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TRANSLATION

MECHANIZATION AND AUTOMATION OF MACHINE (MACHINE TOOL) CONTROL

By

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Chapter 3

MECHANIZATION AND AUTOMATION OF MACHINE (MACHINE TOOL) CONTROL

11. CLASSIFICATION AND PROGRAMS OF CONTROL SYSTEMS

Control automation should provide for the proper regime of the technological process.

The control systems of machines (machine tools) are of two types: rigid (open) and automatic (closed-loop) control.

Thus, a control using cams mounted on camshafts is designed on the basis of a rigid system. In this system, the sequence and nature of the signals, which are independent of the actual value of the controlled quantity, are predetermined. The sequence and nature of movement in a cam system are determined by the configuration and arrangement of the cams on the camshafts. In a rigid control system, noncorrespondence of a motion to that which has been specified may be caused by errors in fabrication and alignment of the cams or by defects in the intermediate elements and supports. In rigid systems, the control circuit is not closed; therefore, they are also termed "systems of open control." In these systems, the setting unit is, so to speak, the guardian of the program. The follow-up units of the machine carry out the necessary movements by means of a transmitting unit.

The automatic-control systems that are systems of closed control are included in the second type. Using these systems, the values of the preset parameters of the automatic process are maintained or varied in accordance with a set program, according to which the actual

position of the follow-up unit of the machine tool also varies continuously or periodically. When the actual position of the follow-up unit deviates from that assigned by the program, the measuring unit will transmit a pulse through a feedback circuit, with the result that the deviation of the actual value from that assigned is, as far as possible, eliminated.

Command signals in the automatic systems may be transmitted in succession as a function of elapsed time or completion of the phases in the process.

In the former case, the systems are known as "time-base" systems. Each component of the entire technological cycle is accomplished in a certain time, which is established by preliminary calculations. This time is recorded by counters that give the command signals at the required moments.

In the latter case, the systems are termed "reflex" systems. In such systems, the command signals are given on completion of each preceding activity, while the latter is evaluated as a function of load, dimensions, or other factors.

There are automatic systems in which the two systems under consideration are combined. In these systems, some of the elementary mechanisms are controlled according to the principle of the time-base systems, while the rest are controlled on the principle of technological completeness. This is a mixed automatic control system.

The sensors and intermediate mechanisms in the automatic control systems may be set up at the same place (centralized control) or they may be distributed among various parts of the machine (decentralized control).

Production machines operate on the basis of certain programs which provide for a series of movements that are executed in a set se-

quence. The programs are of two types: coded programs, which are applied mainly in closed-loop automatic control systems, and uncoded programs, which are used in both rigid and closed-loop automatic control systems.

The coded programs are set up in the following manner. An origin of coordinates is marked on a diagram of the component, generally outside the periphery of the component. The configuration of the component is characterized by reference points which are arranged on the machined surface. Having established the origin of coordinates, we establish the coordinates for each reference point. The running coordinates, which are dependent upon time or one upon the other, describe the surface configuration of the component between adjacent reference points. The coordinates and the nature of the surface between the reference points are entered on a program in code.

In an automatic control system, there is usually a setting unit and a servomechanism. The control signals, which are fed into the servomechanism are formed in the setting unit. The purpose of the latter is to compare assignment with execution and, where there is a disparity, to supply control signals to the follow-up unit directly or through an intermediate unit.

Figure 34 shows a block diagram of an automatic control. The program 2, the decoder 1 and the computing unit 3 are incorporated in the setting unit. The decoder receives the program continuously or periodically; scanning the program, it sends signals to the computing unit. The computing unit calculates ~~the coordinates of the intermediate~~ points in accordance with the coordinates of the reference points and the equation of the lines that connect them. In conformity with the time increment of each coordinate, which is established by the computing unit, impulses produced by the generator 5 are fed into the

comparing unit 6 of the servosystem with the aid of the distributor 4. Feedback signals are generated in the measuring unit 8, which continuously measures the actual displacement. These signals also go to the comparison unit. The comparison unit delivers signals to the follow-up

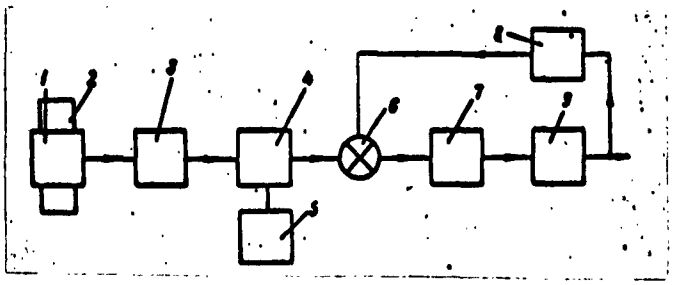

Fig. 34. Block diagram of automatic control.

unit 9 by way of the intermediate units 7 so that the actual movement will not deviate from that specified.

The work program is an important element in an automatic control system. The program may be recorded on a punched card, magnetic tape, motion-picture film or other material. The punched program is entered on a tape or card which is prepared (in cases where electromechanical scanning apparatus are used) from a material with a low electric conductivity and sufficiently high strength. Such materials are paper, fiber and plastics. In cases where photoelectric sensors are used, the tapes or cards should be opaque. Motion-picture film and paper meet this condition.

The motion program of the machine's follow-up units is entered on the tape or card in coded form. To compile such a program, it is necessary to elaborate the production process, ascertain the required movements of the follow-up units and represent them in the form of numbers. The numbers are usually divided into two groups: those that establish the direction of each movement and its length from the configuration of the machined surface and those that establish the machining

patterns, i.e., the velocities of the idle and working movements.

The type of machine and the control system determine what numbers should be entered in the program. Figure 35 shows what numbers should be entered on a punched card or tape for the control system of a milling machine where it is necessary to machine the contour of the curve 3 depicted in Fig. 35a. In the machining process, the center of the milling cutter 1 should theoretically move along the trajectory 2. In actuality, however, the curvilinear trajectory of the milling cutter center will be a broken line passing through the bearing points 1, 2, 3 and so forth (Fig. 35b). Each section of this line is straight, and

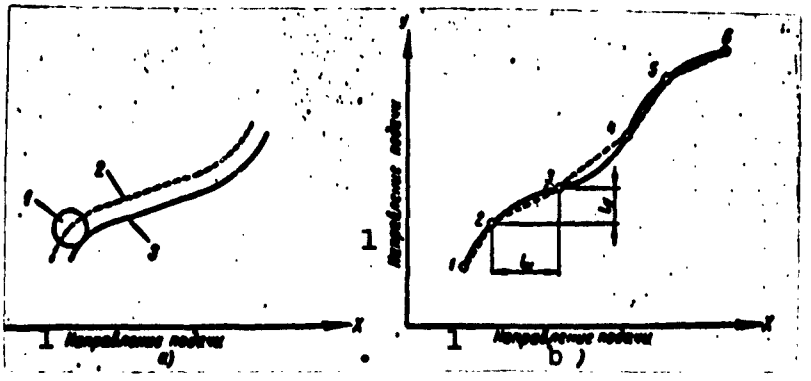

Fig. 35. Trajectory of motion of milling cutter center. a) Theoretical; b) actual. 1) Direction of feed.

the movement is produced by the combination of two feeds with respect to the X and Y axes. The minimum displacement of the follow-up unit with respect to each of the feeds, i.e., the crossfeed and the feed of the milling heads corresponding to one electronic impulse is termed the <u>elementary step</u> t_e. Its magnitude should be less than the permissible error of machining.

