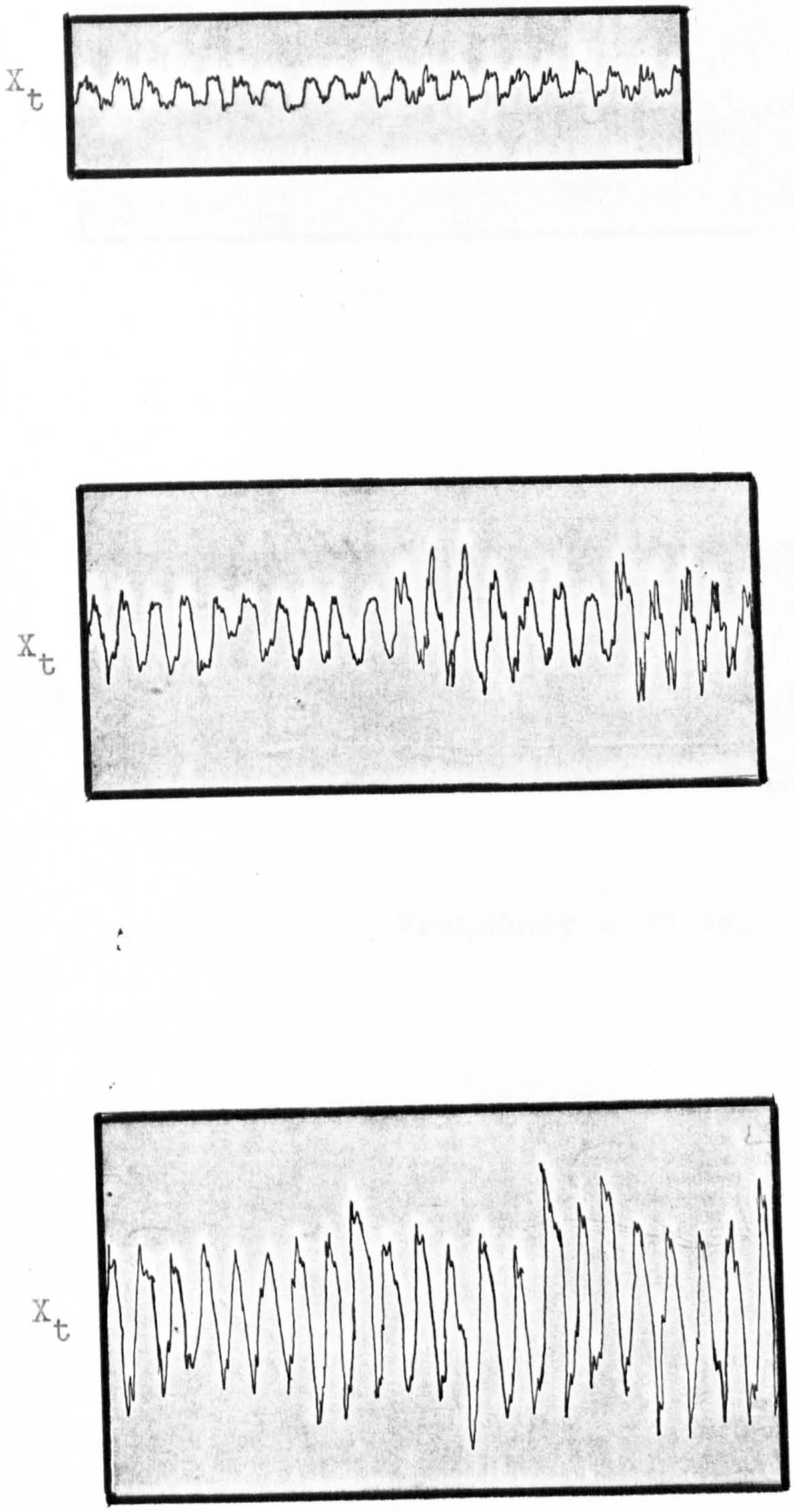
FIG7. 29.



Frequency = 20 Hz.

Tool positioner response.

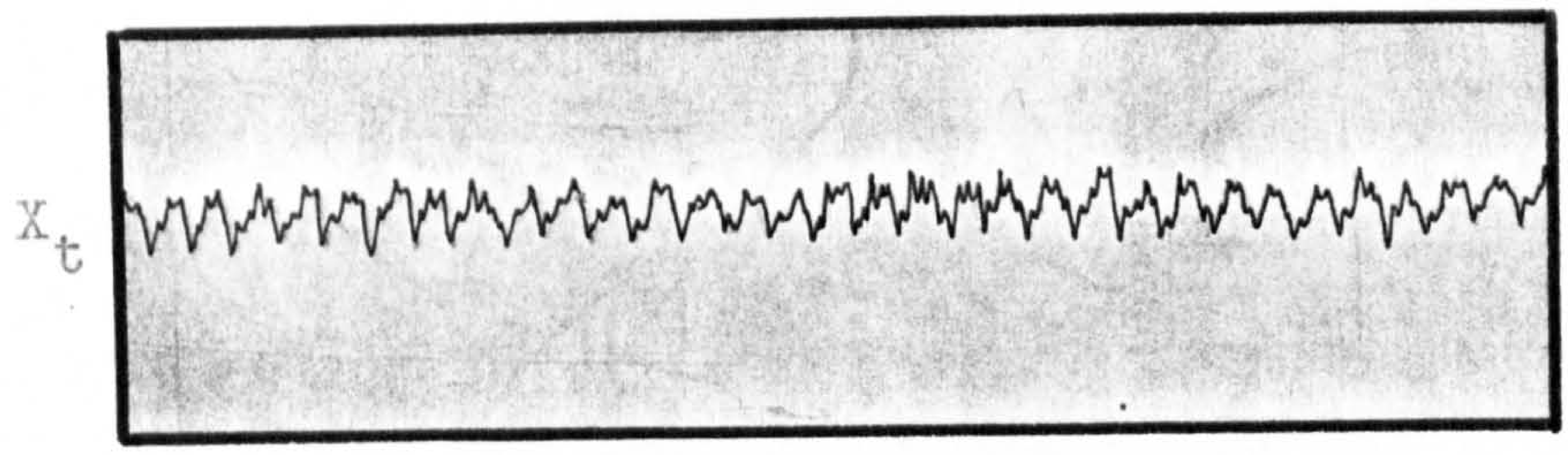
FIG7. 30.

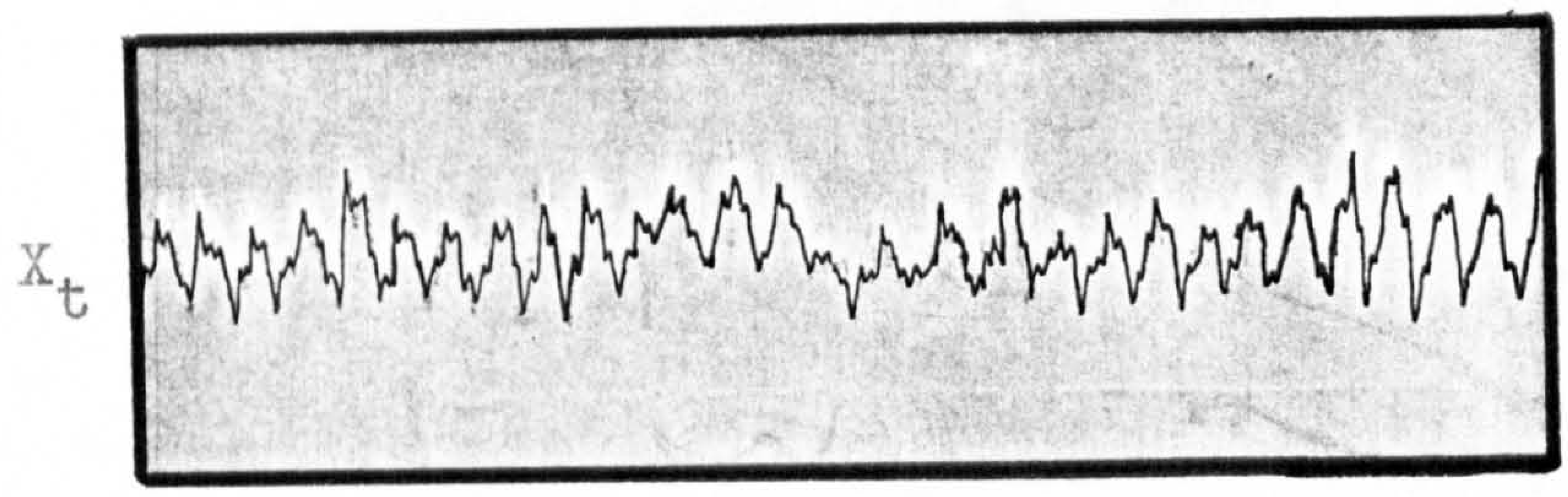


Frequency = 25 Hz.

Tool positioner response.

FIG7. 31.

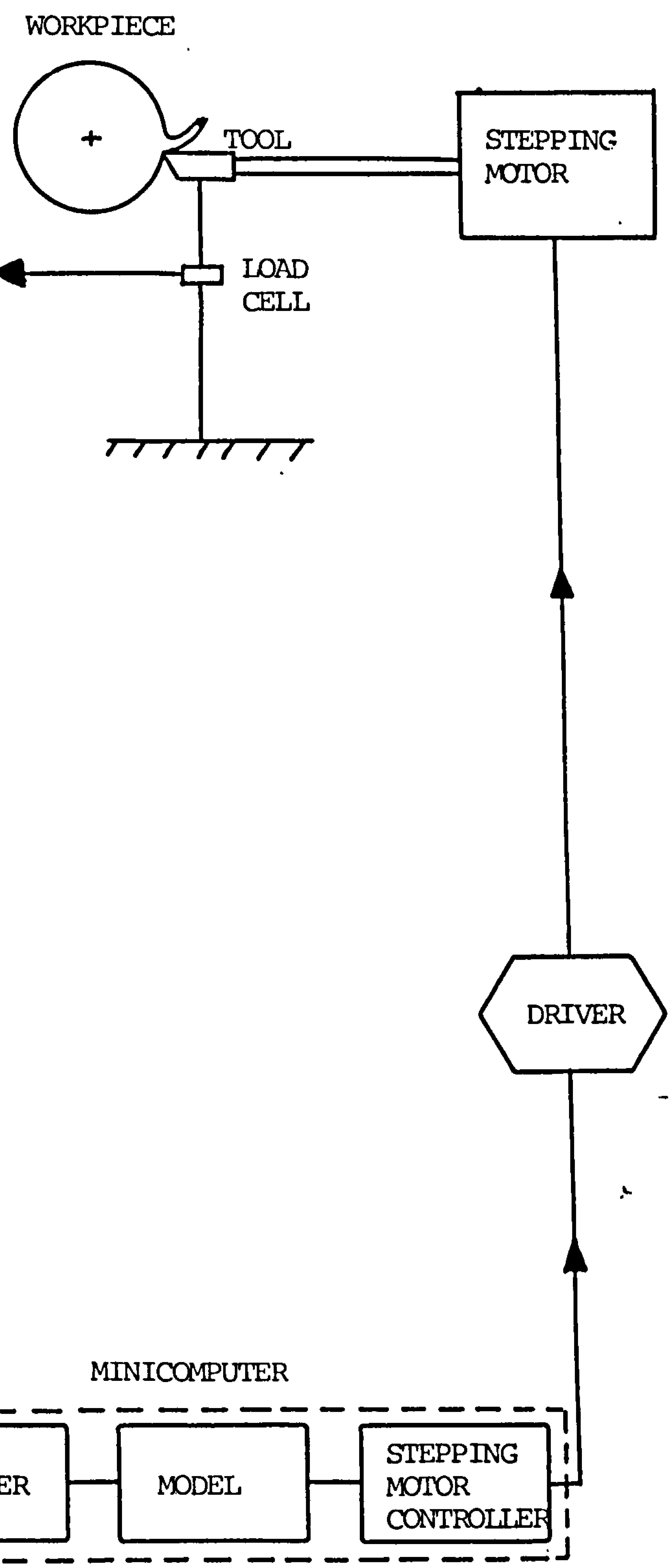




Frequency = 30 Hz.

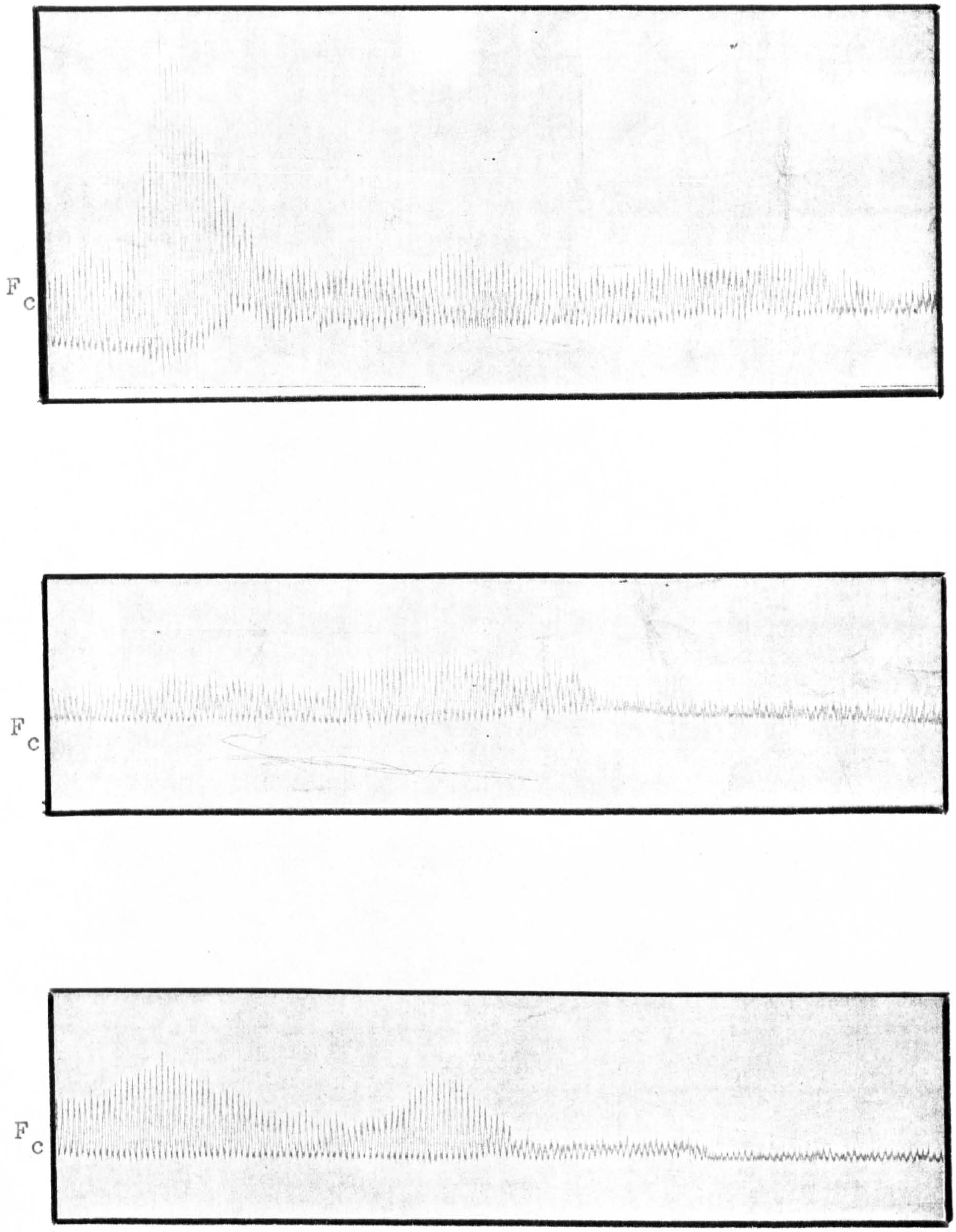
Tool positioner response.

FIG7. 32.



