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ELECTRONIC CONTROL FOR CONTOUR MILLING MACHINES

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1. This invention relates generally to the control of contour milling machines, or of similar reproduction devices, by means of a tracer, or follower moving over a pattern of the article, which the machine is to reproduce, and, more particularly, it relates to an electronic variable capacitance follower for use with contour milling machines.

An object of this invention is to provide a very sensitive and simple control which will not damage the pattern by exerting a heavy load upon it. Another object is to provide a follower which will be rapid and smooth in operation and which will enable the pattern to be accurately reproduced so that the reproduction will require a minimum of surface finishing after the primary milling operation.

Still another object of this invention is to provide a new and improved type of tracer or tracing control head wherein a unitary construction of a high frequency oscillator and capacitive coupling element contained entirely within the tracing head provide control voltages directly, without need of complex bridge or balancing circuits external thereto.

It is well known, of course, that electric controls for automatic contouring machines have been in industrial use for some time. An example of such equipment, illustrating quite well the present state of the art, is described in an article entitled "Machine-tool contour controller" by J. M. Morgan in Electronics Magazine, October 1946, page 92 (McGraw Hill).

The prior art tracing controls have in general followed the principle of providing some member in a tracing head and secured to a stylus, as a component element of an impedance bridge, which is, as a rule, contained outside the tracing head. In the construction described in the aforesaid article, the elements are armatures of magnetic circuits. In other known equipment, the elements are variable capacitors, or magnetostrictive devices. They are provided, in some form or other, as constituents of an electrical bridge, and the stylus deflections operate through the element to upset the balance of the bridge.

The invention disclosed and claimed herein departs from these teachings and makes use of intermediate capacitive members disposed along a neutral plane in a high frequency electric field as the stylus deflection sensing element. The high frequency voltages induced on the members, when stylus deflections force them out of their neutral planes, are rectified and provide unidirectional control voltages. The capacitive members thus form a differential condenser; one side decreases in capacitance as the other increases, giving a linear output against deflection, even for large deflections, and inherently provides compensation for drift due to changes in capacitance from any causes other than stylus deflection. These advantages are not found in any tracer in which only one arm of the measuring bridge is varied by the controlling signal.

In accordurrence with a preferred embodiment of this invention, the high frequency electric field is produced by means of opposed capacitive plates connected to opposite ends of an inductance coupled to an electronic oscillator. The neutral electric plane is established midway between the opposed plates, with reference to a center-tap on the inductance. Furthermore, there are provided three pairs of opposed capacitive plates, orthogonal or mutually perpendicular to each other, and a cascade rectifying circuit is used to integrate the voltages resulting from deflection of the stylus in any direction into a single control voltage, which, through suitable apparatus, operates to withdraw the tracing head and stylus from the template or pattern, thereby relieving the pressure on the stylus.

By this construction, the sensitivity of the control, has been so greatly improved that it is now possible to cut, by automatic contouring, steel reproductions of delicate plaster patterns, with maximum dimensional deviations of no greater than a few thousandths of an inch. Moreover, in comparison with variable inductance pick-ups, usually having iron cores, this construction embodies a moving element of much lower mass, requiring relatively light suspension. Due to this feature the stylus exerts but a few ounces of pressure on the pattern, so that it may be made of a relatively soft material such as plaster with no appreciable wear thereon. It is thought that no such results have ever been achieved with prior art equipment.

Still further objects and advantages of the invention will become apparent during the course of the following description of a preferred embodiment of the same wherein like numerals are employed to designate like parts, and wherein:

Fig. 1 is a side elevation of a tracer unit, constructed in accordance with this invention, with its cover in cross-section;

Fig. 2 is a representation of a simplified mechanical arrangement of the tracer unit depicted in Fig. 1;

Fig. 3 is a block diagram showing the principal
portions of the control mechanism of a contour milling machine;

Fig. 4 is a circuit diagram of a tracer unit and control unit showing a typical application of the fundamental principles of this invention;

Fig. 5 is a diagrammatic representation of a tracer unit and a milling cutter in contact with a pattern and workpiece, respectively, on the machine, and

Fig. 6 is a simplified circuit diagram of a tracer unit, arranged to provide an independent output E. M. F. from each of the three senses of deflection of the unit so that more than one of the operating motors may be automatically and simultaneously controlled.