The motion program of the follow-up units is obtained as follows. The coordinates of the reference points 1, 2, 3 and so forth are established and the values of l_x and l_y determined from the rectilinear

segments. Then, l_x and l_y are divided by the elementary step t_e. The resulting values $n_x = l_x/t_e$ and $n_y = l_y/t_e$ also express the path of the milling-cutter center's motion. These values are recorded on a perforated tape in coded form. For convenience in use, they are arranged in a table. In the system under consideration, the speed of the motion is expressed by numbers corresponding to the time in the course of which the segment in question should be machined. In the programs, however, they are denoted not in seconds, but in the indicators of the number code.

When production machining processes are automated with the use of computing units, the decimal, binary or binary-decimal systems of numeration are most frequently used. In the decimal system, which we generally use, ten permissible digits are provided : 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9.

In the binary system, there are only two digits: 0 and 1. Any number in the decimal system may be represented with these digits. The number 1 in the binary system corresponds to the number 1 in the decimal system. To obtain the next decimal number 2 in the binary system, the last permissible digit 1 is changed to the first (0), and the following binary digit is inserted in next place, i.e., the binary number 10 corresponds to the decimal number 2. To obtain the decimal number 3, the last character of the binary number is replaced by the following number to give the number 11, and so forth. In comparison with the decimal system, the binary system is more convenient because only one line is used to represent a given number and the numbers in the binary system enable us to convey a "yes" or "no." This means that the presence of any phenomenon may be characterized by the digit 1 and its absence by 0.

A work program in the decimal system of numeration (Fig. 36a) is

entered in the following manner: 10 lines are reserved for each command, i.e., as many lines as there are digits used in this system. Vertical columns are reserved according to the number of decimal places that may be encountered in the recorded program. To record the number

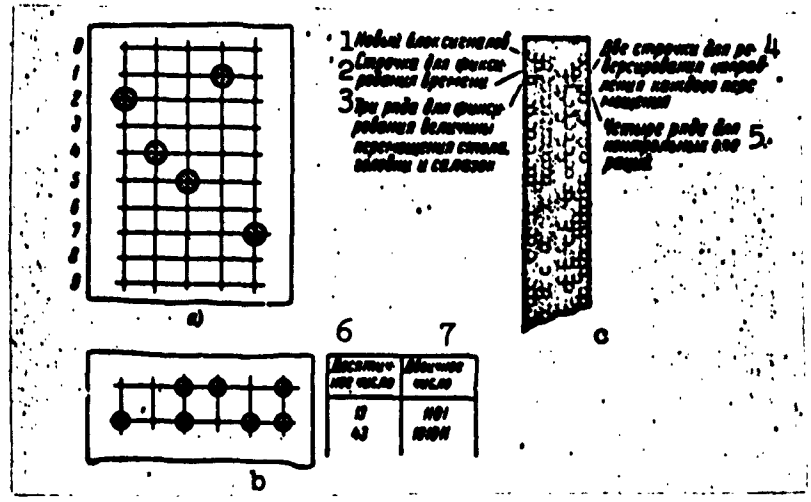

Fig. 36. Punched programs. a) In decimal system of digits; b) in binary system of digits; c) section of punched tape controlling milling machine. 1) New block of signals; 2) line for time fixation; 3) three rows for fixing lengths of table, head and slide displacements; 4) two lines for reversing direction of each displacement; 5) four rows for monitoring operations; 6) decimal number; 7) binary number.

24517, the number 7 is punched in the first column on the right; the number 1 in the second, and so forth. To record on the basis of the binary system, we are limited to one line and generally only the character 1 is punched. Figure 36b shows the notation for the binary number 1101 (decimal 13). The disadvantage of binary digits consists in the fact that many places are used for large decimal numbers.

Recording the program consists in punching round or rectangular holes in cards or tapes. The places where the holes are punched are arranged in a certain relation to the holes which are employed to transport the tape. Various hole-punching procedures are applied, de-

pending on the control system. The holes used to control each activity are punched in a separate column or line of the punched tape (Fig. 36c). Electric, photoelectric or pneumatic decoders are used to decipher a program that has been entered on a tape or card.

In the electric decoders, contacts are made through the punched holes so that electric pulses arise; these are fed into a computing unit to generate the control signals.

All the digits of a number that has been recorded are "read through" simultaneously. The "reading" rate of the electric decoders runs to 100 and that of the photoelectric types to 5000 digits per second in each vertical column.

The photoelectric decoder operates in the following manner. Beams arriving from a light source pass through a slit in a diaphragm which admits the light of only one of the tape holes. At the moment of coincidence of the hole with the slit in the diaphragm, the beam falls on a photoelement situated under the tape and produces an electric pulse. There is a separate element under each vertical column.

Together with the punched programs, programs that are entered on magnetic tape, motion-picture film, programming switch panels and commutators, as well as pushbutton programs are frequently used.

Movements are entered on a magnetic tape in the following manner. The tape, which consists of a neutral underlayer and a ferromagnetic overlayer, is moved past a recording head. An alternating current is passed through the coil of the head and magnetizes the tape. On moving past another head, the reproducing head, this magnetized tape induces the same current in the coils of the latter as was passed through the coil of the recording head. We may also record movements using a rotating drum with a ferromagnetic coating. On adopting the principle of magnetic recording, it is first necessary to prepare the component in

the usual manner and to record the movements executed on magnetic tape. If we insert this tape in the control unit of the machine, the electric signals obtained from the tape will cause the follow-up units to duplicate the movements that have been recorded.

The process of recording on a magnetic tape is simpler than that of recording on a punched tape. In small-scale production, therefore, this principle is considerably more profitable.

The feasibility of control automation of general-purpose machines without radical reworking should be included among positive aspects of the magnetic programs.

Magnetic tape wears well; moreover, duplication of the recording is unlimited and simple.

Uncoded programs. The characteristic property of these programs consists in the fact that a combination of only two conditions – "on" and "off" – forms the basis for them. A required combination of "on" and "off" conditions of the control system's elements corresponds to each operation position of the program. As has been indicated earlier, the uncoded programs are employed in rigid and closed-loop control systems. In the latter case, no computing units are required: the signals of the decoders go to the servosystem directly or after amplification.