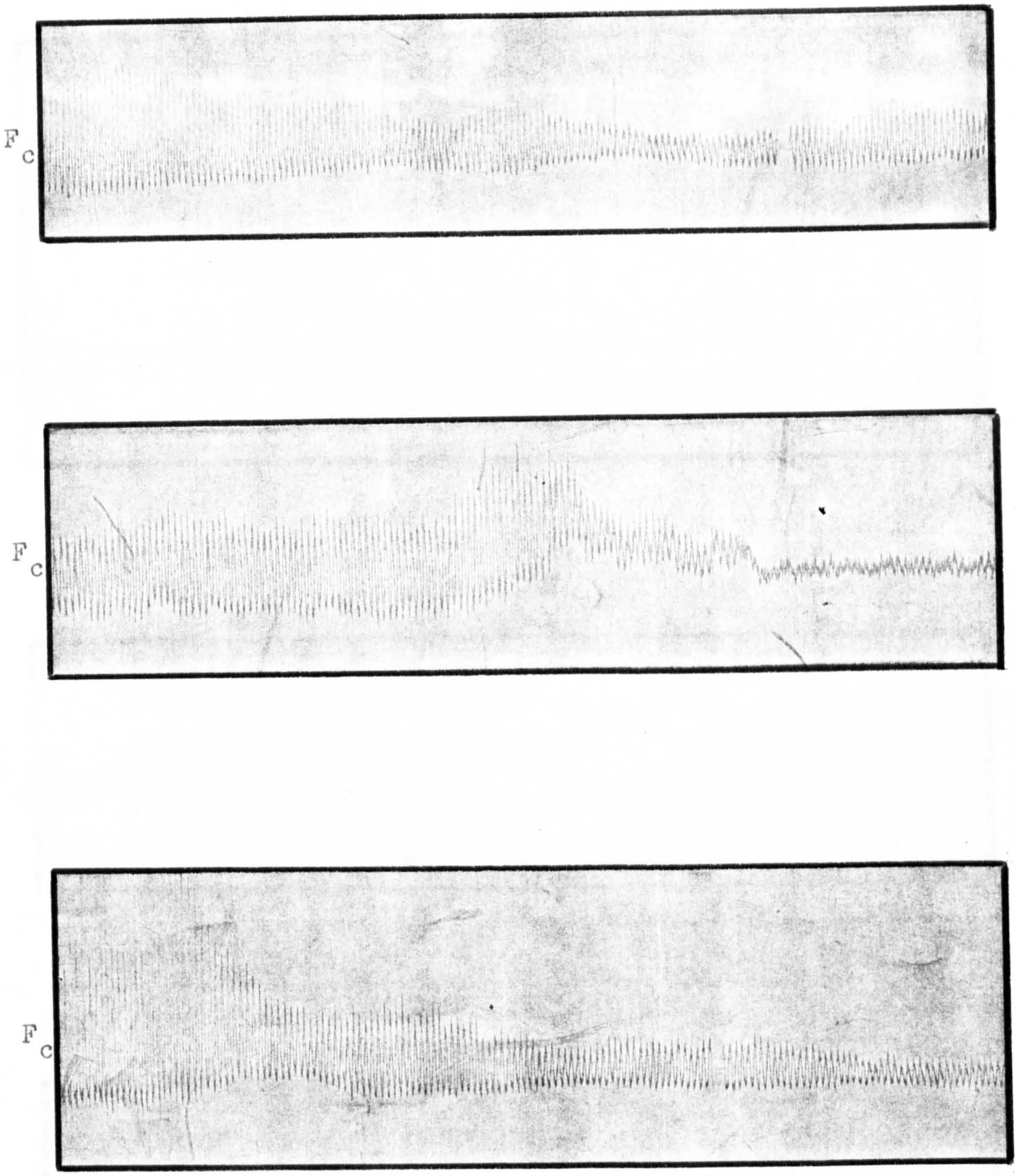
Schematic arrangement for chatter suppression tests.

FIG7. 33.



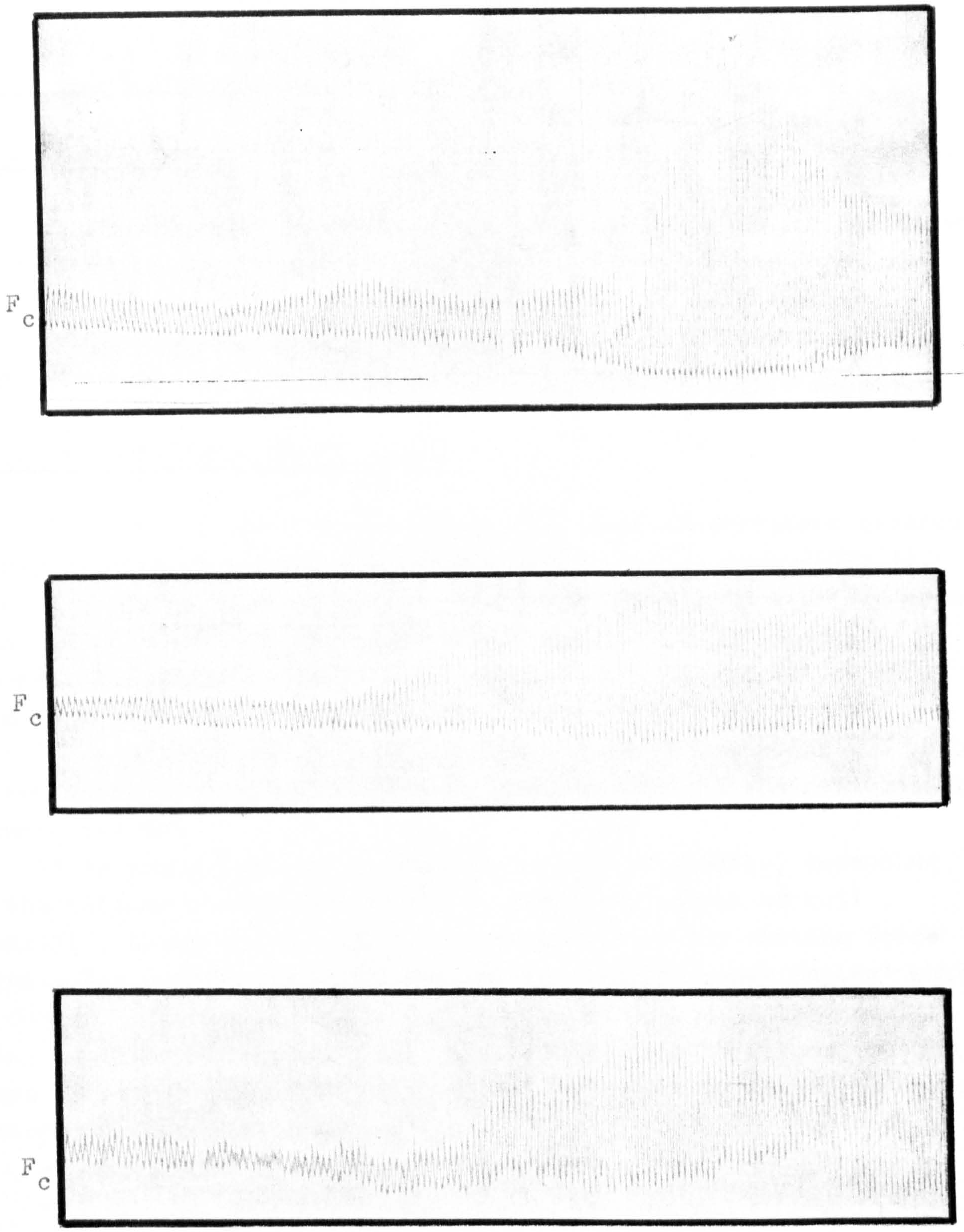
Chatter suppression .- matched model.

FIG7. 34.



Chatter suppression - matched model.

FIG7. 35.



Chatter suppression - mismatched model.

FIG7. 36.

8. DISCUSSION OF RESULTS.

8. 1. Introduction.

The results obtained during the experimental work are discussed and related to the theoretical analysis and simulation. Parallels are drawn between this work and that of Comstock and Nachtigal.

Problems encountered during the project are outlined, with suggestions for further research and development work.

8. 2. Machine-workpiece dynamics.

During the theoretical analysis, the machine-workpiece structure is represented by a dual mass-spring-damper system (see FIG2. 1). This is shown to have a frequency response similar to a second-order system, for practical combinations of machine and workpiece. In general, the experiments designed to evaluate this structure show this to be the case.

The cutting tests primarily provide information about the nature of the cutting force and workpiece displacement and the relationship between the two.

It is found that the cutting force varies greatly, depending on the cutting parameters (speed, feedrate and depth of cut) . Basically, there are two distinct components in the cutting force signal. One appears as a low amplitude, high frequency 'noise' which is due to microscopic variations in the structure of the metal being cut. The other component ranges from large amplitude, random jumps to almost sinusoidal variations. These may be caused by several macroscopic factors, such as:

-- hard spots or weakness in the metal.
-- depth of cut variations.
-- machine vibrations.
-- non-linear effects in the cutting process i.e. slip-stick tool motion.
-- chatter.

Some examples of the types of cutting force signal found during turning operations are given in FIG7. 5 to FIG7. 16, FIG7. 18 and FIG7. 19.

It is observed that the workpiece displacement is much less noisy than the cutting force. This can be seen from FIG7. 8 to FIG7. 13, FIG7. 16 and FIG7. 17.

During chattering, both the force and displacement signals become dominated by a large amplitude, sinusoidal component. This behaviour is predicted by the theory and the digital simulation (see FIG2.14 to FIG2. 19), and also agrees with simulations performed by Comstock (1). On the limit of chatter stability, it is noticed both from the simulation (see FIG2. 14 and FIG2. 17) and the cutting tests (see FIG7. 14 and FIG7. 18) that a 'beats' effect is present. This is due to the regeneration of the vibrations on each cycle of the workpiece.

From the cutting tests, it is found that the dominant frequency component, when using the test workpiece (see PLATE5. 1), is about 200 Hz. This is especially evident during chattering (see FIG7. 14 to FIG7. 17)

The impulse response tests show that the machine-workpiece system behaves approximately like second-order system (see FIG7. 20 and FIG7. 21). There is clearly only one frequency component, however the decay rate is not a smooth exponential. This is probably due to a nonlinearity in the machine structure. Using the test workpiece with the lathe stationary, it is found that the natural frequency is about 260 Hz. and the damping factor is 0.1. When the lathe is running (625 rpm.), the natural frequency is unchanged but the damping factor increases to approximately 0.3. This is most likely due to the effects of the oil circulating in the machine bearings.

Although the chatter frequency observed during the cutting tests and the natural frequency determined from the impulse response tests are of the same order, the theory predicts a much closer correlation. The discrepancy is probably due to the structural modification which is introduced by the tool during the cutting tests. Hence , the results from the impulse tests should be used with care when determining the model parameters for use in the chatter suppressor.

It is found during the on-line identification tests that the accuracy of the results is largely determined by the nature of the input signals. In general, the lower the signal-to-noise ratio, the greater the errors in the parameter estimates. It is well known (14,15,16,17,18) that bias errors may arise in the basic least-squares estimates if either the signal-to noise ratio is low, or if the noise is correlated. During the method evaluation tests, where the signal noise is negligible, the estimates are found to be accurate (see FIG7. 24 and FIG7. 25). However, during the identification tests, the signal-to-noise ratio varies greatly with the cutting conditions. Consequently, the parameter estimates vary over a large range (see FIG7. 26). If those estimates which appear to be wildly incorrect are neglected, the averaging of the remaining results give values which approximately agree with those from the other methods. Because of the inconclusive nature of these results, the estimates cannot be used with confidence, however, they lend support to the other tests.

The basic identification method may be improved by several techniques (14,15,16,17,18) which either filter the input signals prior to the least-squares estimation, or use some other form of statistical criterion, eg. maximum likelyhood. These techniques have been found to give the method better immunity to noise, and generally give more accurate and reliable results.

Another possible reason for the poor results could be the unsuitability of the second-order base used in this implementation, under some or all of the cutting conditions. However, because the method is implemented as a computer programme it could be easily extended to investigate higher order models.

In general, it is felt that the results show that a second-order system is a reasonable approximation for use in the chatter suppressor. This is confirmed both by the results of previous workers (eg. 19,21,23,24) and the success of the second-order model used by Nachtigal (2). It is noted that none of the tests indicate that the machine-workpiece dynamics are second-order, and this is not expected for a structure as complicated as this.

Much work has already been carried out on the investigation of machine tool dynamics (eg. 19,20,23,24). The usefulness of these methods in this application needs to be assessed. It is also felt that further development of the on-line identification will prove worthwhile.

As the theory predicts the chatter frequency to be near the natural frequency, and because the impulse tests are not performed under actual cutting conditions, the results from the cutting tests (chattering) are used as the basis for the model natural frequency. The damping factor is estimated from the results of the impulse tests and the gain (stiffness) via static loading tests.

8. 3. Chatter suppression tests.

The results are discussed in two parts. Firstly, testing of the tool positioner and validation of the chatter suppressor implementation. Secondly, the effectiveness of the chatter suppressor under actual cutting conditions.

8. 3. 1. The tool positioner and chatter suppressor.

The most important factor influencing the performance of the suppressor is the response of the tool positioner. This limits the maximum frequency of chatter that can be suppressed. However, as chatter is a most severe problem during turning of large components (eg. gun barrels, turbine rotors) which have low chatter frequencies, this does not invalidate the current prototype. It can be seen from FIG7. 28 to FIG7.30 that the maximum useable frequency for the test rig is about 30 Hz. for amplitudes up to 1 'thou' (3 steps). The response for single step operation begins to get 'ragged' at about 30 Hz., however this will be damped when used in a cutting situation. It is obvious from all the traces that the positioner is underdamped. This is partly remedied when used during cutting, but additional damping is desirable. It is essential to also improve the frequency-amplitude response if a 'production standard' suppression system is to be developed.

Possible ways of improving the performance were investigated but proved to have certain undesirable side effects. Both 'reverse-pulse' damping (7) and the addition of external dampers were tried. 'Reverse-pulse' damping was found to be effective, but requires careful tuning to the tool positioner dynamics. Other methods of optimal control (10,48) could also be applied to the tool positioner, but these will require further investigation. Many would be easily implemented on the minicomputer and may provide a convenient way of inproving the performance of the existing prototype. Viscous damping was found to be more reliable, but could not be easily incorporated into the original design. A redesign of the tool positioner to include viscous damping and to minimise the mass of the tool holder will result in a better overall dynamic response.

More sophisticated stepping motor drivers are also available which increase the rate of power input to the motor eg. bi-level drive. Several of these methods are described in references 6,7 and 43. There are also more specialised stepping motors becoming available which have both smaller step sizes and faster response times. These will enable improvements to both the speed and accuracy of the tool positioner.

In the present system both the modelling and control functions are performed by the minicomputer. Although the computation time does not, at present, limit the performance of the suppressor it will become more significant as the speed of the other elements increases. It is possible to decrease both the computation time and the cost by using one or more microprocessors in place of the minicomputer. One possible approach would be to use one microprocessor for monitoring the instrumentation system, one for the modelling function, and one to control the stepping motor.

Although the tool positioner is designed primarily for use in the chatter suppressor, it has potential applications in other areas. One of these is the C.N.C. system introduced in Chapter 6. A more sophisticated, two axis prototype is currently under development in the Department of Mechanical Engineering at the University of Newcastle-upon-Tyne. The main advantages of the tool positioner are its stability, accuracy, cheapness, and lack of feedback requirements. Another possible area for application may be in-process measurement and control. This application and some currently available systems are described in reference 47.

8. 3. 2. The suppression method.

Because of the limited response of the prototype chatter suppressor, a special workpiece is used to facilitate testing. The nominal model parameters are determined as described in the previous section. These are then tuned in order to match the model more accurately to the machine-workpiece structure. This is found to be a difficult operation as the system is both sensitive and variable, and only a trial-and-error approach ia available.

The sensitivity is predicted by the theory (see FIG2. 13) and demonstrated by the simulation (see FIG3. 13 and FIG3. 14). It is shown that limits of less than 5% on the natural frequency are required for effective operation of the suppressor. This seems to contradict claims made by Nachtigal (2) that useful limits of 10% were obtained.

Variation of the machine-workpiece dynamics is expected because of changing conditions in the machine, eg. oil pressure and temperature, and the moving cutting position. It was hoped that these variations would be small and would fall within the working range of the suppressor. Unfortunately, this is not the case, and hence the model requires almost continuous tuning.

After tuning of the model, it is found that chatter is successfully suppressed for a limited period. Extensive qualitative tests were not performed, however, it is generally found that cutting rates can be increased by 500%. The experimental results (see FIG7. 34 and FIG7. 35) show how the amplitude of oscillation of the cutting force decreases when the suppressor is switched on. If the model is mis-matched, chatter can be initiated even in a normally stable cutting operation (see FIG7. 36).

It is obvious from the experimental results that two important factors determine the effectiveness of the method:

-- the machine-workpiece dynamics must be accurately identified.

-- the model must be reliably and continuously tuned.

In order that the second condition be fulfilled, it is necessary that the model be made adaptive. This could be achieved by a method which minimises the amplitude of oscillation of the cutting force that occurs during chattering. The advantage of this approach being that it is not required to measure the machine vibration.

8. 4. Comments.

One of the main reasons for choosing a minicomputer to implement the chatter suppression method is to provide flexibility during development. It has already been stated that this flexibility can be used for different types of model and optimal control of the stepping motor, and may be extended to adaptive control of the system. Although these are proposed as possible ways of improving the basic method, and are mainly untested, it is felt that they would form a good starting point for further research and development.

During this research project, contact with skilled machine operators has revealed several other ways of preventing chatter. These seem to fall into three main types:

-- avoiding the chatter regions.

-- 'tricks of the trade'.

-- add-on devices.

In general, the first two merely ensure that the machine operates under optimum conditions, thus making the best of the machine. The third covers such things damper and workpiece steadies which may allow small increases in the machining rate.

The methods of Comstock and Nachtigal, and that described in this thesis, promise much greater increases. How these can be developed to 'production standard', and made suitable for an industrial environment, requires further investigation. However, the continuing progress of technology, especially in the fields of instrumentation, microcomputers, and electrical motors, makes the future availability of a 'production standard' active chatter suppressor seem near.

9. CONCLUSIONS.

9. 1. Conclusions.

In this final section, the main conclusions resulting from this work are summarised.