Magnetic and punched-tape programs and programs entered on panels, pushbuttons and so forth may also be uncoded.

The simplest variety of uncoded program is composed of the various possible templates and models of the components.

2. OPEN-LOOP AUTOMATIC CONTROL SYSTEMS

To control the follow-up units of machine tools, rigid systems of the mechanical, hydraulic, pneumatic, electropneumatic and electric types are most frequently employed. Let us analyze the working princi-

ples of these systems.

Mechanical systems. Mechanical automatic-control systems consist of a complex of elementary mechanical mechanisms, mainly of the cam-lever type. In the time-base systems, disk-type or drum-type cams carried on one or several camshafts which serve as time counters are used as the sensors. The cams operate the follow-up units directly or through intermediate units, for example, levers. One end of the lever is usually provided with a roller or bearing which is pressed to the working surface of the cam while the other end is connected to the follow-up unit. The displacement of the follow-up units for a specified distance with the required velocity, as well as rapid return to the initial position are accomplished as a function of the configuration of the working surface of the cam. Where it becomes necessary to vary the length and speed of the displacement, it would be necessary to prepare new cams and this entails excessive outlays of time and money. Permanent cams and cam mechanisms which permit control of the working-stroke length and the rate of the follow-up displacement provide a way out of this situation. Cam systems admit of any control programs and guarantee high precision of follow-up movement. We should note that the complexity and cost of the cam control systems increase with program complication and with an increase in precision. In connection with this, and in view of the necessity of replacing the cams when the magnitude and velocity of displacement are changed, it is expedient to employ cam systems in building new automatic systems in long-run and mass production.

Path-base systems are used together with the time-base mechanical systems of automatic control. In these systems, rests which also serve as sensors are mounted on moving ~~parts of the machine or on stationary~~ bases. Either direct actuation of the appropriate element by the rest

or actuation through an intermediate unit is usually employed for small displacements.

Where rests are used, the precision of displacement of a machine's follow-up elements is dependent upon their design, the speed of the mechanism whose displacement is limited by the rests, its mass and rigidity. The following precision ranges have been established in practice: from 0.005 to 0.04 mm with the carriage under positive pressure against a fixed cross rest; from 0.05 to 0.2 mm against a fixed traverse rest; from 0.03 to 0.02 mm against the indicator rest; from 0.03 to 0.05 mm with automatic stop of the carriage.

For large displacements, various clutches are employed as the follow-up units of the elementary mechanism. These clutches engage or disengage an appropriate mechanical train.

Hydraulic and electrohydraulic systems. The follow-up motors in both types of systems are hydraulic drives operating off pumping stations. A pumping station may be provided for each automatic-control mechanism separately or for a group of these mechanisms. Finally, the entire control system may be serviced by one pumping station. Individual (for each mechanism) pump stations make the system more ideal, but complicate it and increase its cost.

A pumping station may consist of one or two pumps. Where there is one pump, the velocities of the working and idle strokes are the same; this is the disadvantage of these systems. In pumping stations consisting of two pumps, one of them (high pressure and low capacity) is intended for the working displacements and stabilization of a required position in cases where this position may be changed as a result of heavy loading. The second pump (low pressure and high output) accommodates such auxiliary functions as rapid approach and retraction of moving elements of the machine. It is possible to have both pumps under

high pressure. Then one of the pumps is disengaged for low displacement rates. The liquid flow of both pumps is used to accelerate the movement.

In cases where pumps developing different pressures are applied, we may delimit the circuits of high and low pressure with the use of a nonreturn valve or divider slidevalve and a nonreturn valve, and sometimes with the use of a control valve.

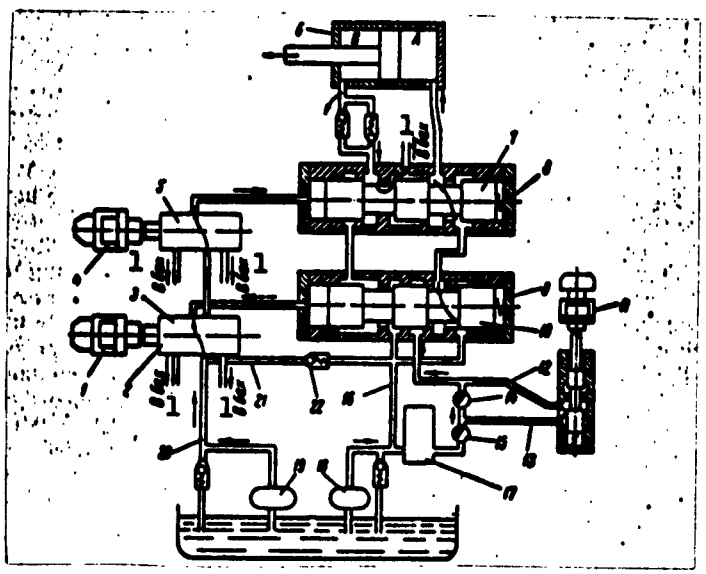

Fig. 37. Standard U4245 hydraulic panel. 1) To reservoir.

Hydraulic systems are used to exercise control of machine tools as a function of path traversed and the pressure of the working medium. Electrohydraulic systems are used only on the basis of path length. Combined systems are normally used; here command signals are produced partly as functions of path and partly as functions of the fluid pressure in the system.

Where control is a function of path, each unit, on completing its displacement, actuates a hydraulic or electric path sensor. This action produces the signal for the next operation.

Where machine tools are controlled on the basis of path traversed,

standard hydraulic panels are frequently applied. Thus, a U4245 panel (Fig. 37) enables us to automate the production cycle as a function of path: rapid approach, first working feed, second working feed, fast retraction and stop. In the fast approach, as is shown in the diagram, the electromagnets 1 and 4 are switched on, the plungers of the auxiliary slidevalves 2 and 5 are moved to the right and the fluid arriving through the pipelines into the left chambers of the slidevalves 8 and 9 holds the plungers 7 and 10 in the right-hand position. The fluid fed by the high-pressure 18 and low-pressure 19 pumps via lines 16, 20 and 21 passes through slidevalves 9 and 8 and the supply line into the chamber A of the motor, while the liquid displaced from chamber B exits through a line and slidevalve 8 into the overflow.

At the moment of completion of the fast approach, the carriage, which is displaced by the motor 6, operates an electric sensor, which disconnects the electromagnets 1. The plunger 3 of the slidevalve 2 is driven back to the left by a spring and connects the left-hand chamber of the slidevalve 9 with the overflow. This also mages it possible for the spring to pull the plunger 10 back to the left and to begin the working stroke. The pressure of the fluid in the system increases, the nonreturn valve 22 isolates the high pressure circuit from the low pressure circuit, and the fluid from the pump 18 moves through the filter 17, the chokes 15 and 14, the line 12, the slidevalve 9, the line and the slidevalve 8 to the plunger 7 and from there into the chamber A, while the excess fluid from the pump goes through a safety valve into the overflow. The rate of the working stroke is controlled by the transmission capacity of the choke 14.

To vary the feed, it is necessary to actuate the path sensor that switches on the electromagnet 11. Then the plunger of the auxiliary slidevalves descends and the fluid passes from the choke 15 through the line 13 into line 12 and then along same path that it took earlier. As a result of this, the carriage feed is determined by the throughput

section of the choke 15. At the end of the working stroke, the carriage actuates the electric path sensors switching the electromagnet 1 on and electromagnet 4 off. The plunger 10 shifts to the right, while the plunger 7 shifts to the left and the two fluid currents from the pumps 18 and 19 are ducted through the slidevalve 9, the line, the slidevalve 7 and line into chamber B, and chamber A is connected via a supply line and the slidevalve 8 to the overflow. If all the electromagnets are on, the plungers 7 and 10 will be at left and the slidevalve plunger of electromagnet 11 will be at its top position. Then access to the chambers A and B is cut off and the pumps will operate through the safety valves into the overflow.

Sequential execution of operations in control systems following the working-medium pressure is attained by many methods. The simplest of these is the use of rigid rests. When a moving part of a machine reaches such a rest, the pressure in the system increases, causing actuation of a corresponding force sensor, which is the source of the signal for the following operation.

Automatic control systems that follow path traversed are used only to control simple technological cycles. The systems generally used combine control as a function of path and control as a function of pressure. Elementary mechanisms embodied in the form of a standard hydropanel, for example, the U2423, are employed for this purpose.

In time-base hydraulic and electrohydraulic systems, each operation must be executed at a specified time. In these, as in the mechanical systems, cams or disks with rests are mounted on a control camshaft. On rotation of the shaft, the cams actuate hydraulic or electric sensors. One revolution of the control camshaft provides for execution of a complete technological cycle.

We should note that for the system under consideration, the kine-

matics of the control-camshaft drive is simplified. This is explained by the fact that the speed of the operation is controlled by the quantity of fluid entering the follow-up motor and is determined by the state of the hydraulic system, while the camshaft is rotated with a constant velocity.

Pneumatic and electropneumatic systems. Pneumatic motors serve as the follow-up motors in both systems, and the working medium is compressed air.

The working principle of the pneumatic control systems is the same as that of the hydraulic systems. Pneumatic control systems may also be of the reflex and time-base types. The use of air under a pressure of 4 or 5 atmospheres as the working medium at discharge velocities from 100 to 300 m/sec enables us to obtain considerably higher actuation speeds in comparison with the hydraulic systems, in which the fluid discharge velocities do not exceed 9 m/sec.

The above advantage of the pneumatic systems justifies their use in controlling auxiliary operations which do not require large forces and uniformity of displacement, for example, in advancing and removing blanks. Hydraulic or pneumohydraulic systems are employed to control the working stroke.

Electric systems. The elementary mechanisms of electric automatic control systems have electric sensors and follow-up motors. The production cycle is automated as a function of time, path and load.

Electric automatic-control systems have pulse-type contacts or prolonged-action contacts. In the latter case, the follow-up unit receives command signals without interruption over the course of the entire operation as the result of persistent actuation of the sensor.

The time-base electric automatic-control systems have either continuously rotating cams or cams which rotate periodically through a

specified angle, depending on operating conditions. As in the other systems, cams which act on the corresponding electric sensors are arranged on a shaft.

Drum-type or cam-type command devices are employed to control the follow-up units which execute the simple technological cycles. In the former case, a drum made of a nonconducting material (dielectric) is mounted on a control shaft. Copper plates connected to one another in accordance with the scheme of the operation being executed are mounted on the drum and a strip of dielectric material is arranged alongside the drum. Spring contacts on the strip are pressed to the drum surface.

In the production cycle, the drum occupies the position in which the required combination of contacts with the plates occurs.

In cam-type command devices, there are also control shafts with cams. When the shaft is rotated, the cams actuate rotating electrocontact sensors, making or breaking contacts which are secured to strips of a dielectric material. More complex cycles are controlled on the same principle, but using another physical design.

In the path-base systems, the working principle of which was described above, command signals are received when an electric path sensor is tripped.

3. CLOSED-LOOP AUTOMATIC-CONTROL SYSTEMS

On the basis of the nature of their operation closed automatic control systems (servosystems) may be relay systems (with intermittent control) and continuous systems.

The following servosystems are most frequently applied for automatic control of machine tools: systems with computer-type comparison units, potentiometer systems, two-selsyn and electrohydraulic systems. Before proceeding with description of some of these automatic control systems under consideration, let us examine the basic units that are

specific for each of the systems that we have named.

Computing unit. Binary counters, whose basis is a trigger cell (Fig. 38) are employed most frequently as pulse counters in the digital computing units. Each cell consists of two triodes and can have two stable states: tube L_1 opened and tube L_2 closed and, conversely, tube L_1 closed and tube L_2 opened. Transition from one stable position to the other is determined by delivery of an input signal. The operating speed of a counter of simple design is 10 pulses per microsecond. In many cases, the binary counter has two inputs. Delivery of a signal to one input produces one of the counter's stable states. It is retained until a signal arrives at the second input.

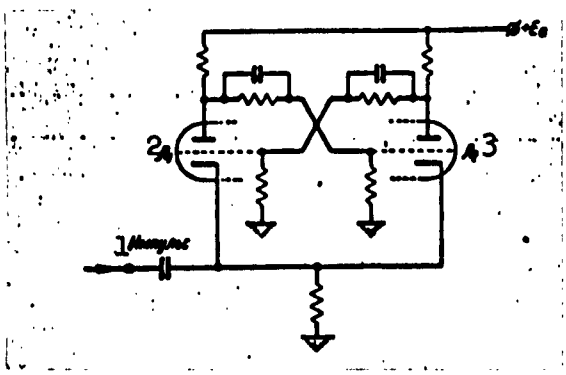

Fig. 38. Trigger cell. 1) Pulse; 2) L_1; 3) L_2.

A multiple-place binary counter consists of several counters, the number of which is a multiple of two, for example, four (Fig. 39). The pulses subject to counting are supplied at the counter input of place I. Let us denote the counter states by digits: 0 for L_4 closed; 1 for tube open. A positive pulse appears at the output of each counter only on shifting from state 1 to state 0. On transition of each counter from state 0 to state 1 a negative pulse arises at its output; this pulse does not influence the next following counter in order. Let us assume that at the initial moment, the tubes L_4 of all the counters are closed and the counters indicate the binary number 0000. A pulse is applied to counter I; then state 0 is changed to state 1 and a negative pulse arises at the output. In this case, the states of all the remaining counters remain unchanged and the multiple-place counter

will indicate the binary number 0001. Then the next pulse strikes counter I and its state 1 is changed to 0, and a positive pulse at the counter-I output drives counter II from 0 to 1. No changes occur in the remaining two counters, and the binary number 0010 appears on the multiple discharge counter; this corresponds to the decimal number 2. Further counting is carried out in the same manner. When the number of pulses is the decimal number 16, the four-discharge binary counter will be in its initial state and will indicate 0000.