Throughout this project, the emphasis has been placed on developing a flexible chatter suppression system. It is shown that this primary objective has been fulfilled, resulting in a system which is amenable to future modification and expansion. It is clearly shown that the basic suppression method is sound, although several problem areas were encountered. These are mainly associated with the practical aspects of the implementation, and are discussed in detail in the main text. Solutions to the problems are proposed, with suggestions for other possible improvements.

The simple machining model used for the chatter analysis and simulation accurately predicts the observed behaviour during chattering. This model is then used to investigate the effects of the chatter suppression method under a variety of conditions. The digital simulation technique was found to be particularly useful as it is easy to use and allows the inclusion of many additional variables, eg. the tool positioner dynamics. The Describing Function method was found to be restricted to a simplified analysis only, as it becomes unwieldy if many variables are included. It does, however provide some qualitative results.

The selection of a suitable model for use in the suppressor turned out to be the most challenging problem. It was found that neither the cutting tests, impulse tests, or on-line identification provided other than nominal model parameters. These then had to be tuned by 'trial-and-error'. It was found that accurate tuning of the model parameters was essential for effective operation of the method. A realistic limit of less than 5% was found, which contradicts the results of Nachtigal, who quoted 10 %.

The most important future development of the suppressor would be to make the model self-tuning (adaptive). Also, the performance of the tool positioner needs to be inproved. Investigation is also required to extend the method to other machine tools.

It is hoped that the work described in this thesis will, to some extent, contribute to the development of more efficient machine tools, and will form the basis of further work.

REFERENCES.

1. Comstock T.J.,"Chatter suppression by controlled mechanical impedance",Ph.D. thesis,Ohio State University,1968.

2. Nachtigal C.L.,Cook N.H.,"Active control of machine-tool chatter",Journal of basic engineering,Trans. A.S.M.E.,June 1970,pp 238-244.

3. Stone B.J.,"The introduction of vibration damping into machinery".

4. Raven F.H.,"Automatic control engineering",McGraw-Hill.

5. Ibbett R.N.,"Digital techniques in measurement instrumentation", Jour. measurement and control,Vol. 2,March 1969.

6. Kennedy D.W.,"High performance stepping motor alternative to analog servos",Computer design,Jan. 1973.

7. Sigma Instruments Inc.,"Stepping motor handbook",1972.

8. Truxal J.G.,"Automatic feedback control system synthesis", McGraw-Hill.

9. Oldenburger R.,"Frequency response",McMillan.

10. Netushil A.,"Theory of automatic control",Mir Moscow.

11. Savas E.S.,"Computer control of industrial processes", McGraw-Hill.

12. Gelb,Van der Velde,"Multiple input describing functions and nonlinear system design",McGraw-Hill.

13. Kalman R.E.,"Design of a self-optimizing control system", Trans. A.S.M.E.,Feb. 1958.

14. Clarke D.W.,"Generalized least-squares estimation of the parameters of a dynamic model".

15. Astrom K.J.,Wittenmark B.,"On self tuning regulators", Automatica,Vol. 9,1973.

16. Astrom K.J.,"Computer control of a paper machine - an application of linear stochastic control theory",I.B.M. Jour., July 1967.

17. Dahlin E.B.,"On-line identification of process dynamics", I.B.M. Jour.,July 1967.

18. Eykhoff P.,"Some fundamental aspects of process-parameter estimation",I.E.E.E. Trans. on automatic control,Oct. 1963.

19. Kwiatkowski A.W.,Al Samarai H.M.,"Progress in the application of random signal analysis methods to the identification of machine tool structures",Proc. 9th. Int. M.T.D.R. Conf.,Birmingham,1968.

20. Sato H.,Akutsu T.,"A study of identification of dynamic characteristics of machine tools by means of micro tremor", Proc. 12th. Int. M.T.D.R. Conf.,Manchester,1971.

21. Hanna N.H.,Kwiatkowski A.W.,"Effect of feedmotion during dynamic tests on the chatter prediction of a lathe",Proc. 13th. Int. M.T.D.R. Conf.,Birmingham,1972.

22. Das M.K.,Knight W.A.,Sadek M.M.,"A critical assessment of cutting force models in the analysis of machine tool instability",Proc. 11th. M.T.D.R. Conf.,Birmingham,1970.

23. Kwiatkowski A.W.,Bennett F.E.,"Application of random force excitation to the determination of receptances of machine tool structures",Proc. 6th. Int. M.T.D.R. Conf.,Manchester, 1965.

24. Kwiatkowski A.W.,Bennett F.E.,"Correlation method of system identification - computer programme and experimental design considerations",Proc. 7th. Int. M.T.D.R. Conf.,Birmingham, 1966.

25. Burney F.A.,Pandit S.M.,Wu S.M.,"A stochastic approach to characterization of machine tool system dynamics under actual working conditions",Jour. of engineering for industry, Trans. A.S.M.E.,May 1976.

26. Knight W.A.,Sadek M.M.,"The assessment of the chatter resistance of machine tools".

27. Chiriacescu S.T.,Rudu,Mangeron,Oguztoreli,"On the stability of cutting machine tools",Proc. I.Mech.E.,1975.

28. Tobias S.A.,"Machine tool vibrations",Blackie,1965.

29. Slavicek J.,Bollinger J.G.,"Design and application of a self-optimising damper for increasing machine tool performance", Proc. 10th. Int. M.T.D.R. Conf.,Manchester,1969.

30. Abu-Akeel A.K.,"The electrodynamic vibration absorber as a passive or active device",Jour. of engineering for industry, Trans. A.S.M.E.,Vol. 89,Ser. B,No. 4,1967.

31. Boyle A.,Cowley A.,"A theoretical investigation into the characteristics of a feedback controlled damping unit", Proc. 9th. Int. M.T.D.R. Conf.,Birmingham,1968.

32. Wolfe C.J.,Woods C.J.,Andrew C.,"Damping inserts in vibrating structures",Jour. of mechanical engineering science, No. 5,1969.

33. Peters J.,"Damping in machine tool construction",Proc. 6th. Int. M.T.D.R. Conf.,Manchester,1965.

34. De Ro M.,"The magnetic exciter as applied to active damping of machine tools"Proc. 9th. Int. M.T.D.R. Conf., Birmingham,1968.

35. I.B.M. Publications,"C.S.M.P. Manual".

36. Froberg C.E.,"Introduction to numerical analysis",Addison-Wesley,1972.

37. Southern Instruments Publication,"Miniature proximity vibration transducers - Types G323A,G323B,G324A,G324B".

38. Kistler Instrument Publications,"Quartz force links - series 9300".

39. Kistler Instrument Publications,"Charge amplifier - Type 5001".

40. Burr-Brown Publications,"Universal active filters - Type UAF31".

41. Burr-Brown Publications,"Sample-hold amplifiers - Type SHC85".

42. Data General Publications,"How to use the NOVA line computers", Ref. 015-000009-09.

43. Unimatic Engineers Publications,"Constant current stepper drive",Ref. USD844.

44. Johnson Precision Publications,"Recirculating ball bearings".

45. EAI Publications,"Analogue computers - Model PACE TR48".

46. MacLean D.,"Mathematical models of electrical machines", Jour. I.M.C.,Vol. 11,No. 6,June 1978.

47. Ertl F.,Stockermann Th.,"In-process measurement and control in production",Ind. & Prod. Eng.,No. 1,1977.

48. Tou J.T.,"Modern control theory",McGraw-Hill.

APPENDICES.

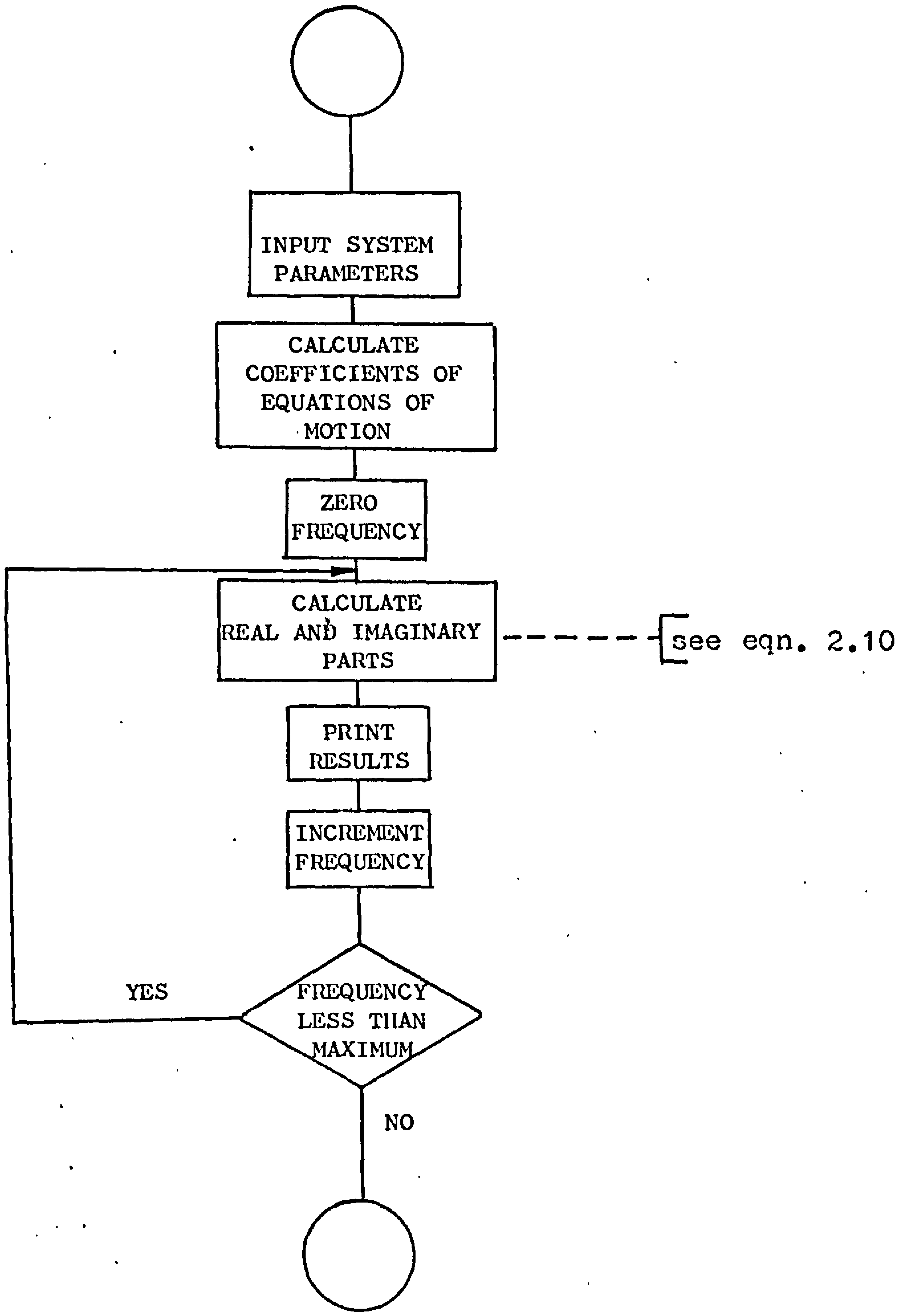
In the following appendices, the flowcharts and listings of the various programmes used during this research are given. The accompanying notes are intended only to provide a brief description of the programmes, and how to use them.

Appendix A contains the flowcharts and Appendix B contains the listings. Programmes written in the NOVA assembler language are extensively commented to aid understanding.

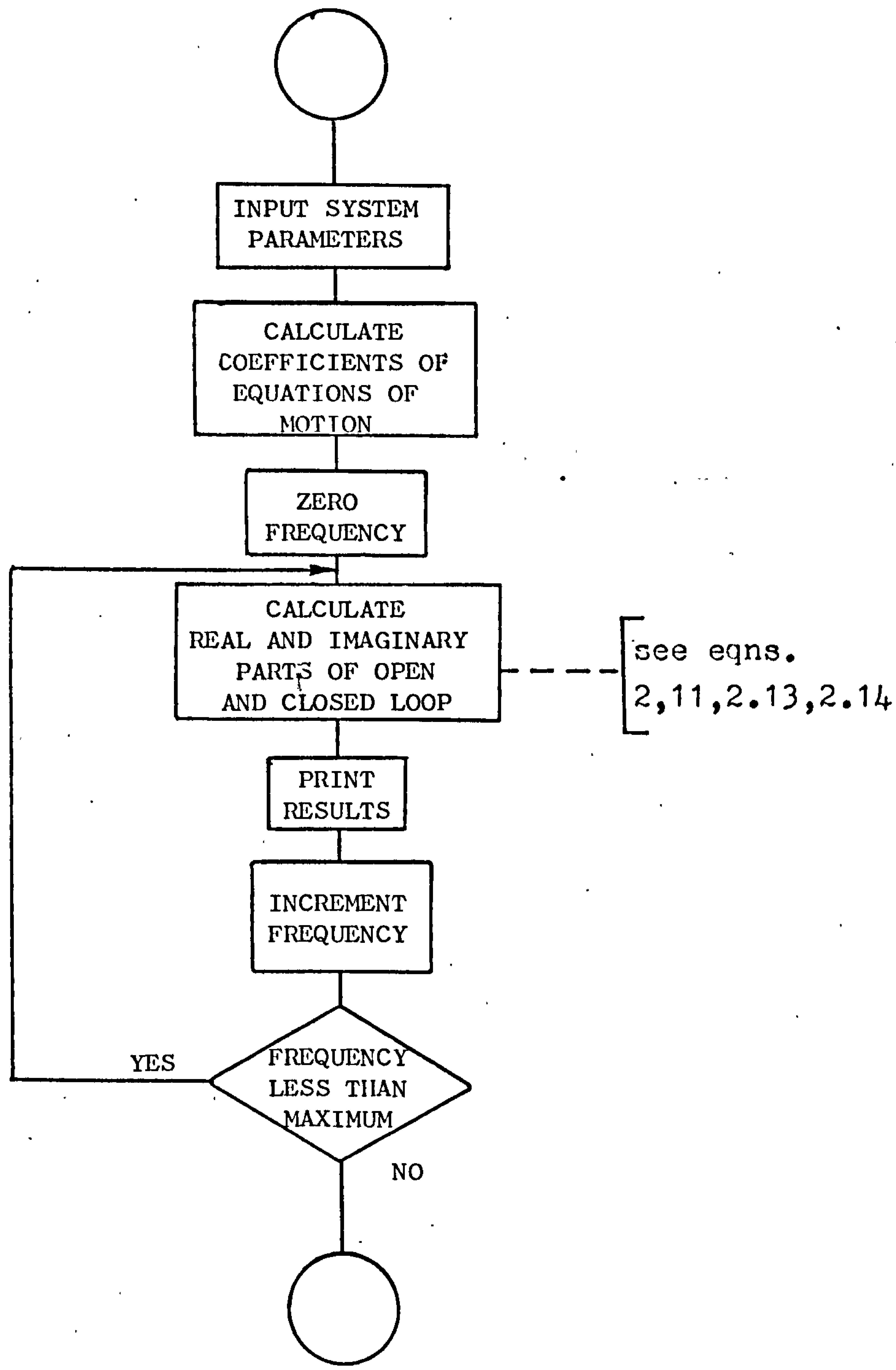
APPENDIX A.

Flowcharts and block diagrams for the computer programmes.

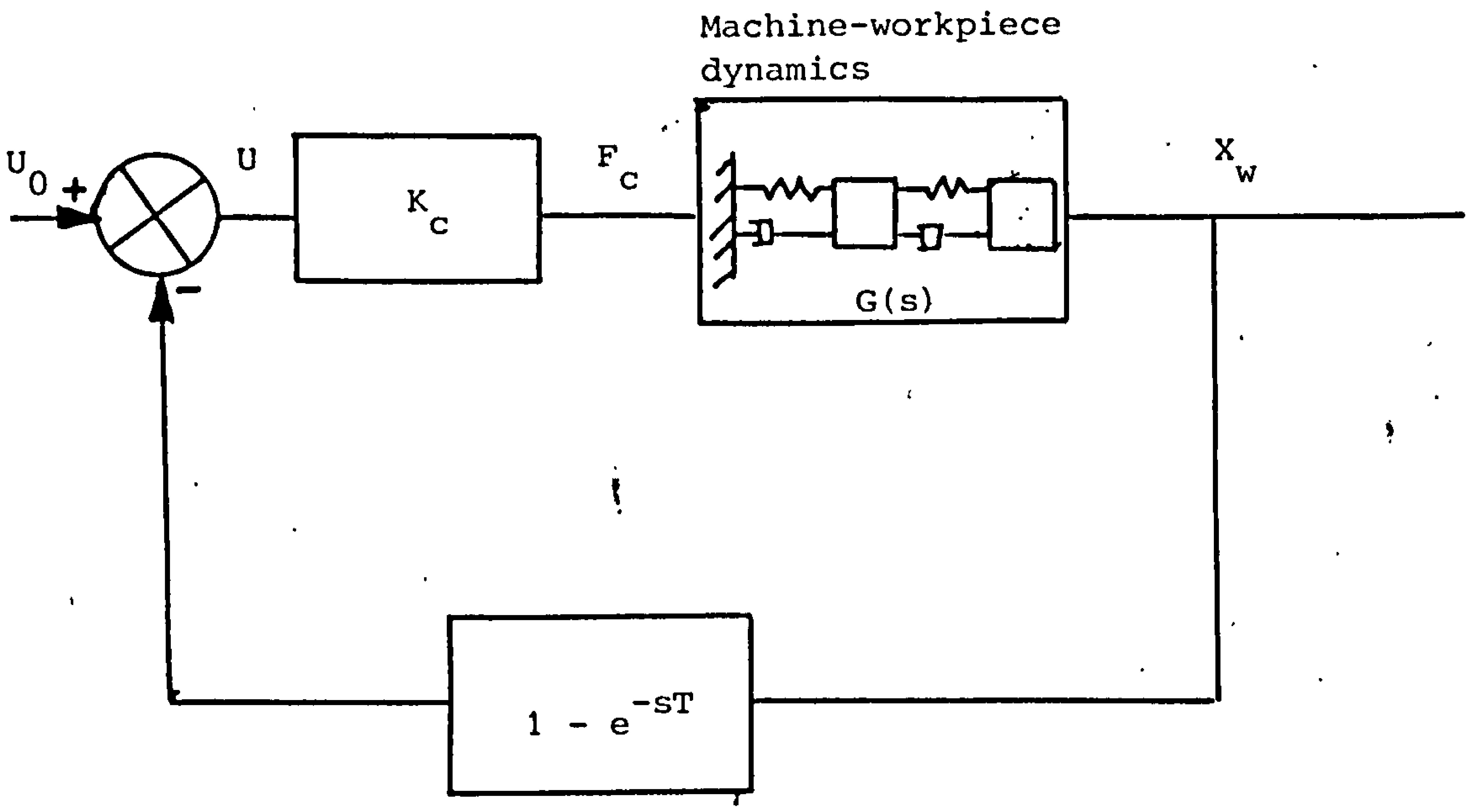
A. 1. Machine-workpiece frequency response.
A. 2. Open and closed loop frequency response of chatter model.
A. 3. Model used for chatter simulation.
A. 4. Dual-input describing function for idealised controller.
A. 5. Model used for chatter suppression simulation.
A. 6. C.N.C. turning.
A. 7. On-line identification programme.
A. 8. Active control of machine tool chatter.