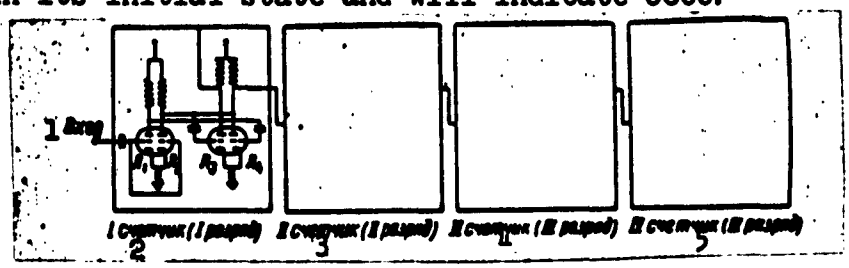

Fig. 39. Circuit of four-place binary counter. 1) Input; 2) counter I (place I); 3) counter II (place II); 4) counter III (place III); 5) counter IV (place IV).

Comparison units. A reversing trigger counter is usually employed as a computer-type comparison unit. In the reversing trigger counter, the count in the forward direction is run by pulses from the setting unit, while the backward count is by pulses which characterize the actual feed. On equality in the number of input pulses and feedback pulses, there are no deviations in feed from that specified.

In potentiometer servosystems, two types of compensation circuits are applied: circuits with electronic and electromechanical potentiometers. Their working principle is the same: an electromotive force corresponding to the given value and an electromotive force in the opposite direction, i.e., that characterizing the actual value of the quantity that we are controlling, should be equal in magnitude.

Figure 40 shows a compensation circuit with an electromechanical potentiometer. If the system is not balanced, the high-sensitivity re-

lay 1 will make contact 3 or 2, depending on the direction of the current, and will switch the follow-up motor 6 into forward or reverse operation. The movement of the carriage 7 causes displacement of the slide 5 of the potentiometer 4 until the system is balanced, at which point the current I in the circuit will be zero. Then the armature of the relay will occupy its neutral position and the motor will be switched off. In compensation circuits with electronic potentiometers, the relay is replaced by an electronic amplifier connected with the follow-up motor; it is this that distinguishes these systems from the electromechanical systems. The essential disadvantages of the potentiometers when they are used in a servodrive lie in the fact that we cannot produce circular motion and the generation of noise, i.e., signal disturbances resulting from breaks in contact as the slide passes from turn to turn.

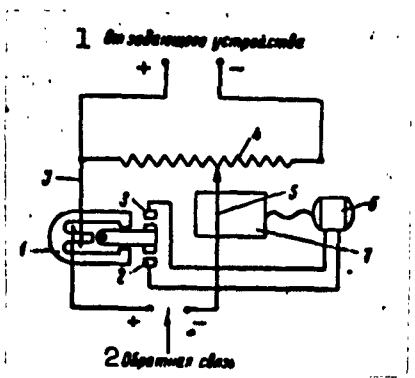

Fig. 40. Compensation circuit with electromechanical potentiometer. 1) From setting unit; 2) feedback.

Where the systems are supplied from an alternating-current line and to transmit angular displacements, rotary transformers (VT) and selsyns are used. In their design, the selsyns are reminiscent of induction motors and are classified as contact and noncontact selsyns. The selsyns are electric machines of the induction type and are used for remote transmission (they usually operate in pairs; transmitting selsyn and receiving selsyn) of angular displacements or to convert an angular mismatch-signal into a voltage that is a function of it. In accordance with these functions, two possible modes of the selsyn pair are distinguished: the indicator and transformer modes.

Measurement units. Measurement units are used to measure the

speed or displacement of a machine unit continuously and to generate broken (discrete) or continuous feedback signals. The designs of the measurement units are dependent upon the nature of the controlled movement and the type of signal generated.

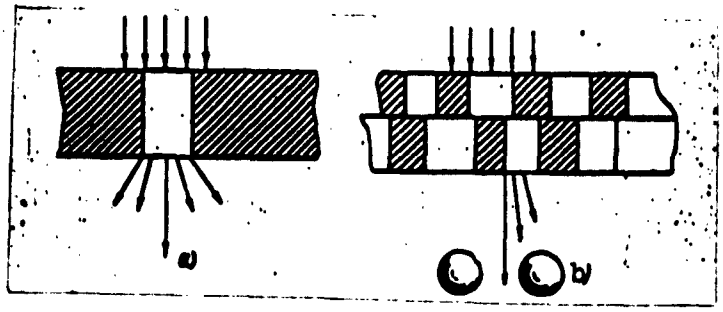

Fig. 41. Working principle of "Ferranti" converter. a) Scattering of light on transmission through thin slit; b) diagram of converter operation.

The function of converter of shaft rotation into discrete signals may be performed by a lobed cam mounted on the shaft and actuating the breaker contacts. The number of closings and openings of the circuit in one revolution of the shaft is equal to the number of lobes on the cam. Therefore, the number of current pulses will characterize the speed of the shaft rotation. The speed of a shaft's rotation is frequently determined by means of an inductive converter of rotary motion into discrete signals. A disk with a series of pole-magnets arranged along the circumference of the disk at equal intervals is secured to the shaft in place of the cam. An electromagnetic head is placed opposite the disk, which turns together with the shaft. On rotation of the disk, pulses of electromotive force from whose frequency we may judge the velocity of the shaft rotation arise in the head winding.

Devices in which the phenomenon of light diffraction is used are frequently employed to measure translational displacement. On passing

through a thin transparent slit, a beam of light is scattered. Here, the greater the angle formed by the scattered light beam with the initial beam, the weaker will be the light intensity.

In the converter of the English firm "Ferranti" (Fig. 41), there are two diffraction gratings made of a transparent material. Opaque stripes with thicknesses equal to the spaces between them are arrayed on the gratings at equal intervals from one another. If we secure one

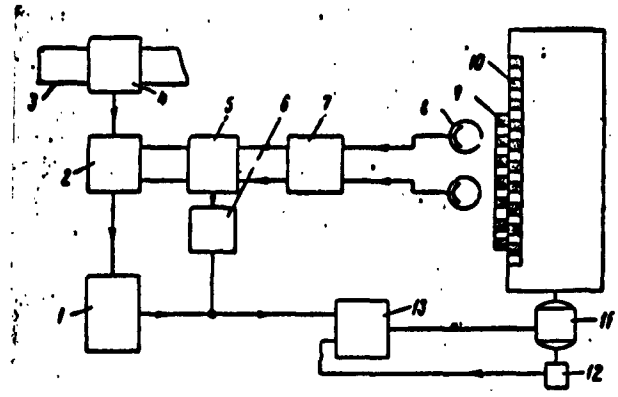

Fig. 42. Block diagram of servosystem with computer-type comparison unit.

diffraction grating to a moving part of a machine tool, for example, to the table of a milling machine, and another grating to a stationary part, and place the light source on the side of the moving grating and two photoelements on the side of the fixed grating, the number of pulses created by each element will be proportional to the displacement. In the "Ferranti" firm's converter, 2500 stripes were drawn on 1 mm of the grating for a milling machine; thus, on each pulse, the table is displaced by 2.5 μ and the speed of the displacement may be judged from the frequency of the pulses per unit of time.