A.1 Machine-workpiece frequency response

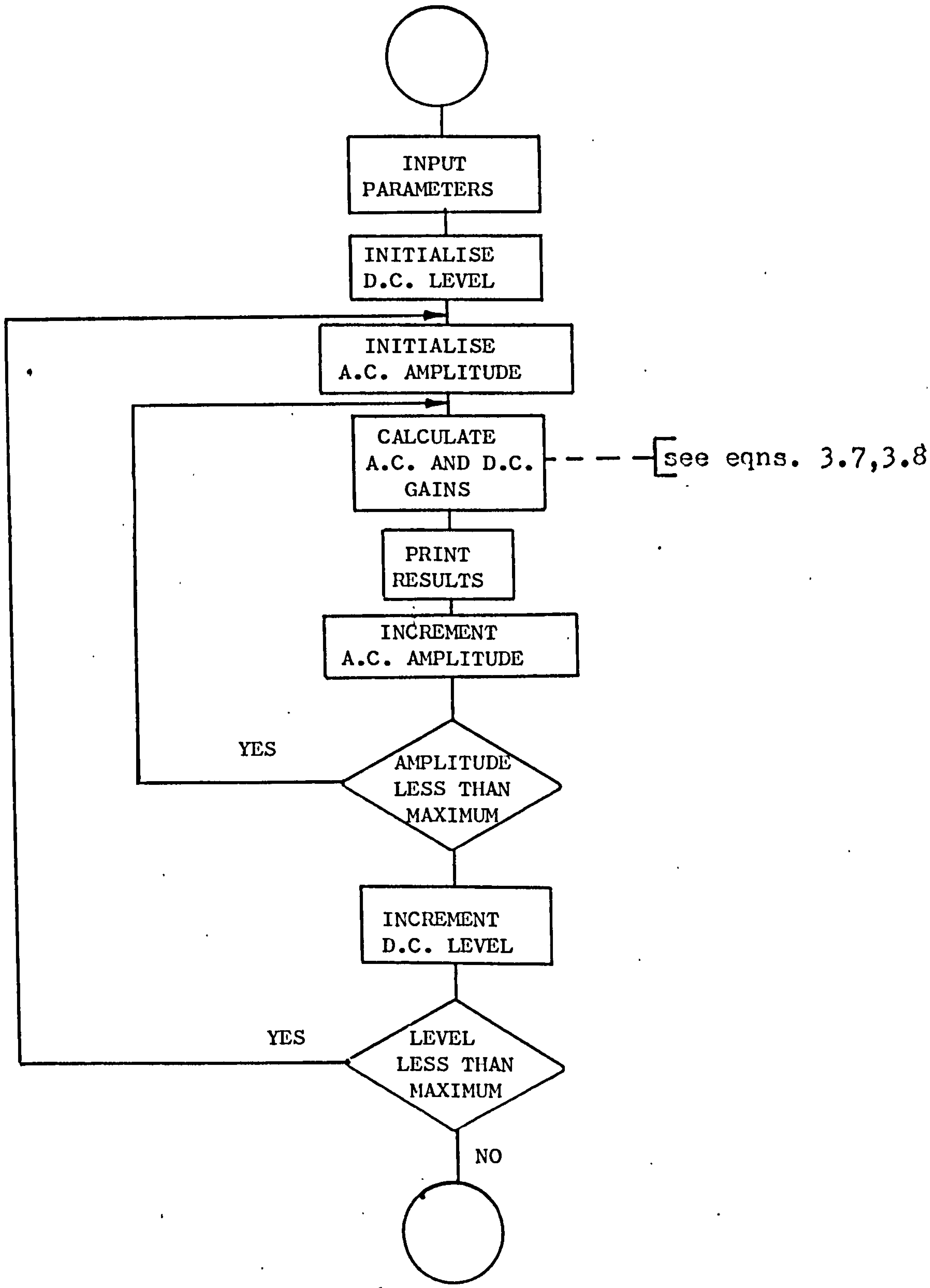


A.2 Open and closed loop frequency response of chatter model



See equation 2.5 for expression of G(S)

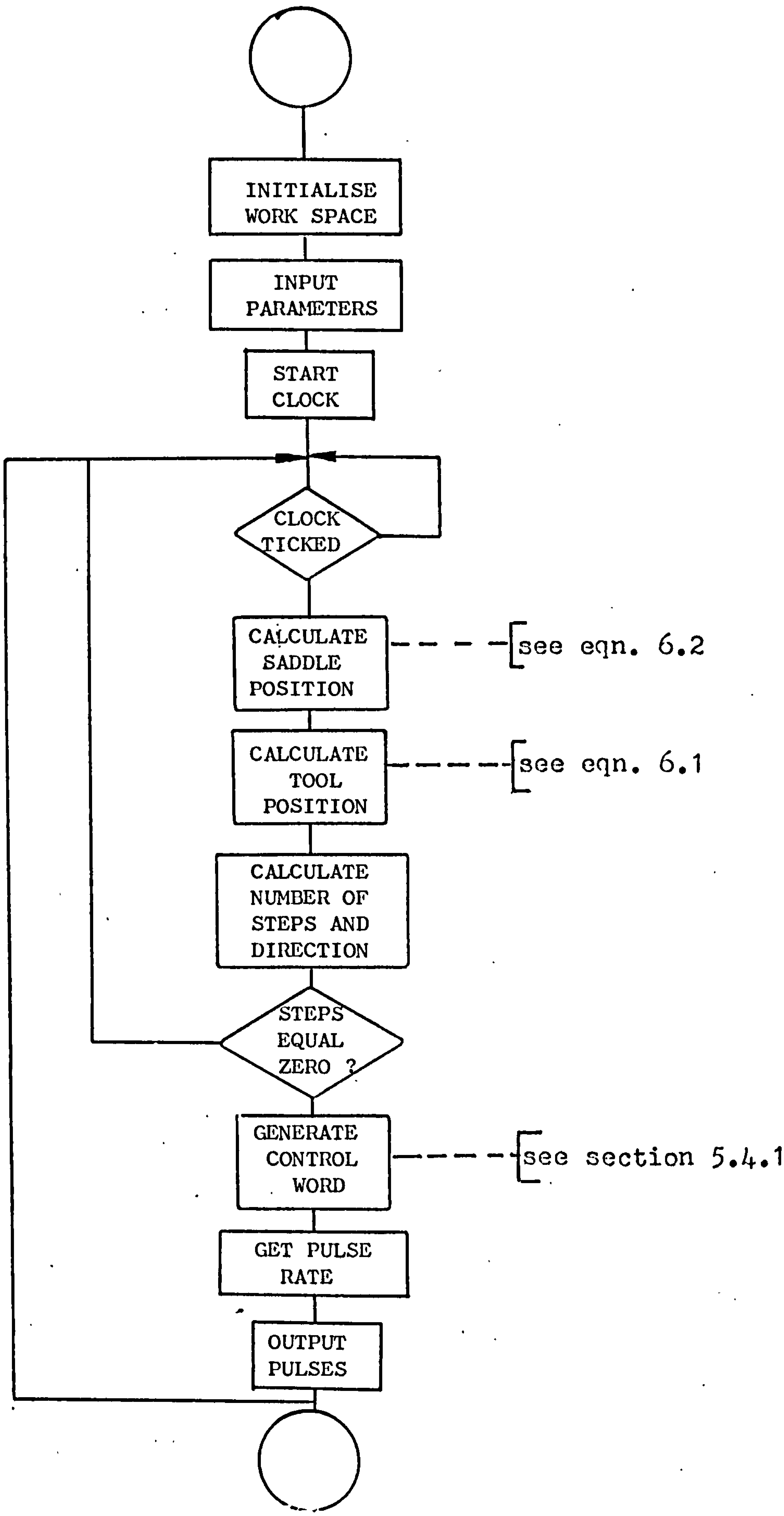
A.3 Model used for chatter simulation



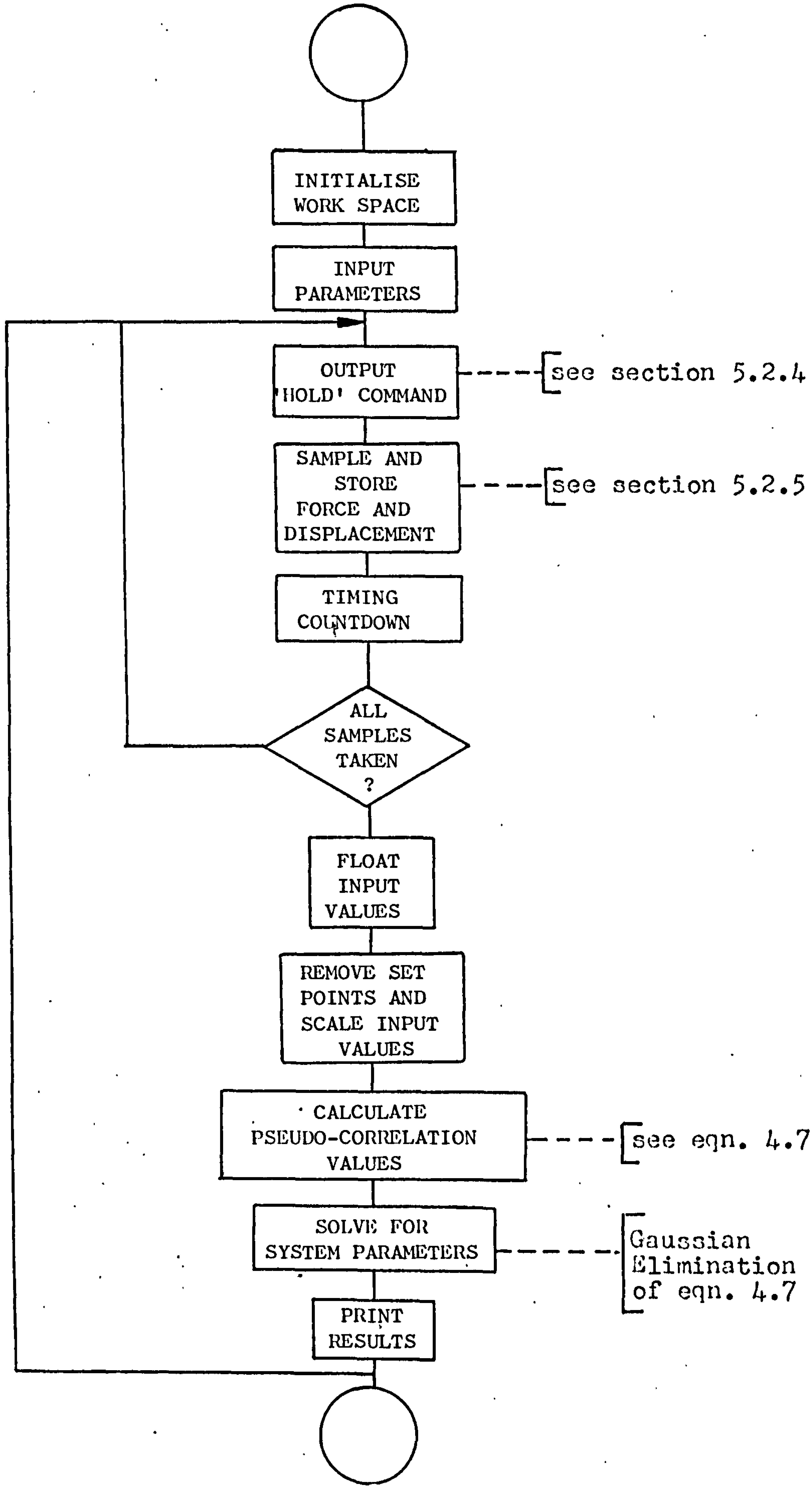
A.4 Dual input Describing function for idealised controller

See FIGS. 8.

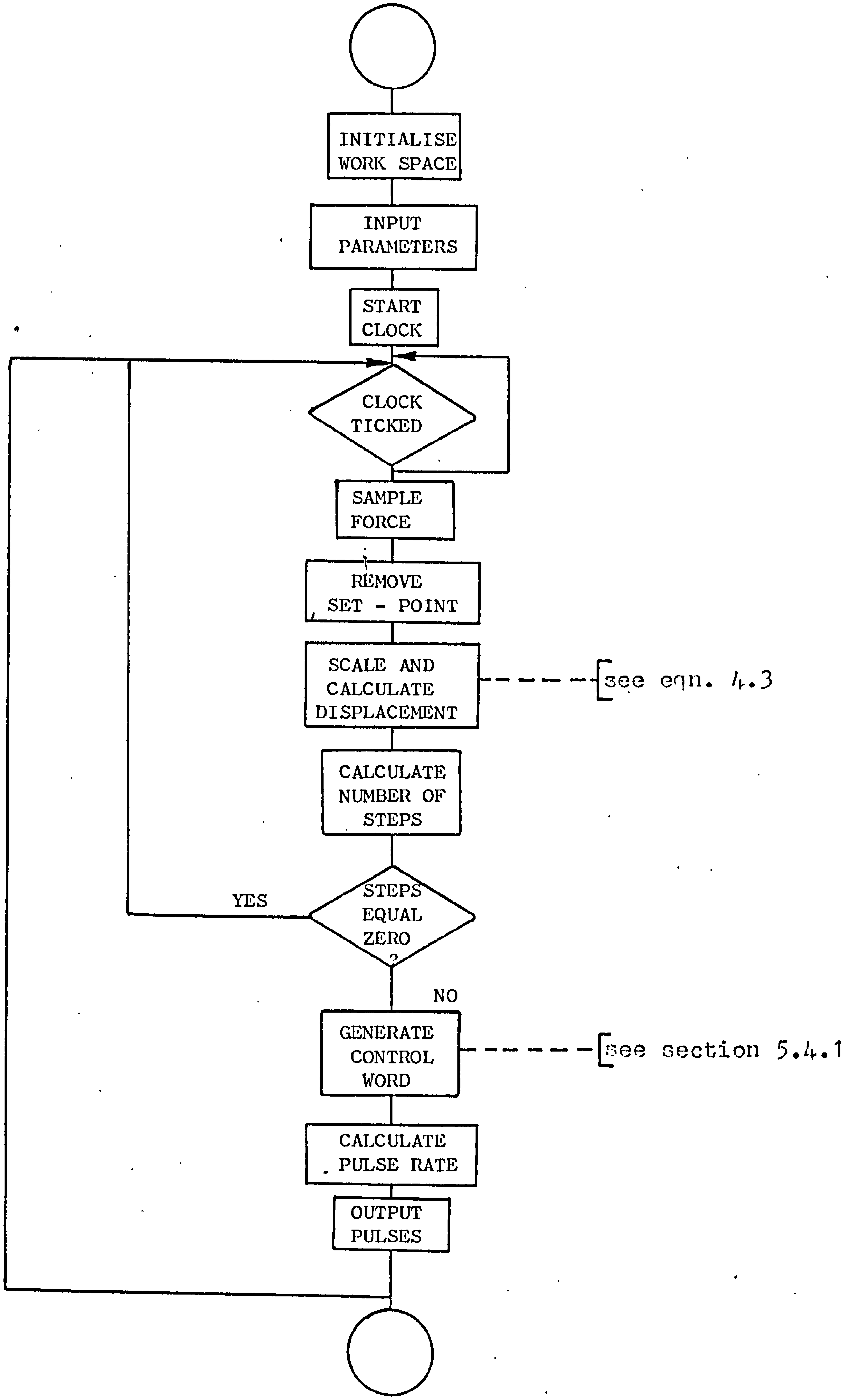
A.5 Model used for chatter suppression simulation



A.6 CNC turning



A.7 On-line identification



A.8 Active control of machine tool chatter

APPENDIX B.

Listings of computer programmes.

B. 1. Machine-workpiece frequency response (BASIC)
B. 2. Open and closed loop frequency response of chatter model (FORTRAN)
B. 3. Chatter simulation (C.S.M.P.)
B. 4. Dual-input describing function for idealised controller (FORTRAN)
B. 5. Chatter suppression simulation (C.S.M.P.)
B. 6. C.N.C. turning (ASSEMBLER)
B. 7. On-line identification programme (ASSEMBLER)
B. 8. Active control of machine tool chatter (ASSEMBLER)

PROGRAMME DESCRIPTION.

Purpose: To calculate the frequency reponse of the Machine-workpiece structure.

Language: Basic

Associated Equations: 2.5 and 2.6

Associated Figures: FIG 2.1

Inputs:

Name	Type	Comments
M_1	Floating point in Data statement	$\equiv M_M$
C_1	↓	$\equiv C_M$
K_1	↓	$\equiv K_M$
M_2	↓	$\equiv M_W$
C_2	↓	$\equiv C_W$
K_2	↓	$\equiv K_W$

Outputs:

Name	Type	Comments
F	Floating point	Frequency (rad/sec)
R	↓	Real part
I	↓	Imaginary part
G	↓	Gain
P	↓	Phase

B.1 Machine-workpiece frequency response.

```
100 READ M1,C1,K1
110 READ M2,C2,K2
120 DATA 0.03,0.1,120000
130 DATA 0.03,0.01,12000
140 LET A0=K1+K2
150 LET A1=C1+C2
160 LET A2=M1
170 LET B0=K1*K2
180 LET B1=C2*K1+K2*C1
190 LET B2=M2*K1+M2*K2+C2*C1+M1*K2
200 LET B3=M2*C1+M2*C2+M1*C2
210 LET B4=M1*M2
220 FOR W=0 TO 1000 STEP 1
230 LET X1=A0-A2*W*W
240 LET X2=A1*W
250 LET Y1=B4*(W↑4)-B2*W*W+B0
260 LET Y2=B1*W-B3*(W↑3)
270 LET R=(X1*Y1+X2*Y2)/(Y1*Y1+Y2*Y2)
280 LET I=(X2*Y1-X1*Y2)/(Y1*Y1+Y2*Y2)
290 LET G=SQR(R*R+I*I)
300 LET P=ATN(I/R)
310 PRINT W,R,I,G,P
320 NEXT W
330 STOP
340 END
```

PROGRAMME DESCRIPTION

Purpose: To calculate the open + closed loop frequency responses of the machining system.

Language: Fortran

Associated Equations: 2.5, 2.10, 2.11, 2.13 and 2.14

Associated Figures: FIG2.4

Inputs:

Name	Type	Comments
M_1	E5.3	As for B.1
C_1	E5.3	As for B.1
K_2	E8.1	As for B.1
M_2	E5.3	As for B.1
C_2	E5.3	As for B.1
K_2	E8.1	As for B.1
K	E5.1	As for B.1
T	E4.2	$\equiv K_c$
DELT	E4.2	Workpiece rotation period (secs)
		Frequency increment

Outputs:

Name	Type	Comments
W	F12.5	Frequency (rad/sec)
REOL	↓	Real part - open loop
IMOL	↓	Imaginary part - open loop
RECL	↓	Real part - closed loop
IMCL	↓	Imaginary part - closed loop
GAIN	↓	Gain - closed loop
PHASE	↓	Phase - closed loop

B.2 Open and closed loop frequency response of chatter model.

```
      REAL M1,M2,K1,K2,K,IMOL,IMCL
      READ(5,100)M1,C1,K1
      READ(5,100)M2,C2,K2
      READ(5,110)K,T,DELT
  100 FORMAT(2F5.3,F8.1)
  110 FORMAT(F5.1,2F4.2)
      WRITE(6,120)
  120 FORMAT(25X,9HOPEN LOOP,20X,1H:,35X,11HCLOSED LOOP)
      WRITE(6,121)
  121 FORMAT(8X,9HFREQUENCY,6X,2(1X,9HREAL PART,6X,14HIMAGINARY PART
     &,4X),4HGAIN,12X,5HPHASE)
      B0=K2*(K1+K2)-K2*K2
      B1=C2*(K1+K2)+K2*(C1+C2)-2.0*C2*K2
      B2=M2*(K1+K2)+C2*(C1+C2)+M1*K2-C2*C2
      B3=M2*(C1+C2)+M1*C2
      B4=M1*M2
      A0=K1+K2
      A1=C1+C2
      A2=M1
      DO 140 IW=0,2000,1
      W=IW*DELT
      E1=A0-A2*W*W
      E2=A1*W
      F1=B4*(W**4)-B2*W*W+B0
      F2=B1*W-B3*(W**3)
      X=E1*F1+E2*F2
      Y=E2*F1-E1*F2
      Z=F1*F1+F2*F2
      P=1.0-COS(W*T)
      Q=SIN(W*T)
      U=X*P-Y*Q
      V=Y*P+X*Q
      REOL=U*K/Z
      IMOL=V*K/Z
      S=(Z/K+U)**2+V**2
      RECL=(X*(Z/K+U)+Y*V)/S
      IMCL=(Y*(Z/K+U)-X*V)/S
      GAIN=SQRT(RECL**2+IMCL**2)
      PHASE=ATAN(IMCL/RECL)
      WRITE(6,130)W,REOL,IMOL,RECL,IMCL,GAIN,PHASE
  130 FORMAT(7(5X,F12.5))
  140 CONTINUE
      STOP
      END
```

PROGRAMME DESCRIPTION

Purpose: Digital simulation of the machining system – chatter model.

Language: C.S.M.P.

Associated Equations: —

Associated Figures: See A.3

Inputs:

Name	Type	Comments
K_c	Floating point : Parameter Blocks	$\equiv K_c$
T	↓	Workpiece rotation period
$U\phi$	↓	Normal depth of cut
P_1	↓	Parameters for random noise generator to modify K_c
P_2	↓	
P_3	↓	
M_1	↓	As for B.1
C_1	↓	
K_1	↓	
M_2	↓	
C_2	↓	
K_2	↓	

Outputs:

Name	Type	Comments
F	Plotted	$\equiv F_c$
X	↓	$\equiv X_M$
Y	↓	$\equiv X_\omega$

B.3 Chatter simulation.

```
TITLE CHATTER SIMULATION-SERIAL.
INITIAL
METHOD RKSFX
INCON   IC1=0.0,IC2=0.0,IC3=0.0,IC4=0.0
PARAM   KC=750.0,T=0.2,U0=0.02
PARAM   P1=1,P2=1.0,P3=0.2
PARAM   M1=0.03,C1=0.1,K1=120000
PARAM   M2=0.03,C2=0.01,K2=12000
DYNAMIC
        F=KC*U*GAUSS(P1,P2,P3)
        YDD=(F+C2*XD+K2*X-C2*YD-K2*Y)/M2
        YD=INTGRL(IC1,YDD)
        Y=INTGRL(IC2,YD)
        XDD=(C2*YD+K2*Y-(C1+C2)*XD-(K1+K2)*X)/M1
        XD=INTGRL(IC3,XDD)
        X=INTGRL(IC4,XD)
        U=U0-Y+DELAY(200,T,Y)
TIMER   DELT=0.0005,FINTIM=0.5,OUTDEL=0.001
PRTPLT F,X,Y
END
STOP
ENDJOB
```

PROGRAMME DESCRIPTION

Purpose: To calculate the D.I.D.F. for the simplified clatter suppressor.

Language: Fortran

Associated Equations: 3.7 and 3.8

Associated Figures: FIG 3.5

Inputs:

Name	Type	Comments
D	E12.5	} Quantiser parameters
H	↓	}
CA	↓	A increment
CB	↓	B increment

Outputs:

Name	Type	Comments
A	F12.5	AC amplitude
B	↓	DC level
NA	↓	AC gain
NB	↓	DC gain

B.4 Dual input describing function for idealised controller.

```
      REAL NA,NB
      READ(5,100)D,H,CA,CB
  100 FORMAT(4E12.5)
      WRITE(6,90)
   90 FORMAT(47H           A            B             NA             NB)
      DO 200 K=1,100
      A=CA*K
      DO 190 J=1,10
      B=CB*J
      NA=1.0
      NB=1.0
      DO 170 I=1,100
      RI=FLOAT(I)
      G1=(((2.0*RI-1.0)/2.0)*H+B)/A
      G2=(((2.0*RI-1.0)/2.0)*H-B)/A
      IF(ABS(G1).LE.1.0) GO TO 120
      Q1=0.0
      IF(G1.GT.1.0) GO TO 110
      P1=-0.5
      GO TO 130
  110 P1=0.5
      GO TO 130
  120 P1=ARSIN(G1)/3.1416
      Q1=SQRT(1.0-G1*G1)*2.0/3.1416
  130 IF(ABS(G2).LE.1.0) GO TO 150
      Q2=0.0
      IF(G2.GT.1.0) GO TO 140
      P2=-0.5
      GOTO 160
  140 P2=0.5
      GO TO 160
  150 P2=ARSIN(G2)/3.1416
      Q2=SQRT(1.0-G2*G2)*2.0/3.1416
  160 CONTINUE
      NB=NB-D/B*(P1-P2)
      NA=NA-D/A*(Q1+Q2)
  170 CONTINUE
      WRITE(6,180)A,B,NA,NB
  180 FORMAT(E12.5,1X,E12.5,1X,E12.5,1X,E12.5)
  190 CONTINUE
  200 CONTINUE
      STOP
      END
```

PROGRAMME DESCRIPTION

Purpose: Digital simulation of the machining system with the chatter suppressor

Language: C.S.M.P.

Associated Equations: —

Associated Figures: FIG 3.8

Inputs:

Name	Type	Comments
KC	Floating point in parameters block	As for B.3
T	↓	As for B.3
Uφ	↓	As for B.3
S	↓	$\equiv S_s$ - step size
P1	↓	As for B.3
P2	↓	As for B.3
P3	↓	As for B.3
M1, C1, K1	↓	As for B.1
M2, C2, K2	↓	As for B.1
K7	↓	Tool positioner dynamics
K8	↓	Tool positioner dynamics
M3	↓	Tool positioner dynamics

Outputs:

Name	Type	Comments
F	Plotted	$\equiv F_c$
X	↓	$\equiv X_M$
Y	↓	$\equiv X_\omega$
XP	↓	$\equiv X_p'$
XQ	↓	$\equiv X_c'$
XT	↓	$\equiv X_t'$
D	↓	$= X_\omega - X_t'$

B.5 Chatter suppression simulation.

```
      TITLE CHATTER SUPPRESSION
      INITIAL
      METHOD RKSFX
      INCON   IC1=0.0,IC2=0.0,IC3=0.0,IC4=0.0
      INCON   IC5=0.0,IC6=0.0,IC7=0.0,IC8=0.0
      PARAM   KC=2000.0,T=0.2,U0=0.02,S=0.00067
      PARAM   P1=1,P2=1.0,P3=0.2
      PARAM   M1=0.03,C1=0.1,K1=120000
      PARAM   M2=0.09,C2=0.01,K2=12000
      PARAM   K7=0.2,K8=750.0
      PARAM   M3=0.099
              K4=K2
              K6=SQRT(K2/M3)
              K5=C2/(2.0*M2*K6)
      DYNAMIC
              F=KC*U*GAUSS(P1,P2,P3)
              YDD=(F+C2*XD+K2*X-C2*YD-K2*Y)/M2
              YD=INTGRL(IC1,YDD)
              Y=INTGRL(IC2,YD)
              XDD=(C2*YD+K2*Y-(C1+C2)*XD-(K1+K2)*X)/M1
              XD=INTGRL(IC3,XDD)
              X=INTGRL(IC4,XD)
              U=U0-D+DELAY(200,T,D)
              XF=F*K6*K6/K4
              XP=CMPXPL(IC5,IC6,K5,K6,XF)
              XQ=QNTZR(S,XP)*K8*K8
              XT=CMPXPL(IC7,IC8,K7,K8,XQ)
              D=Y-XT
       TIMER   DELT=0.001,FINTIM=0.5,OUTDEL=0.002
       PRTPLT  F,X,Y,XP,XQ,XT,D
       END
       STOP
       ENDJOB
```

PROGRAMME DESCRIPTION

Purpose: To drive the tool positioner as a C.N.C. system

Language: Data General Assembler

Associated Equations: 6.2 and 6.3

Associated Figures: —

Inputs:

Name	Type	Comments
RPM	Floating point	Speed
FEED	↓	Feedrate
SF	↓	Scaling factor
DT	↓	Time increment
SS	↓	Step size
ZERO	↓	Ø.Ø

Outputs:

Name	Type	Comments

NB. (i) Needs subroutines PARAMS and EQUNS
PARAMS – inputs F.P. shape parameters
EQUNS – calculates the tool displacement for a given axial displacement

(ii) SF is a factor to maintain consistency of units in the calculation of axial displacement.