Servosystems with computer-type comparison unit. A block diagram of such a system for controlling a column-and-knee-type milling machine, which was developed by "Ferranti," is shown in Fig. 42. The control is carried out with a magnetic program drawn up from a coded

punched program. The latter is auxiliary in nature. The magnetic program 3 is passed through the decoder 4, at the output of which appear pulses that are fed into the relay block 2. From the relay block, the pulses go to one of the two reversing counters of block 5 and, simultaneously, to the digital-to-analog converter 1. The feedback signals arising from the photoelements 8 as a result of displacement of the machine-table with the grating 10 relative to the grating 9 pass into the corresponding counter by way of the amplifier 7. These feedback pulses run the backward count.

In the presence of mismatch, i.e., if the difference between the program and feedback pulses is not zero, the control signals which enter the digital-to-analog converter 6 appear at the output of the counter, and a voltage proportional to the number of pulses appears at the converter output. Signals proportional not to the number, but to the frequency of the pulses appear at the output of the converter 1; this enables us to control the table movement with respect to the amount and speed of displacement. The resultant magnitude of the output voltages from the converters 6 and 1, plus that of the tachometer generator 12 acting as a stabilizer, go to the comparison unit 13 with its electronic amplifier. On mismatch, the signal arising at the output of the comparison unit actuates the follow-up unit 11 and the machine table is displaced accordingly.

Stabilization with the use of a tachometer generator proceeds in the following manner. In accordance with the decrease in the following error, the signal to the motor is also varied, but the latter continues to rotate on inertia without changing speed. Because the tachometer generator is set on the same shaft as the motor, the tachometer-generator voltage will exceed that of the error signal and the polarity of the voltage at the output of the comparison unit is reversed;

this guarantees sharp braking of the motor.

Potentiometer servosystems. As seen from the diagram in Fig. 43a, the potentiometer resistances R_1, R_2, R_3 and R_4 are connected in a bridge circuit to effect a progressive feed in one direction.

If the slides are in the center position, the circuit is balanced and no current flows in the diagonal. Displacement of the setting slide with respect to a potentiometer gives rise to a current in the

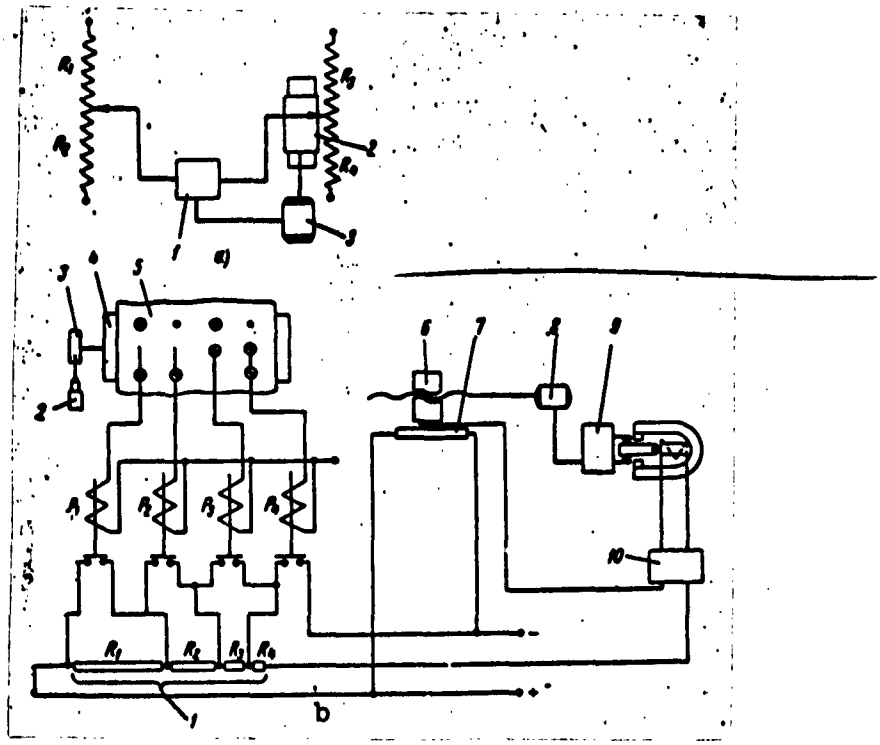

Fig. 43. Diagram of servosystem with potentiometers used to accomplish progressive feed. 1) In one direction; 2) in two directions.

diagonal. The latter passes through the amplifier 1 to set the follow-up motor 3 in rotation, and the carriage 2 of the rest begins to move. Together with it, the slide is shifted on the potentiometer. When the current in the diagonal disappears, the carriage will stop its motion. This occurs at the moment when the slide being displaced by the carriage reaches the same displacement as the setting slide, and the sys-

tem will be balanced. In certain designs, the bridge diagonal, which is formed by potentiometer segments, incorporates a relay winding, passage of current through which closes contacts to start the follow-up motor.

A diagram of a servosystem used to accomplish progressive feed in two directions is shown in Fig. 43b. The program recorded on the punched tape 5 is passed over the metallic drum 4. Each of the decoder contact brushes is connected to the winding of one of the relays P_1, P_2, P_3 and P_4, the number of which is dependent upon the conditions under which the operation is executed. The system uses two potentiometers, 7 and 1. The latter consists of several segments – R_1, R_2, R_3 and R_4; here, the resistance of each successive segment is double that of the preceding. The potentiometer resistance is cut in by contacts closed by the relays. The potentiometer 7 is connected to a fixed member of the machine and its slide is displaced together with the carriage 6. The potentiometers are connected in a bridge circuit.

If the sum of the resistances of the potentiometer 1 does not equal the total resistance of the potentiometer 7 as a result of relay actuation, current will begin to flow through the diagonal. The current will pass through the amplifier 10 and a polarized relay and cut in the starter 9 of the reversible electric motor 8 for the forward or reverse direction, depending on whether a positive or negative voltage difference has formed at the ends of the diagonal. Together with the potentiometer slide, the carriage 6 will be displaced until the voltage at the ends of the diagonal is equalized. When the movement of the carriage in one direction stops, the drum is turned through a specified angle and the tape will be displaced through one step to the following operating position. This is effected by actuation of the solenoid 2, which turns the ratchet wheel 3 mounted on the axis of the drum.