B.6 C.N.C turning.

```
      NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                              PAGE    1
 CARD     ERRORS   LOC    VALUE                   INPUT CARD
ORDINAL
 NO.
  1                      000000                 .LOC 0
  2               00000  000000                 0
  3               00001  024042                 INTER                   ;ADDRESS OF INTERRUPT ROUTINE
  4                      000007                 .LOC 7
  5               00007  027000                 27000                   ;ADDRESS OF WRITEABLE AREA
  6                      000040                 .LOC 40
  7               00040  024160                 GETC                    ;ADDRESSES OF I/O ROUTINES
  8               00041  024177                 PUTC                    ;
  9                      000044                 .LOC 44
 10               00044  026000         PARAM:26000                     ;ADDRESS OF S/R TO INPUT SHAPE PARAMETERS
 11               00045  026100         EQUNS:26100                     ;ADDRESS OF S/R TO GENERATE PROFILE
 12               00046  024024         REP:LOOP
 13                      024000                 .LOC 24000
 14               24000  102400                 SUB   0,0               ;CLEAR AC'S AND CARRY
 15               24001  126400                 SUB   1,1
 16               24002  152400                 SUB   2,2
 17               24003  176440                 SUBO  3,3
 18               24004  054544                 STA   3,PP              ;EMPTY WORKING STORAGE
 19               24005  006005                 FINI
 20               24006  006004                 FFTR
 21               24007  006044                 FJSR  @PARAM            ;INPUT SHAPE PARAMETERS
 22               24010  120000                 FDFC  0                 ;INPUT F.P.CONSTANTS
 23               24011  040514                 FSTA  0,RPM
 24               24012  120000                 FDFC  0
 25               24013  040514                 FSTA  0,FEED
 26               24014  120000                 FDFC  0
 27               24015  040514                 FSTA  0,SF
 28               24016  120000                 FDFC  0
 29               24017  040514                 FSTA  0,DT
 30               24020  120000                 FDFC  0
 31               24021  040514                 FSTA  0,SS
 32               24022  120000                 FDFC  0
 33               24023  040514                 FSTA  0,ZERO
 34               24024  020513         LOOP:   FLDA  0,ZERO            ;EMPTY F.P.WORKING STORAGE
 35               24025  040514                 FSTA  0,T
 36               24026  040515                 FSTA  0,X
 37               24027  040516                 FSTA  0,N
 38               24030  100000                 FEXT
 39               24031  063077                 HALT                    ;WAIT FOR 'CONTINUE'
 40               24032  060177                 INTEN
 41               24033  020524                 LDA   0,MASK
 42               24034  062077                 MSKO  0                 ;MASK ALL BUT CLOCK
 43               24035  020512                 LDA   0,TICK
 44               24036  061114                 DOAS  0,RTC             ;START CLOCK
 45               24037  000401         WAIT:   JMP   .+1               ;WAIT FOR CLOCK TO TICK
 46               24040  000777                 JMP   .-1
 47               24041  000777                 JMP   .-1
 48               24042  060114         INTER:  NIOS  RTC               ;CLOCK TICKED,RESTART CLOCK
 49               24043  060177                 INTEN                   ;RE-ENABLE INTERUPTS
 50               24044  006005                 FINI
 51               24045  006004                 FFTR
 52               24046  020473                 FLDA  0,T               ;CALCULATE SADDLE(X) POSITION
 53               24047  024464                 FLDA  1,DT
 54               24050  123000                 FADD  1,0
```

```
CARD      ERRORS   LOC     VALUE                  INPUT CARD
ORDINAL
NO.
 55                24051   040470            FSTA   0,T
 56                24052   024453            FLDA   1,RPM
 57                24053   120100            FMPY   1,0
 58                24054   024453            FLDA   1,FEED
 59                24055   120100            FMPY   1,0
 60                24056   024453            FLDA   1,SF
 61                24057   120100            FMPY   1,0
 62                24060   006045            FJSR   @FQUNS       ;CALCULATE TOOL(Y) POSITION
 63                24061   024454            FLDA   1,SS
 64                24062   120200            FDIV   1,0          ;CALCULATE NUMBER OF STEPS
 65                24063   040462            FSTA   0,N
 66                24064   074461            FFIX   N            ;FIX N
 67                24065   100000            FEXT
 68                24066   020460            LDA    0,NA
 69                24067   024461            LDA    1,PP
 70                24070   122400            SUB    1,0          ;CALCULATE NUMBER OF STEPS TO MOVE
 71                24071   101015            MOV#   0,0,SNR
 72                24072   000432            JMP    NOSTP        ;NO STEPS,WAIT FOR NEXT TICK
 73                24073   024456            LDA    1,FOR        ;GENERATE MOTOR CONTROL WORDS
 74                24074   030457            LDA    2,PLUS
 75                24075   101113            MOVL#  0,0,SNC
 76                24076   000406            JMP    .+6
 77                24077   126520            SUBZL  1,1
 78                24100   122400            SUB    1,0
 79                24101   100000            COM    0,0
 80                24102   024450            LDA    1,REV
 81                24103   030451            LDA    2,MINUS
 82                24104   040451            STA    0,STEPS
 83                24105   066176       OP:  DOBS   1,76         ;OUTPUT PULSES
 84                24106   060477            READS  0            ;READ PULSES RATE FROM SWITCHES
 85                24107   040447            STA    0,CNT
 86                24110   014446            DSZ    CNT
 87                24111   000777            JMP    .-1
 88                24112   060276            NIOC   76
 89                24113   060477            READS  0
 90                24114   040442            STA    0,CNT
 91                24115   014441            DSZ    CNT
 92                24116   000777            JMP    .-1
 93                24117   020431            LDA    0,PP
 94                24120   143000            ADD    2,0          ;UPDATE PRESENT POSITION
 95                24121   040427            STA    0,PP
 96                24122   014433            DSZ    STEPS
 97                24123   000762            JMP    OP
 98                24124   000713     NOSTP: JMP    WAIT         ;WAIT FOR NEXT TICK
 99                24125   000000     RPM:0
100                24126   000000     RPMA:0
101                24127   000000     FEED:0
102                24130   000000     FEEDA:0
103                24131   000000     SF:0
104                24132   000000     SFA:0
105                24133   000000     DT:0
106                24134   000000     DTA:0
107                24135   000000     SS:0
108                24136   000000     SSA:0
```

```
NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                PAGE    3
 CARD     ERRORS  LOC    VALUE               INPUT CARD
ORDINAL
 NO.
 109              24137  000000   ZERO:0
 110              24140  000000   ZEROA:0
 111              24141  000000   T:0
 112              24142  000000   TA:0
 113              24143  000000   X:0
 114              24144  000000   XA:0
 115              24145  000000   N:0
 116              24146  000000   NA:0
 117              24147  000001   TICK:1
 118              24150  000000   PP:0
 119              24151  120000   FOR:120000                   ;MOTOR CONTROL WORD-FORWARD
 120              24152  160000   REV:160000                   ;MOTOR CONTROL WORD-REVERSE
 121              24153  000001   PLUS:1
 122              24154  177777   MINUS:177777
 123              24155  000000   STEPS:0
 124              24156  000000   CNT:0
 125              24157  177773   MASK:177773
 126              24160  054431   GETC:    STA    3,SGET       ;S/R TO INPUT CHARACTER FROM TTY
 127              24161  060110            NIOS   TTI
 128              24162  063610            SKPDN  TTI
 129              24163  000777            JMP    .-1
 130              24164  060610            DIAC   0,TTI
 131              24165  034430            LDA    3,C177
 132              24166  163400            AND    3,0
 133              24167  004410            JSR    PUTC
 134              24170  034423            LDA    3,CR
 135              24171  116404            SUB    0,3,SZR
 136              24172  002417            JMP    @SGET
 137              24173  020421            LDA    0,LF
 138              24174  004403            JSR    PUTC
 139              24175  020416            LDA    0,CR
 140              24176  002413            JMP    @SGET
 141              24177  063511   PUTC:    SKPBZ  TTO          ;S/R TO OUTPUT CHARACTER TO TTY
 142              24200  000777            JMP    .-1
 143              24201  061111            DOAS   0,TTO
 144              24202  101004            MOV    0,0,SZR
 145              24203  001400            JMP    0,3
 146              24204  054406            STA    3,SPUT
 147              24205  020406            LDA    0,CR
 148              24206  004771            JSR    PUTC
 149              24207  102400            SUB    0,0
 150              24210  002402            JMP    @SPUT
 151              24211  000000   SGET:0
 152              24212  000000   SPUT:0
 153              24213  000015   CR:15
 154              24214  000012   LF:12
 155              24215  000177   C177:177
 156                     100000            .END
```

CROSS REFERENCE TABLE

NAME	LOC & TYPE	CARD ORDINAL NUMBER			
CNT	024156	85	86	90	91
CR	024213	134	139	147	
C177	024215	131			
DT	024133	29	53		
DTA	024134				
EQUNS	000045	62			
FEED	024127	25	58		
FEEDA	024130				
FOR	024151	73			
GETC	024160	7			
INTER	024042	3			
LF	024214	137			
LOOP	024024	12			
MASK	024157	41			
MINUS	024154	81			
N	024145	37	65	66	
NA	024146	68			
NOSTP	024124	72			
OP	024105	97			
PARAM	000044	21			
PLUS	024153	74			
PP	024150	18	69	93	95
PUTC	024177	8	133	138	148
REP	000046				
REV	024152	80			
RPM	024125	23	56		
RPMA	024126				
SF	024131	27	60		
SFA	024132				
SGET	024211	126	136	140	
SPUT	024212	146	150		
SS	024135	31	63		
SSA	024136				
STEPS	024155	82	96		
T	024141	35	52	55	
TA	024142				
TICK	024147	43			
WAIT	024037	98			
X	024143	36			
XA	024144				
ZERO	024137	33	34		
ZEROA	024140				

* ABSOLUTE ASSEMBLY

0 THERE WERE AT LEAST 0 ERRORS IN THIS ASSEMBLY

PROGRAMME DESCRIPTION

Purpose: On-line identification programme

Language: Data General Assembler

Associated Equations: 4.5, 4.6 (see ref. 36), 5.1 and 5.2

Associated Figures: —

Inputs:

Name	Type	Comments
ALPHA	Floating point	Weighting term = 1.ϕ
SP1	↓	} set points for displacement I/P's
SP2	↓	
SFϕ	↓	} Scaling factors for force + displacement I/P's
SF1	↓	
SF2	↓	
SQRT2	↓	√2 = 1.414
ZERO	↓	ϕ.ϕ

Outputs:

Name	Type	Comments
Y2	Floating point	≡ B2
Y1	↓	≡ B1
X2	↓	≡ A2
X1	↓	≡ A1

B.7 On-line identification programme.

```
NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                    PAGE    1
 CARD      ERRORS    LOC    VALUE                INPUT CARD
ORDINAL
 NO.
   1                        000007               .LOC 7
   2                00007   000270               270                    ;ADDRESS OF WRITEABLE AREA
   3                        000040               .LOC 40
   4                00040   001175               GETC                   ;
   5                00041   001214               PUTC                   ;ADDRESSES OF I/O ROUTINES
   6                        000044               .LOC 44
   7                00044   000517               CALC                   ;
   8                00045   000426               NEXT                   ;ADDRESSES OF PROGRAMME STEPS
   9                00046   000000      A11:0
  10                00047   000000      A11A:0
  11                00050   000000      A12:0
  12                00051   000000      A12A:0
  13                00052   000000      A13:0
  14                00053   000000      A13A:0
  15                00054   000000      A14:0
  16                00055   000000      A14A:0
  17                00056   000000      F1:0
  18                00057   000000      F1A:0
  19                00060   000000      A21:0
  20                00061   000000      A21A:0
  21                00062   000000      A22:0
  22                00063   000000      A22A:0
  23                00064   000000      A23:0
  24                00065   000000      A23A:0
  25                00066   000000      A24:0
  26                00067   000000      A24A:0
  27                00070   000000      F2:0
  28                00071   000000      F2A:0
  29                00072   000000      A31:0
  30                00073   000000      A31A:0
  31                00074   000000      A32:0
  32                00075   000000      A32A:0
  33                00076   000000      A33:0
  34                00077   000000      A33A:0
  35                00100   000000      A34:0
  36                00101   000000      A34A:0
  37                00102   000000      F3:0
  38                00103   000000      F3A:0
  39                00104   000000      A41:0
  40                00105   000000      A41A:0
  41                00106   000000      A42:0
  42                00107   000000      A42A:0
  43                00110   000000      A43:0
  44                00111   000000      A43A:0
  45                00112   000000      A44:0
  46                00113   000000      A44A:0
  47                00114   000000      F4:0
  48                00115   000000      F4A:0
  49                00116   000000      SQRT2:0
  50                00117   000000      SQRTB:0
  51                00120   000000      ALPHA:0
  52                00121   000000      ALPHB:0
  53                00122   000000      SP1:0
  54                00123   000000      SP1A:0
```

CARD ORDINAL NO.	ERRORS	LOC	VALUE	INPUT CARD
55		00124	000000	SP2:0
56		00125	000000	SP2A:0
57		00126	000000	SF0:0
58		00127	000000	SF0A:0
59		00130	000000	SF1:0
60		00131	000000	SF1A:0
61		00132	000000	SF2:0
62		00133	000000	SF2A:0
63		00134	000000	M1:0
64		00135	000000	M1A:0
65		00136	000000	C1X:0
66		00137	000000	C1XA:
67		00140	000000	C1:0
68		00141	000000	C1A:0
69		00142	000000	M2:0
70		00143	000000	M2A:0
71		00144	000000	C2X:0
72		00145	000000	C2XA:0
73		00146	000000	C2:0
74		00147	000000	C2A:0
75		00150	000000	M3:0
76		00151	000000	M3A:0
77		00152	000000	C3X:0
78		00153	000000	C3XA:0
79		00154	000000	C3:0
80		00155	000000	C3A:0
81		00156	000000	A22X:0
82		00157	000000	A22XA:0
83		00160	000000	A23X:0
84		00161	000000	A23XA:0
85		00162	000000	A24X:0
86		00163	000000	A24XA:0
87		00164	000000	F2X:0
88		00165	000000	F2XA:0
89		00166	000000	F3X:0
90		00167	000000	F3XA:0
91		00170	000000	A34X:0
92		00171	000000	A34XA:0
93		00172	000000	A33X:0
94		00173	000000	A33XA:0
95		00174	000000	A32X:0
96		00175	000000	A32XA:0
97		00176	000000	A42X:0
98		00177	000000	A42XA:0
99		00200	000000	A43X:0
100		00201	000000	A43XA:0
101		00202	000000	A44X:0
102		00203	000000	A44XA:0
103		00204	000000	F4X:0
104		00205	000000	F4XA:0
105		00206	000000	X1:0
106		00207	000000	X1A:0
107		00210	000000	X2:0
108		00211	000000	X2A:0

```
NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                  PAGE    3
 CARD     ERRORS   LOC    VALUE                 INPUT CARD
ORDINAL
 NO.
 109               00212  000000      Y1:0
 110               00213  000000      Y1A:0
 111               00214  000000      Y2:0
 112               00215  000000      Y2A:0
 113               00216  007610      ADST:7610                             ;START ADDRESS FOR SAMPLE STORAGE
 114               00217  000530      TIMER:530                             ;TIMING COUNT FOR SAMPLE INPUT(530 GIVES 1MSEC)
 115               00220  000000      CNTD:0
 116               00221  000000      CHAN:0
 117               00222  000250      SAMP1:250                             ;NUMBER OF SETS OF SAMPLES
 118               00223  000070      SAMP.33:70                            ;NUMBER OF GROUPS OF SETS(SAMP1/3)
 119               00224  000000      CNT1:0
 120               00225  000000      CNT.33:0
 121               00226  000011      NINE:11
 122               00227  000000      CNT:0
 123               00230  000000      CSL:0
 124               00231  000134      ADM1:M1                               ;ADDRESS OF START OF STORAGE FOR GROUPS
 125               00232  000000      ZERO:0
 126               00233  000000      ZEROA:0
 127               00234  000000      PNT:0
 128               00235  000003      THREE:3
 129               00236  000000      SGET:0
 130               00237  000000      SPUT:0
 131               00240  000000      SAVE:0
 132               00241  000007      C7:7
 133               00242  000177      C177:177
 134               00243  000015      CR:15
 135               00244  000012      LF:12
 136                      000400               .LOC 400
 137               00400  102400      START:   SUB    0,0                    ;CLEAR AC'S AND CARRY
 138               00401  126400               SUB    1,1
 139               00402  152400               SUB    2,2
 140               00403  176440               SUBO   3,3
 141               00404  006005               FINI
 142               00405  006004               FFTR
 143               00406  120000               FDFC   0                      ;INPUT F.P.CONSTANTS AND ZERO
 144               00407  040120               FSTA   0,ALPHA
 145               00410  120000               FDFC   0
 146               00411  040122               FSTA   0,SP1
 147               00412  120000               FDFC   0
 148               00413  040124               FSTA   0,SP2
 149               00414  120000               FDFC   0
 150               00415  040126               FSTA   0,SF0
 151               00416  120000               FDFC   0
 152               00417  040130               FSTA   0,SF1
 153               00420  120000               FDFC   0
 154               00421  040132               FSTA   0,SF2
 155               00422  120000               FDFC   0
 156               00423  040116               FSTA   0,SQRT2
 157               00424  120000               FDFC   0
 158               00425  040232               FSTA  0,ZERO
 159               00426  020232      NEXT:    FLDA  0,ZERO                   ;EMPTY WORKING STORAGE
 160               00427  040046               FSTA   0,A11
 161               00430  040050               FSTA   0,A12
 162               00431  040052               FSTA   0,A13
```

B-~~20~~ 21

```
      NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                   PAGE    4
 CARD     ERRORS   LOC    VALUE               INPUT CARD
ORDINAL
 NO.
 163               00432  040054              FSTA   0,A14
 164               00433  040056              FSTA   0,F1
 165               00434  040060              FSTA   0,A21
 166               00435  040062              FSTA   0,A22
 167               00436  040064              FSTA   0,A23
 168               00437  040066              FSTA   0,A24
 169               00440  040070              FSTA   0,F2
 170               00441  040072              FSTA   0,A31
 171               00442  040074              FSTA   0,A32
 172               00443  040076              FSTA   0,A33
 173               00444  040100              FSTA   0,A34
 174               00445  040102              FSTA   0,F3
 175               00446  040104              FSTA   0,A41
 176               00447  040106              FSTA   0,A42
 177               00450  040110              FSTA   0,A43
 178               00451  040112              FSTA   0,A44
 179               00452  040114              FSTA   0,F4
 180               00453  100000              FEXT
 181               00454  020216     INPUT:   LDA    0,ADST         ;INITIALISE PROGRAMME CONTROL WORDS
 182               00455  040230              STA    0,CSL
 183               00456  020217              LDA    0,TIMER
 184               00457  040220              STA    0,CNTD
 185               00460  020222              LDA    0,SAMP1
 186               00461  040224              STA    0,CNT1
 187               00462  020244              LDA    0,LF           ;LINE FEED TO TTY
 188               00463  063511              SKPBZ  TTO
 189               00464  000777              JMP    .-1
 190               00465  061111              DOAS   0,TTO
 191               00466  020235     LOOP:    LDA    0,THREE
 192               00467  040221              STA    0,CHAN
 193               00470  102440              SUBO   0,0
 194               00471  061076              DOA    0,76           ;OUTPUT HOLD COMMAND TO S/H
 195               00472  024221     IP:      LDA    1,CHAN         ;INPUT SAMPLES FROM ADCV
 196               00473  065121              DOAS   1,ADCV
 197               00474  063621              SKPDN  ADCV
 198               00475  000777              JMP    .-1
 199               00476  066621              DICC   1,ADCV
 200               00477  046230              STA    1,@CSL
 201               00500  010230              ISZ    CSL
 202               00501  014221              DSZ    CHAN
 203               00502  000770              JMP    IP
 204               00503  102520              SUBZL  0,0
 205               00504  061076              DOA    0,76           ;OUTPUT SAMPLE COMMAND TO S/H
 206               00505  014220              DSZ    CNTD           ;TIMING COUNT-WAIT UNTIL NEXT SAMPLES DUE
 207               00506  000777              JMP    .-1
 208               00507  020217              LDA    0,TIMER
 209               00510  040220              STA    0,CNTD
 210               00511  014224              DSZ    CNT1
 211               00512  000754              JMP    LOOP
 212               00513  034223              LDA    3,SAMP.33
 213               00514  054225              STA    3,CNT.33
 214               00515  034216              LDA    3,ADST
 215               00516  054234              STA    3,PNT
 216               00517  034226     CALC:    LDA    3,NINE
```