If the potentiometer 1 has an appropriate set of resistors and they are properly proportioned, we may obtain the required carriage displacement with an accuracy to 0.0125 mm.

Servosystems with two selsyns. A block diagram of this system is shown in Fig. 44. If the rotor of selsyn 1 is turned by the gear drive 8, a voltage appears at the output of selsyn 3, which is operating in the transformer mode with selsyn 1 and a current will flow through the amplifier 2 to the follow-up motor 7. As a result of the motor's rotation, the movement will be transmitted to the lead screw 5 which displaces the carriage 6. Then, as the carriage displaces, the rotor of selsyn 3 is turned due to the feedback in the same direction as that of selsyn 1 by the gearing 4. The carriage will move until the positions of the rotors of the two selsyns coincide and the motor stops due to the absence of a voltage at the output of selsyn 3.

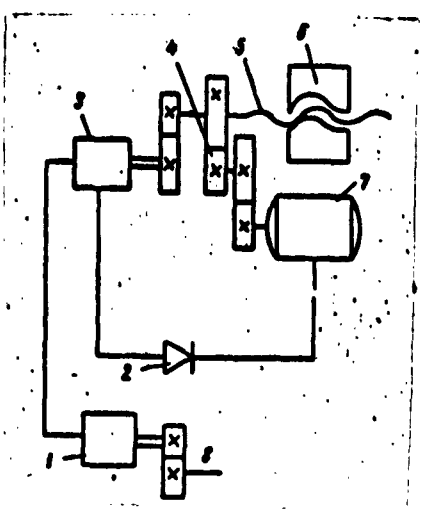

Fig. 44. Block diagram of servosystem with two selsyns.

In the [closed] automatic-control systems that we have described, electrohydraulic servosystems with setting units like those described above are frequently employed.

The follow-up motors in these systems are hydraulic. The electric signals received by the servosystem are transformed into hydraulic signals.

4. CONTROL WITH DUPLICATING PROGRAMS

Various duplicating systems are frequently applied to automate machine-tool follow-up units: mechanical, electromechanical, hydraulic, electrohydraulic and pneumohydraulic types.

The duplicating systems are single-coordinate with independent or dependent driving-motion speed or multicoordinate, according to the number of servomovements.

The duplicating systems are built into the machine tools and provided in the form of separate units readily connected to the machines.

In the mechanical duplicating systems, the setting unit is a flat or three-dimensional template. The template corresponds in shape to the component that is being machined. These systems are encountered most frequently on milling, planning and grinding machines. High hardness is imparted to the working surface of the template; this makes it quite expensive to machine them. Therefore the duplicating systems described below are more frequently applied.

Electromechanical duplicating systems. We may subdivide these systems into two groups as a function of the characteristics of the follow-up unit: Systems with control by means of electromagnetic clutches and systems based on the use of variable-speed direct-current motors. The electric sensors employed in these systems may be with and without contacts.

Let us examine the electromechanical duplicating system with a three-position contact-type sensor (Fig. 45) as an example of a system of the former group. The tool 7 and sensor 5 are placed on the carriage 6, which accomplishes the follower feed. The slide 3 serves as the feed mechanism. A screw connected to the feed mechanism by the electromagnetic clutches 1 and 2 shifts the carriage. The sensor controls clutch engagement for carriage feed in the transverse direction. If the sensor's feeler is not in contact with the template 4, the contacts A are closed and the crossfeed proceeds on the workpiece. The contacts A are usually closed. On contact of the feeler with the tem-

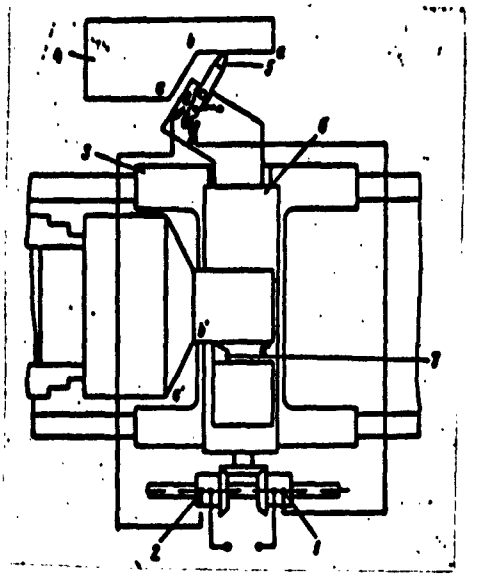

Fig. 45. Electromechanical duplicating system with three-position sensor.

plate at point a, they open, the follower feed is disengaged and only the drive feed is retained. In this case, the segment $a^1 - b^1$ of the component profile is machined. As soon as the feeler reaches the inclined profile b – c of the template, it is deflected even further from the normal position by the template and the contacts B are closed, i.e., the workpiece follower feed is engaged. Now segment $b^1 - c^1$ will be machined. From this feed, the feeler will leave the template, the contacts A close and the workpiece feed is again engaged. The feeds alternate very rapidly. Slight steps are produced on inclined and curvilinear surfaces, but the surfaces parallel to the driving motion are rendered smooth.

There are no such drawbacks (graduations) in electromechanical duplicating systems.

Figure 46 shows the control diagram of a 6441 duplicating milling machine of T.N. Sokolov's system. In this machine, control of the movement does not proceed with intermittent closing and opening of contacts, but by the smooth regulation of the feed motors on the basis of the so-called Leonard system. An inductive duplicating head consisting of two induction coils 5 and the flat ~~spring 3 between them, on~~ which the armature 4 is suspended, serves as the sensor. The feeler 2, which sweeps the template 1, is connected to the armature. If the position of the armature is changed, the voltage in the coils also changes; the phases between the grid (cathode) and plate voltages of the amplifier

thyratrons are shifted. The voltage is supplied from the duplicating-head amplifier into the driving amplifiers No. 1 and No. 2, which rectify and step up the alternating voltage. Then the voltage influences energizing windings of EMU [amplidyne] 1, in which the voltage that is

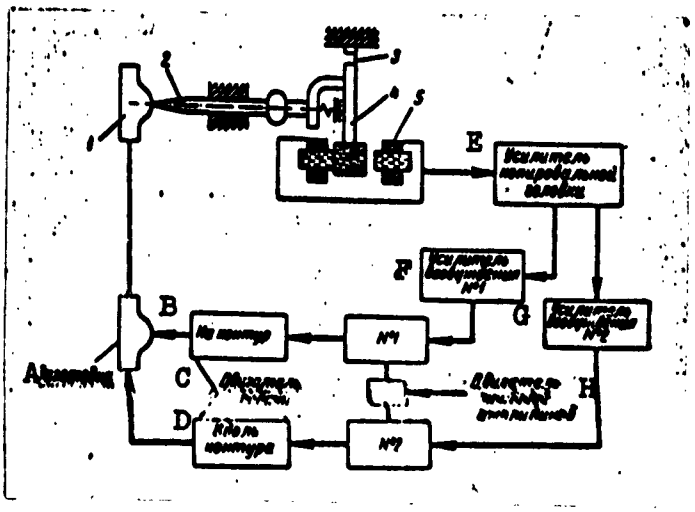

Fig. 46. Control diagram of 6441 duplicating milling machine. A) Blank; B) onto contour; C) feed motor; D) along contour; E) duplicating-head amplifier; F) driver amplifier No. 1; G) driving amplifier No. 2; H) amplidyne – [illegible] – motor.

used to supply the feed motor arises at the output terminals.