B-2T 22

```
CARD     ERRORS  LOC    VALUF               INPUT CARD
ORDINAL
NO.
217              00520  054227              STA   3,CNT
218              00521  034231              LDA   3,ADM1
219              00522  102440    FLOAT:    SUBO  0,0          ;PREPARE SAMPLES FOR FLOATING
220              00523  026234              LDA   1,@PNT
221              00524  125112              MOVL# 1,1,SZC
222              00525  100000              COM   0,0
223              00526  041400              STA   0,0,3
224              00527  045401              STA   1,1,3
225              00530  175400              INC   3,3
226              00531  175400              INC   3,3
227              00532  010234              ISZ   PNT
228              00533  014227              DSZ   CNT
229              00534  000766              JMP   FLOAT
230              00535  006005              FINI
231              00536  006004              FFTP
232              00537  064235              FLD3   THREE
233              00540  070227              FST3   CNT
234              00541  064231              FLD3   ADM1
235              00542  070230              FST3   CSL
236              00543  062230    SCALE:    FFLO   @CSL         ;FLOAT,REMOVE SET POINT,AND SCALE
237              00544  022230              FLDA   0,@CSL
238              00545  024126              FLDA   1,SF0
239              00546  120100              FMPY   1,0
240              00547  042230              FSTA   0,@CSL
241              00550  010230              FISZ   CSL
242              00551  010230              FISZ   CSL
243              00552  062230              FFLO   @CSL
244              00553  022230              FLDA   0,@CSL
245              00554  024122              FLDA   1,SP1
246              00555  122400              FSUB   1,0
247              00556  024130              FLDA   1,SF1
248              00557  104100              FMPY   0,1
249              00560  010230              FISZ   CSL
250              00561  010230              FISZ   CSL
251              00562  062230              FFLO   @CSL
252              00563  022230              FLDA   0,@CSL
253              00564  030124              FLDA   2,SP2
254              00565  142400              FSUB   2,0
255              00566  030132              FLDA   2,SF2
256              00567  140100              FMPY   2,0
257              00570  123000              FADD   1,0
258              00571  024116              FLDA   1,SQRT2
259              00572  120200              FDIV   1,0
260              00573  042230              FSTA   0,@CSL
261              00574  010230              FISZ   CSL
262              00575  010230              FISZ   CSL
263              00576  014227              FDSZ   CNT
264              00577  000744              FJMP   SCALE
265              00600  034120    UPDATE:   FLDA   3,ALPHA
266              00601  020046              FLDA   0,A11        ;UPDATE A11
267              00602  160100              FMPY   3,0
268              00603  024142              FLDA   1,M2
269              00604  030142              FLDA   2,M2
270              00605  144100              FMPY   2,1
```

```
 CARD     ERRORS   LOC    VALUE              INPUT CARD
ORDINAL
 NO.
 271               00606  123000             FADD  1,0
 272               00607  040046             FSTA  0,A11    ;
 273               00610  020050             FLDA  0,A12    ;UPDATE A12 & A21
 274               00611  160100             FMPY  3,0
 275               00612  024134             FLDA  1,M1
 276               00613  144100             FMPY  2,1
 277               00614  123000             FADD  1,0
 278               00615  040050             FSTA  0,A12    ;
 279               00616  040060             FSTA  0,A21    ;
 280               00617  020052             FLDA  0,A13    ;UPDATE A13 & A31
 281               00620  160100             FMPY  3,0
 282               00621  024146             FLDA  1,C2
 283               00622  144100             FMPY  2,1
 284               00623  124400             FNEG  1,1
 285               00624  123000             FADD  1,0
 286               00625  040052             FSTA  0,A13    ;
 287               00626  040072             FSTA  0,A31    ;
 288               00627  020054             FLDA  0,A14    ;UPDATE A14 & A41
 289               00630  160100             FMPY  3,0
 290               00631  024140             FLDA  1,C1
 291               00632  130100             FMPY  1,2
 292               00633  150400             FNEG  2,2
 293               00634  143000             FADD  2,0
 294               00635  040054             FSTA  0,A14    ;
 295               00636  040104             FSTA  0,A41    ;
 296               00637  020066             FLDA  0,A24    ;UPDATE A24 & A42
 297               00640  160100             FMPY  3,0
 298               00641  030134             FLDA  2,M1
 299               00642  144100             FMPY  2,1
 300               00643  124400             FNEG  1,1
 301               00644  123000             FADD  1,0
 302               00645  040066             FSTA  0,A24    ;
 303               00646  040106             FSTA  0,A42    ;
 304               00647  020062             FLDA  0,A22    ;UPDATE A22
 305               00650  160100             FMPY  3,0
 306               00651  024134             FLDA  1,M1
 307               00652  144100             FMPY  2,1
 308               00653  123000             FADD  1,0
 309               00654  040062             FSTA  0,A22    ;
 310               00655  020064             FLDA  0,A23    ;UPDATE A23 & A32
 311               00656  160100             FMPY  3,0
 312               00657  024146             FLDA  1,C2
 313               00660  130100             FMPY  1,2
 314               00661  150400             FNEG  2,2
 315               00662  143000             FADD  2,0
 316               00663  040064             FSTA  0,A23    ;
 317               00664  040074             FSTA  0,A32    ;
 318               00665  020076             FLDA  0,A33    ;UPDATE A33
 319               00666  160100             FMPY  3,0
 320               00667  030146             FLDA  2,C2
 321               00670  130100             FMPY  1,2
 322               00671  143000             FADD  2,0
 323               00672  040076             FSTA  0,A33    ;
 324               00673  020100             FLDA  0,A34    ;UPDATE A34 & A43
```

```
 CARD      ERRORS   LOC     VALUE                 INPUT CARD
ORDINAL
 NO.
 325               00674   160100           FMPY   3,0
 326               00675   030140           FLDA   2,C1
 327               00676   144100           FMPY   2,1
 328               00677   123000           FADD   1,0
 329               00700   040100           FSTA   0,A34        ;
 330               00701   040110           FSTA   0,A43        ;
 331               00702   020112           FLDA   0,A44        ;UPDATE A44
 332               00703   160100           FMPY   3,0
 333               00704   024140           FLDA   1,C1
 334               00705   144100           FMPY   2,1
 335               00706   123000           FADD   1,0
 336               00707   040112           FSTA   0,A44        ;
 337               00710   020114           FLDA   0,F4         ;UPDATE F4
 338               00711   160100           FMPY   3,0
 339               00712   024154           FLDA   1,C3
 340               00713   130100           FMPY   1,2
 341               00714   150400           FNEG   2,2
 342               00715   143000           FADD   2,0
 343               00716   040114           FSTA   0,F4         ;
 344               00717   020070           FLDA   0,F2         ;UPDATE F2
 345               00720   160100           FMPY   3,0
 346               00721   030134           FLDA   2,M1
 347               00722   130100           FMPY   1,2
 348               00723   143000           FADD   2,0
 349               00724   040070           FSTA   0,F2         ;
 350               00725   020102           FLDA   0,F3         ;UPDATE F3
 351               00726   160100           FMPY   3,0
 352               00727   030146           FLDA   2,C2
 353               00730   130100           FMPY   1,2
 354               00731   150400           FNEG   2,2
 355               00732   143000           FADD   2,0
 356               00733   040102           FSTA   0,F3         ;
 357               00734   020056           FLDA   0,F1         ;UPDATE F1
 358               00735   160100           FMPY   3,0
 359               00736   030142           FLDA   2,M2
 360               00737   130100           FMPY   1,2
 361               00740   143000           FADD   2,0
 362               00741   040056           FSTA   0,F1         ;
 363               00742   100000           FEXT
 364               00743   014225           DSZ    CNT.33
 365               00744   002044           JMP    @44
 366               00745   006005   GAUSEL: FINI                ;SOLVE FOR PARAMETERS USING GAUSSIAN ELIMATION
 367               00746   006004           FFTR
 368               00747   034046           FLDA   3,A11        ;FORM A11/A21
 369               00750   020060           FLDA   0,A21
 370               00751   114200           FDIV   0,3          ;
 371               00752   020062           FLDA   0,A22        ;FORM A22'
 372               00753   160100           FMPY   3,0
 373               00754   024050           FLDA   1,A12
 374               00755   122400           FSUB   1,0
 375               00756   040156           FSTA   0,A22X       ;
 376               00757   020064           FLDA   0,A23        ;FORM A23'
 377               00760   160100           FMPY   3,0
 378               00761   024052           FLDA   1,A13
```

```
      NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                          PAGE    8
 CARD     ERRORS   LOC    VALUE             INPUT CARD
ORDINAL
 NO.
 379               00762   122400           FSUB   1,0
 380               00763   040160           FSTA   0,A23X      ;
 381               00764   020066           FLDA   0,A24       ;FORM A24'
 382               00765   160100           FMPY   3,0
 383               00766   024054           FLDA   1,A14
 384               00767   122400           FSUB   1,0
 385               00770   040162           FSTA   0,A24X      ;
 386               00771   020070           FLDA   0,F2        ;FORM F2'
 387               00772   160100           FMPY   3,0
 388               00773   030056           FLDA   2,F1
 389               00774   142400           FSUB   2,0
 390               00775   040164           FSTA   0,F2X       ;
 391               00776   034046           FLDA   3,A11       ;FORM A11/A31
 392               00777   020072           FLDA   0,A31
 393               01000   114200           FDIV   0,3         ;
 394               01001   020102           FLDA   0,F3        ;FORM F3'
 395               01002   160100           FMPY   3,0
 396               01003   142400           FSUB   2,0
 397               01004   040166           FSTA   0,F3X       ;
 398               01005   020100           FLDA   0,A34       ;FORM A34'
 399               01006   160100           FMPY   3,0
 400               01007   122400           FSUB   1,0
 401               01010   040170           FSTA   0,A34X      ;
 402               01011   020076           FLDA   0,A33       ;FORM A33'
 403               01012   160100           FMPY   3,0
 404               01013   024052           FLDA   1,A13
 405               01014   122400           FSUB   1,0
 406               01015   040172           FSTA   0,A33X      ;
 407               01016   020074           FLDA   0,A32       ;FORM A32'
 408               01017   160100           FMPY   3,0
 409               01020   030050           FLDA   2,A12
 410               01021   142400           FSUB   2,0
 411               01022   040174           FSTA   0,A32X      ;
 412               01023   034046           FLDA   3,A11       ;FORM A11/A41
 413               01024   020104           FLDA   0,A41
 414               01025   114200           FDIV   0,3         ;
 415               01026   020106           FLDA   0,A42       ;FORM A42'
 416               01027   160100           FMPY   3,0
 417               01030   142400           FSUB   2,0
 418               01031   040176           FSTA   0,A42X      ;
 419               01032   020110           FLDA   0,A43       ;FORM A43'
 420               01033   160100           FMPY   3,0
 421               01034   122400           FSUB   1,0
 422               01035   040200           FSTA   0,A43X      ;
 423               01036   020112           FLDA   0,A44       ;FORM A44'
 424               01037   160100           FMPY   3,0
 425               01040   024054           FLDA   1,A14
 426               01041   122400           FSUB   1,0
 427               01042   040202           FSTA   0,A44X      ;
 428               01043   020114           FLDA   0,F4        ;FORM F4'
 429               01044   160100           FMPY   3,0
 430               01045   024056           FLDA   1,F1
 431               01046   122400           FSUB   1,0
 432               01047   040204           FSTA   0,F4X       ;
```

```
      NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                PAGE    9
CARD        ERRORS   LOC     VALUE                INPUT CARD
ORDINAL
 NO.
 433                 01050   034156               FLDA   3,A22X       ;FORM A22/A32
 434                 01051   020174               FLDA   0,A32X
 435                 01052   114200               FDIV   0,3          ;
 436                 01053   020172               FLDA   0,A33X       ;FORM A33''
 437                 01054   160100               FMPY   3,0
 438                 01055   024160               FLDA   1,A23X
 439                 01056   122400               FSUB   1,0
 440                 01057   040172               FSTA   0,A33X       ;
 441                 01060   020170               FLDA   0,A34X       ;FORM A34''
 442                 01061   160100               FMPY   3,0
 443                 01062   024162               FLDA   1,A24X
 444                 01063   122400               FSUB   1,0
 445                 01064   040170               FSTA   0,A34X       ;
 446                 01065   020166               FLDA   0,F3X        ;FORM F3''
 447                 01066   160100               FMPY   3,0
 448                 01067   030164               FLDA   2,F2X
 449                 01070   142400               FSUB   2,0
 450                 01071   040166               FSTA   0,F3X        ;
 451                 01072   034156               FLDA   3,A22X       ;FORM A22/A42
 452                 01073   020176               FLDA   0,A42X
 453                 01074   114200               FDIV   0,3          ;
 454                 01075   020204               FLDA   0,F4X        ;FORM F4''
 455                 01076   160100               FMPY   3,0
 456                 01077   142400               FSUB   2,0
 457                 01100   040204               FSTA   0,F4X        ;
 458                 01101   020202               FLDA   0,A44X       ;FORM A44''
 459                 01102   160100               FMPY   3,0
 460                 01103   122400               FSUB   1,0
 461                 01104   040202               FSTA   0,A44X       ;
 462                 01105   020200               FLDA   0,A43X       ;FORM A43''
 463                 01106   160100               FMPY   3,0
 464                 01107   024160               FLDA   1,A23X
 465                 01110   122400               FSUB   1,0
 466                 01111   040200               FSTA   0,A43X       ;
 467                 01112   034172               FLDA   3,A33X       ;FORM A33/A43
 468                 01113   020200               FLDA   0,A43X
 469                 01114   114200               FDIV   0,3          ;
 470                 01115   020202               FLDA   0,A44X       ;FORM A44'''
 471                 01116   160100               FMPY   3,0
 472                 01117   024170               FLDA   1,A34X
 473                 01120   122400               FSUB   1,0
 474                 01121   040202               FSTA   0,A44X       ;
 475                 01122   030204               FLDA   2,F4X        ;FORM F4'''
 476                 01123   170100               FMPY   3,2
 477                 01124   024166               FLDA   1,F3X
 478                 01125   132400               FSUB   1,2
 479                 01126   050204               FSTA   2,F4X        ;
 480                 01127   110200               FDIV   0,2          ;Y2=F4'''/A44'''
 481                 01130   050214               FSTA   2,Y2
 482                 01131   150000               FFDC   2            ;OUTPUT Y2
 483                 01132   020170               FLDA   0,A34X
 484                 01133   140100               FMPY   2,0          ;Y2*A34''
 485                 01134   024166               FLDA   1,F3X
 486                 01135   106400               FSUB   0,1          ;F3''-Y2*A34''
```

```
      NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                           PAGE   10
 CARD     ERRORS   LOC    VALUE               INPUT CARD
ORDINAL
 NO.
 487               01136  034172              FLDA   3,A33X
 488               01137  164200              FDIV   3,1          ;Y1=(F3''-Y2*A34'')/A33''
 489               01140  044212              FSTA   1,Y1
 490               01141  144000              FFDC   1            ;OUTPUT Y1
 491               01142  034162              FLDA   3,A24X
 492               01143  154100              FMPY   2,3          ;Y2*A24'
 493               01144  020164              FLDA   0,F2X
 494               01145  162400              FSUB   3,0          ;F2'-Y2*A24'
 495               01146  034160              FLDA   3,A23X
 496               01147  134100              FMPY   1,3          ;Y1*A23'
 497               01150  162400              FSUB   3,0          ;F2'-Y2*A24'-Y1*A23'
 498               01151  034156              FLDA   3,A22X
 499               01152  160200              FDIV   3,0          ;X2=(F2'-Y2*A24'-Y1*A23')/A22'
 500               01153  040210              FSTA   0,X2
 501               01154  140000              FFDC   0            ;OUTPUT X2
 502               01155  034054              FLDA   3,A14
 503               01156  170100              FMPY   3,2          ;Y2*A14
 504               01157  034052              FLDA   3,A13
 505               01160  164100              FMPY   3,1          ;Y1*A13
 506               01161  034050              FLDA   3,A12
 507               01162  160100              FMPY   3,0          ;X2*A12
 508               01163  034056              FLDA   3,F1
 509               01164  116400              FSUB   0,3          ;F1-X2*A12
 510               01165  136400              FSUB   1,3          ;F1-X2*A12-Y1*A13
 511               01166  156400              FSUB   2,3          ;F1-X2*A12-Y1*A13-Y2*A14
 512               01167  020046              FLDA   0,A11
 513               01170  114200              FDIV   0,3          ;X1=(F1-X2*A12-Y1*A13-Y2*A14)/A11
 514               01171  054206              FSTA   3,X1
 515               01172  154000              FFDC   3            ;OUTPUT X1
 516               01173  002045              FJMP   @45          ;REPEAT PROGRAMME,GO TO NEXT
 517               01174  100000              FEXT
 518               01175  054236      GETC:   STA    3,SGET       ;S/R TO INPUT CHARACTER FROM TTY
 519               01176  060110              NIOS   TTI
 520               01177  063610              SKPDN  TTI
 521               01200  000777              JMP    .-1
 522               01201  060610              DIAC   0,TTI
 523               01202  034242              LDA    3,C177
 524               01203  163400              AND    3,0
 525               01204  004410              JSR    PUTC
 526               01205  034243              LDA    3,CR
 527               01206  116404              SUB    0,3,SZR
 528               01207  002236              JMP    @SGET
 529               01210  020244              LDA    0,LF
 530               01211  004403              JSR    PUTC
 531               01212  020243              LDA    0,CR
 532               01213  002236              JMP    @SGET
 533               01214  063511      PUTC:   SKPBZ  TTO          ;S/R TO OUTPUT CHARACTER TO TTY
 534               01215  000777              JMP    .-1
 535               01216  061111              DOAS   0,TTO
 536               01217  101004              MOV    0,0,SZR
 537               01220  001400              JMP    0,3
 538               01221  054237              STA    3,SPUT
 539               01222  020243              LDA    0,CR
 540               01223  004771              JSR    PUTC
```

```
CARD     ERRORS  LOC    VALUE             INPUT CARD
ORDINAL
 NO.
 541             01224  020244            LDA   0,LF
 542             01225  004767            JSR   PUTC
 543             01226  102400            SUB    0,0
 544             01227  002237            JMP    @SPUT
 545             01230  054240   OCTBN:   STA   3,SAVE
 546             01231  126400            SUB   1,1
 547             01232  004743   OCTL:    JSR   GETC
 548             01233  034243            LDA   3,CR
 549             01234  116415            SUB#  0,3,SNR
 550             01235  002240            JMP   @SAVE
 551             01236  034241            LDA   3,C7
 552             01237  163400            AND   3,0
 553             01240  127120            ADDZL 1,1
 554             01241  125120            MOVZL 1,1
 555             01242  107000            ADD   0,1
 556             01243  000767            JMP   OCTL
 557                    100000            .END
```

CROSS REFERENCE TABLE

NAME	LOC & TYPE	CARD ORDINAL NUMBER						
ADM1	000231	218	234					
ADST	000216	181	214					
ALPHA	000120	144	265					
ALPHB	000121							
A11	000046	160	266	272	368	391	412	512
A11A	000047							
A12	000050	161	273	278	373	409	506	
A12A	000051							
A13	000052	162	280	286	378	404	504	
A13A	000053							
A14	000054	163	288	294	383	425	502	
A14A	000055							
A21	000060	165	279	369				
A21A	000061							
A22	000062	166	304	309	371			
A22A	000063							
A22X	000156	375	433	451	498			
A22XA	000157							
A23	000064	167	310	316	376			
A23A	000065							
A23X	000160	380	438	464	495			
A23XA	000161							
A24	000066	168	296	302	381			
A24A	000067							
A24X	000162	385	443	491				
A24XA	000163							
A31	000072	170	287	392				
A31A	000073							
A32	000074	171	317	407				
A32A	000075							
A32X	000174	411	434					
A32XA	000175							
A33	000076	172	318	323	402			
A33A	000077							
A33X	000172	406	436	440	467	487		
A33XA	000173							
A34	000100	173	324	329	398			
A34A	000101							
A34X	000170	401	441	445	472	483		
A34XA	000171							
A41	000104	175	295	413				
A41A	000105							
A42	000106	176	303	415				
A42A	000107							
A42X	000176	418	452					
A42XA	000177							
A43	000110	177	330	419				
A43A	000111							
A43X	000200	422	462	466	468			
A43XA	000201							
A44	000112	178	331	336	[illegible]			
A44A	000113							
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
[illegible]	[illegible]							

```
CNT     000227     217  228  233  263
CNTD    000220     184  206  209
CNT.3   000225     213  364
CNT1    000224     186  210
CR      000243     526  531  539  548
CSL     000230     182  200  201  235  236  237  240  241  242  243  244  249  250  251
                   252  260  261  262
C1      000140     290  326  333
C1A     000141
C1X     000136
C1XA    000137
C177    000242     523
C2      000146     282  312  320  352
C2A     000147
C2X     000144
C2XA    000145
C3      000154     339
C3A     000155
C3X     000152
C3XA    000153
C7      000241     551
FLOAT   000522     229
F1      000056     164  357  362  388  430  508
F1A     000057
F2      000070     169  344  349  386
F2A     000071
F2X     000164     390  448  493
F2XA    000165
F3      000102     174  350  356  394
F3A     000103
F3X     000166     397  446  450  477  485
F3XA    000167
F4      000114     179  337  343  428
F4A     000115
F4X     000204     432  454  457  475  479
F4XA    000205
GAUSE   000745
GETC    001175       4  547
INPUT   000454
IP      000472     203
LF      000244     187  529  541
LOOP    000466     211
M1      000134     124  275  298  306  346
M1A     000135
M2      000142     268  269  359
M2A     000143
M3      000150
M3A     000151
NEXT    000426       8
NINE    000226     216
OCTBN   001230
OCTL    001232     556
PNT     000234     215  220  227
PUTC    001214       5  525  530  540  542
SAMP.   000223     212
SAMP1   000222     185
SAVE    000240     545  550
SCALE   000543     264
SFO     000126     150  238
SFOA    000127
```

```
SF1     000130          152   247
SF1A    000131
SF2     000132          154   255
SF2A    000133
SGET    000236          518   528   532
SPUT    000237          538   544
SP1     000122          146   245
SP1A    000123
SP2     000124          148   253
SP2A    000125
SQRTB   000117
SQRT2   000116          156   258
START   000400
THREE   000235          191   232
TIMER   000217          183   208
UPDAT   000600
X1      000206          514
X1A     000207
X2      000210          500
X2A     000211
Y1      000212          489
Y1A     000213
Y2      000214          481
Y2A     000215
ZERO    000232          158   159
ZEROA   000233
      * ABSOLUTE ASSEMBLY
0 THERE WERE AT LEAST    0 ERRORS IN THIS ASSEMBLY
```

PROGRAMME DESCRIPTION

Purpose: To sample the cutting force, predict the workpiece displacement, and control the tool position.

Language: Data General Assembler

Associated Equations: 8.2 and 5.3

Associated Figures: FIG1.5, FIG3.8 and FIG7.33

Inputs:

Name	Type	Comments
SP	Integer	Set point = Ø.Ø
K	↓	Scaled step size (S_s)
IA1	↓	Scaled A1
IA2	↓	Scaled A2
IB1	↓	Scaled B1
IB2	↓	Scaled B2
TICK	↓	Clock frequency
TIMER	↓	Step timer

Outputs:

Name	Type	Comments

NB. IA1, IA2, IB1, IB2 and K are the set of lowest integer values such that:-

$$\frac{IA1}{K} = \frac{A1}{S_s} ; \frac{IA2}{K} = \frac{A2}{S_s} ; \frac{IB1}{K} = \frac{B1}{S_s} ; \frac{IB2}{K} = \frac{B2}{S_s}$$

B.8 Active control of machine tool chatter.

```
    NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                PAGE    1
 CARD      ERRORS    LOC    VALUE              INPUT CARD
ORDINAL
 NO.
   1                       000200              .LOC 200
   2                00200  000000       N:0
   3                00201  000000       PP:0
   4                00202  000000       N1:0
   5                00203  000225       ADST:SP
   6                00204  000000       PNT:0
   7                00205  000177       C177:177
   8                00206  000015       CR:15
   9                00207  000052       C52:52
  10                00210  000007       C7:7
  11                00211  000012       LF:12
  12                00212  000004       CHAN:4
  13                00213  000000       R1:0
  14                00214  000000       R2:0
  15                00215  016000       REV:16000                        ;MOTOR CONTROL WORD-REVERSED
  16                00216  177777       MINUS:177777
  17                00217  012000       FOR:12000                        ;MOTOR CONTROLWORD-FORWARDD
  18                00220  000001       PLUS:1
  19                00221  000000       CNT:0
  20                00222  000000       SAVE:0
  21                00223  000000       STEPS:0
  22                00224  000000       SIGN:0
  23                00225  000000       SP:0
  24                00226  000000       K:0
  25                00227  000000       IA1:0
  26                00230  000000       IB1:0
  27                00231  000000       IB2:
  28                00232  000000       TICK:0                           ;CLOCK FREQUENCY CONTROL WORD
  29                00233  000000       TIMER:0
  30                       000400              .LOC 400
  31                00400  102440       START:  SUBO    0,0              ;CLEAR ACO AND CARRY
  32                00401  040200               STA     0,N              ;EMPTY WORKING STORAGE
  33                00402  040201               STA     0,PP
  34                00403  040202               STA     0,N1
  35                00404  020203               LDA     0,ADST
  36                00405  040204               STA     0,PNT
  37                00406  126440       DATA:   SUBO    1,1
  38                00407  060110       NEXT:   NIOS    TTI              ;INPUT CONSTANTS
  39                00410  063610               SKPDN   TTI
  40                00411  000777               JMP     .-1
  41                00412  060610               DIAC    0,TTI
  42                00413  030205               LDA     2,C177
  43                00414  143400               AND     2,0
  44                00415  063511               SKPBZ   TTO
  45                00416  000777               JMP     .-1
  46                00417  061111               DOAS    0,TTO
  47                00420  030206               LDA     2,CR
  48                00421  112405               SUB     0,2,SNR
  49                00422  000412               JMP     LAST
  50                00423  030207               LDA     2,C52
  51                00424  112405               SUB     0,2,SNR
  52                00425  000416               JMP     CLK
  53                00426  030210               LDA     2,C7
  54                00427  143400               AND     2,0
```

```
CARD     ERRORS   LOC     VALUE              INPUT CARD
ORDINAL
NO.
 55               00430   127120             ADDZL   1,1
 56               00431   125120             MOVZL   1,1
 57               00432   107000             ADD     0,1
 58               00433   000754             JMP     NEXT
 59               00434   030211   LAST:     LDA     2,LF
 60               00435   063511             SKPBZ   TTO
 61               00436   000777             JMP     .-1
 62               00437   071111             DOAS    2,TTO
 63               00440   046204             STA     1,@PNT
 64               00441   010204             ISZ     PNT
 65               00442   000744             JMP     DATA
 66               00443   020232   CLK:      LDA     0,TICK      ;START CLOCK
 67               00444   061114             DOAS    0,RTC
 68               00445   063614   WAIT:     SKPDN   RTC         ;WAIT FOR CLOCK TO TICK
 69               00446   000402             JMP     .+2
 70               00447   063077             HALT
 71               00450   063614             SKPDN   RTC
 72               00451   000777             JMP     .-1
 73               00452   060114             NIOS    RTC         ;CLOCK TICKS,RESTART
 74               00453   020212             LDA     0,CHAN
 75               00454   061121             DOAS    0,ADCV      ;START ADCV
 76               00455   063621             SKPDN   ADCV
 77               00456   000777             JMP     .-1
 78               00457   062621             DICC    0,ADCV      ;INPUT FORCE
 79               00460   024225             LDA     1,SP
 80               00461   132400             SUB     1,2         ;REMOVE SET POINT
 81               00462   024227             LDA     1,IA1
 82               00463   004531             JSR     SGTT
 83               00464   102440             SUBO    0,0
 84               00465   073301             MUL
 85               00466   030224             LDA     2,SIGN
 86               00467   151015             MOV#    2,2,SNR
 87               00470   000404             JMP     POS1
 88               00471   152520             SUBZL   2,2
 89               00472   147000             ADD     2,1
 90               00473   124000             COM     1,1
 91               00474   044213   POS1:     STA     1,R1        ;R1=IA1*FORCE
 92               00475   024230             LDA     1,IB1
 93               00476   030200             LDA     2,N
 94               00477   004515             JSR     SGTT
 95               00500   102440             SUBO    0,0
 96               00501   030224             LDA     2,SIGN
 97               00502   151015             MOV#    2,2,SNR
 98               00503   000404             JMP     POS2
 99               00504   152520             SUBZL   2,2
100               00505   147000             ADD     2,1
101               00506   124000             COM     1,1
102               00507   044214   POS2:     STA     1,R2        ;R2=IB1*N
103               00510   024231             LDA     1,IB2
104               00511   030202             LDA     2,N1
105               00512   004502             JSR     SGTT
106               00513   102440             SUBO    0,0
107               00514   073301             MUL
108               00515   030224             LDA     2,SIGN
```

```
NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                    PAGE    3
 CARD     ERRORS   LOC     VALUE                 INPUT CARD
ORDINAL
 NO.
 109               00516   151015                MOV#    2,2,SNR
 110               00517   000404                JMP     POS3
 111               00520   152520                SUBZL   2,2
 112               00521   147000                ADD     2,1
 113               00522   124000                COM     1,1
 114               00523   020213       POS3:    LDA     0,R1
 115               00524   122400                SUB     1,0
 116               00525   024214                LDA     1,R2
 117               00526   122400                SUB     1,0               ;IA1*FORCE-IB1*N-IB2*N1
 118               00527   105000                MOV     0,1
 119               00530   030226                LDA     2,K
 120               00531   004463                JSR     SGTT
 121               00532   102440                SUBO    0,0
 122               00533   C73101                DIV                       ;N=(IA1*FORCE-IB1*N-IB2*N1)/K
 123               00534   030224                LDA     2,SIGN
 124               00535   151005                MOV     2,2,SNR
 125               00536   000406                JMP     POS4
 126               00537   152520                SUBZL   2,2
 127               00540   147000                ADD     2,1
 128               00541   124000                COM     1,1
 129               00542   030200                LDA     2,N
 130               00543   050202                STA     2,N1
 131               00544   044200       POS4:    STA     1,N               ;CALCULATE NUMBER OF STEPS TO MOVE
 132               00545   101112                MOVL#   0,0,SZC
 133               00546   010200                ISZ     N
 134               00547   030200                LDA     2,N
 135               00550   024201                LDA     1,PP
 136               00551   132400                SUB     1,2
 137               00552   151015                MOV#    2,2,SNR
 138               00553   000440                JMP     NOSTP             ;NO STEPS,WAIT FOT NEXT TICK
 139               00554   151113                MOVL#   2,2,SNC
 140               00555   000413                JMP     POS
 141               00556   126520                SUBZL   1,1
 142               00557   132400                SUB     1,2
 143               00560   150000                COM     2,2
 144               00561   050223                STA     2,STEPS
 145               00562   024233                LDA     1,TIMER
 146               00563   102440                SUBO    0,0
 147               00564   073101                DIV                       ;CALCULATE PULSE RATE AND DIRECTION
 148               00565   030215                LDA     2,REV
 149               00566   034216                LDA     3,MINUS
 150               00567   000407                JMP     LOOP
 151               00570   050223       POS:     STA     2,STEPS
 152               00571   024233                LDA     1,TIMER
 153               00572   102440                SUBO    0,0
 154               00573   073101                DIV
 155               00574   030217                LDA     2,FOR
 156               00575   034220                LDA     3,PLUS
 157               00576   072176       LOOP:    DOBS    2,76              ;OUTPUT PULSES
 158               00577   044221                STA     1,CNT
 159               00600   014221                DSZ     CNT
 160               00601   000777                JMP     .-1
 161               00602   060276                NIOC    76
 162               00603   044221                STA     1,CNT
```

```
     NOVA/SUPERNOVA ASSEMBLER VERSION 1.04                                        PAGE    4
 CARD      ERRORS   LOC    VALUE                  INPUT CARD
ORDINAL
 NO.
 163                00604   014221                DSZ    CNT
 164                00605   000777                JMP    .-1
 165                00606   020201                LDA    0,PP
 166                00607   163000                ADD    3,0
 167                00610   040201                STA    0,PP
 168                00611   014223                DSZ    STEPS
 169                00612   000764                JMP    LOOP
 170                00613   000632       NOSTP:   JMP    WAIT           ;FINISHED,WAIT FOR NEXT TICK
 171                00614   054222       SGTT:    STA    3,SAVE         ;S/R TO GENERATE SIGN OF A PRODUCT
 172                00615   102440                SUBO   0,0
 173                00616   125113                MOVL#  1,1,SNC
 174                00617   000405                JMP    .+5
 175                00620   100000                COM    0,0
 176                00621   176520                SUBZL  3,3
 177                00622   166400                SUB    3,1
 178                00623   124000                COM    1,1
 179                00624   151133                MOVZL# 2,2,SNC
 180                00625   000405                JMP    .+5
 181                00626   100000                COM    0,0
 182                00627   176520                SUBZL  3,3
 183                00630   166400                SUB    3,1
 184                00631   124000                COM    1,1
 185                00632   040224                STA    0,SIGN
 186                00633   034222                LDA    3,SAVE
 187                00634   001400                JMP    0,3
 188                        100000                .END
```

CROSS REFFRENCE TABLE

NAME	LOC & TYPE	CARD ORDINAL NUMBER					
ADST	000203	35					
CHAN	000212	74					
CLK	000443	52					
CNT	000221	158	159	162	163		
CR	000206	47					
C177	000205	42					
C52	000207	50					
C7	000210	53					
DATA	000406	65					
FOR	000217	155					
IA1	000227	81					
IB1	000230	92					
IB2	000231	103					
K	000226	119					
LAST	000434	49					
LF	000211	59					
LOOP	000576	150	169				
MINUS	000216	149					
N	000200	32	93	129	131	133	134
NEXT	000407	58					
NOSTP	000613	138					
N1	000202	34	104	130			
PLUS	000220	156					
PNT	000204	36	63	64			
POS	000570	140					
POS1	000474	87					
POS2	000507	98					
POS3	000523	110					
POS4	000544	125					
PP	000201	33	135	165	167		
REV	000215	148					
R1	000213	91	114				
R2	000214	102	116				
SAVE	000222	171	186				
SGTT	000614	82	94	105	120		
SIGN	000224	85	96	108	123	185	
SP	000225	5	79				
START	000400						
STEPS	000223	144	151	168			
TICK	000232	66					
TIMER	000233	145	152				
WAIT	000445	170					

* ABSOLUTE ASSEMBLY

0 THERE WERE AT LEAST 0 ERRORS IN THIS ASSEMBLY