Hydraulic duplicating systems. In these systems (Fig. 47), the template and blank that we are machining are placed on the table 3 which is connected with the operating feed.

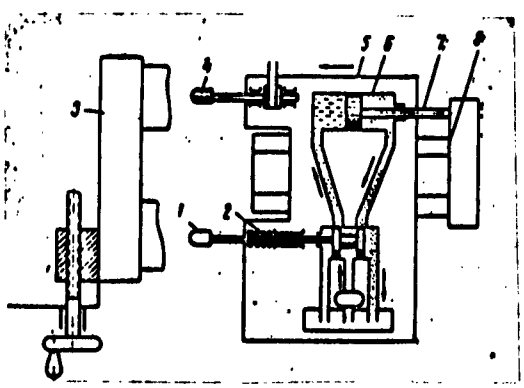

Fig. 47. Hydraulic duplicating system.

The hydraulic cylinder 6 is rigidly secured to the carriage 5, which is displaced along guide rails. The piston in the cylinder is also firmly secured to a fixed member 8 of the machine by means of the rod 7. The duplicating head consists of a slidevalve with a rod

which is connected to the feeler 1. The spring 2 displaces the probe to the left and the oil from the pump enters the left chamber of the cylinder, which, together with the carriage and the cutter 4, moves to the left. When the feeler, which abuts against the template, is displaced, oil from the pump is ducted to the right into the right-hand chamber of the cylinder. At the neutral position of the slidevalve, the zones of the profile parallel to the driving feed are machined. Thus, the feed of the tool and the blank is controlled.

Hydraulic duplicating systems are [closed] automatic-control systems and have recently come into extensive use. They include, for example, the KST-1 hydraulic duplicating device for the 1A62 engine lathe . The negligible force exerted by the probe on the template enables us to duplicate from a standard (rod or flat) template part prepared from a soft material. This provides for rapid retooling from machining a detail of one shape to another with a duplication precision from ± 0.02 to ± 0.05 mm.

Electrohydraulic duplicating systems. Among the advantages of electrohydraulic systems, we should note quick response, the negligible pressure of the feeler on the template and the high sensitivity of the system, particularly if vibration slideblocks or contacts are used.

Figure 48 shows an electrohydraulic duplicating system with vibration contact. As in other systems, the sensor is secured to the machine component which executes the follower feed. The intermediate unit consists of solenoids, the slideblock 1 and the pump 4 with its electric motor. It is enclosed in a housing alongside the machine. The follow-up hydraulic motor 2 together with the reducer 3 is generally connected to the intermediate unit. The output shaft of the reducer is most frequently connected to the screw of the follower feed by a telescoping shaft. The contact at the end of the lever is set in vibration by

the cam 7, which is seated on the shaft of the auxiliary electric motor 8. There is a contact at one end of the lever; the other end of the lever is in contact with the cam 7. Figure 48 shows the contact in the position with which the slideblock is in its middle position. In this position, the follower feed is disengaged and only the driving

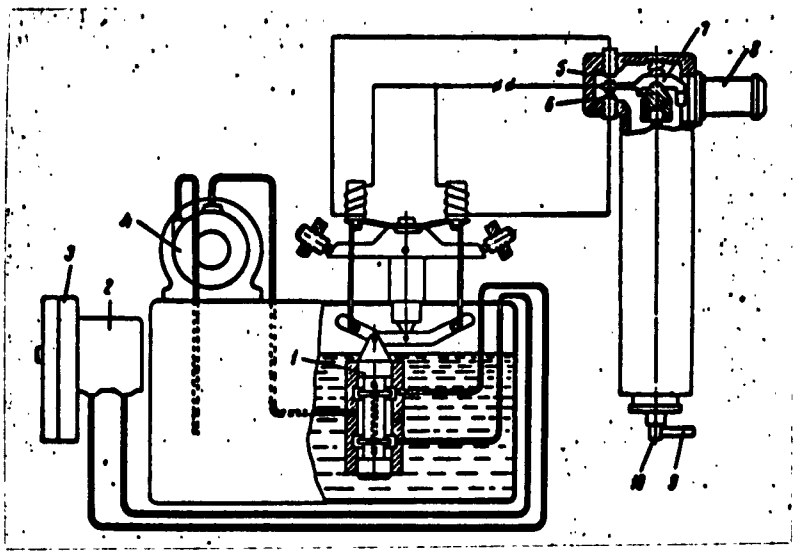

Fig. 48. Electrohydraulic duplicating system with vibrating contact.

feed operates.

When the feeler 10 is moved by the template 9, the lower contacts 6 of the sensor are closed and an electric current flows into the right-hand solenoid, with the result that the slideblock is lowered and feed proceeds off the workpiece. If the template does not drive the probe, the upper contact 5 is closed. In this case, the current goes to the left-hand solenoid, the slideblock is displaced into its uppermost position and the feed proceeds into the workpiece.

Together with the system under consideration, electrohydraulic systems without templates are applied, for example, for milling machines. The duplication in these systems is accomplished directly from a drawing. Generally, photoelements are used in duplicating from draw-

ings. For these plan-duplicating machines, electronic control and current-conducting ink have been used in the USSR by Doctor of Technical Sciences V.S. Vikhman and in England by the "New England" firm. Thus, the plan is included in the electronic circuit of the machine as an integral part of it. Sparks from a small high-voltage current jump continuously between the disk probe and the line on the plan. When the spark gap is varied, the current at the output of the control circuit also varies. This [output current] maintains the clearance between the drawn line and the disk probe at 0.025 mm by means of magnetic clutches and transmission mechanisms.

The high sensitivity of the electrohydraulic servosystems guarantees precision on a curvilinear machined surface to within ±0.05 mm with a feed rate of from 10 to 400 mm/minute. Little time is lost in retooling the machine for work on other workpieces, while the cost of the template and other accessories is minor. In many cases, only 15 to 20% of the overall cost of a machine has been spent on facilities for automation of its control.

Manuscript Page No.	[List of Transliterated Symbols]
5	э = e = elementarnyy = elementary
17	Л = L = Lampa = Tube
17	a = a = anod = plate
19	ВТ = VT = vrashchayushchiysya transformator = rotary transformer
19	ЭМУ = EMU = elektromashinnyy usilitel' = amplidyne

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