With reference to Figs. 1 and 2 it will be seen that a tracer constructed in accordance with this invention comprises a casing 3 from one end of which extends a pressure sensitive portion in the form of a stylus 8 and within which are housed there variable split-stator condensers 9, 10 and 11. The stylus 8 and the central plates of the condensers 8, 10 and 11 are mounted by means of insulating washers on a quill 12 which is supported at its forward end by a spring diaphragm 13 and at its remote end by a retaining spring 14. The quill 12 is rigid and any movement of stylus 8 is thereby transmitted to the variable condensers 9, 10 and 11. To avoid damage in the event of failure of any part of the electronic control, safety contacts comprising spigot 15 and plate 16 are provided; these close on excessive deflection of the quill, thereby causing disengagement of the magnetic clutches which control the application of electrical power to the traverse, indexing and feed drives of the machine.

Spigot 15 moves in hole 16 in plate 16, the diameter of said hole being substantially greater than the diameter of the spigot, but smaller than the diameter of shoulder 18 on spigot 15. The safety circuit is made when the spigot is displaced sufficiently to bring it or its shoulder into contact with plate 16.

The spring diaphragm 13 supports the quill 12 at the point of balance of the latter to eliminate lateral deflections due to vibration of the machine on which the tracer is mounted. In other respects the diaphragm 13 acts as a universal pivot and allows the stylus 8 to have a limited degree of movement in all directions.

The condenser 9 consists of three plates or discs which are preferably circular and mounted concentrically with, and transversely of, the tracer unit axis. The outer annular stator plates 17 and 18 of condenser 9 are fixed to, but insulated from, body 19 of the unit, as shown in Fig. 1, the axial holes in the stator plates providing sufficient clearance for quill 12 which passes therethrough. The third plate 20 is disposed between plates 17 and 18 and on quill 12 as previously described. Condensers 10 and 11 each comprise four plane rectangular plane, the outermost two of which are fixed longitudinally to body 19 of the unit, but insulated therefrom, while the innermost two are secured to quill 12. Electrically each pair of intermediate plates mounted on the quill may be regarded as one plate, since they are connected to each other by brass mounting screws extending therebetween.

Condensers 10 and 11 lie in orthogonal planes, that is, planes perpendicular to each other and mutually perpendicular to the plane of the condenser 9.

During assembly, axial alignment of the quill is effected by means of an adjustable anchorage of spring 14 as seen particularly in Fig. 1. This anchorage comprises plate 21 to which the spring is fastened, angle bracket 22 secured to body 19, screws 23, wash plate 24 and spring steel lock washer 25. The holes in angle bracket 22 are oversize, thereby permitting a certain amount of lateral adjustment in order to achieve a satisfactory degree of axial alignment.

After having adjusted the position of quill 12, as described in the preceding paragraph, it is necessary to balance the condensers 10 and 11 electrostatically and for this purpose two small fixed condensers 26 and 27 (see Fig. 4) and two small adjustable condensers 20* and 27* are provided, the latter being arranged for convenience of adjustment adjacent condenser 11. The adjustment of condensers 26* and 27* will be subsequently described.

The tracer unit also houses an oscillating tube 25, which supplies through centre tapped transformer 28, a high frequency voltage of the order of 600 k.c./s. to the aforementioned condensers. The ends of the winding 29 are connected to the outer plates of each of condensers 9, 10 and 11. Hence, if the electrical capacitance between one of the outer plates and the corresponding inner plate of any one of the condensers differs from the electrical capacitance between the other outer plate and the said inner plate of the high frequency voltage will exist between the inner plate, and the centre tap of secondary winding 29. More strictly speaking, the outer or opposed capacitive plates establish a high frequency electric field, wherein the intermediate plates, when disposed midway between, lie in a plane which is electrically neutral with respect to the center-tap of transformer 28. Any movement of the intermediate plates out of their neutral plane causes a high frequency voltage to be generated thereon with respect to the center tap. It should be evident that since an appreciable E. M. F. ought to exist between any one of the inner plates of condensers 9, 10 and 11 and the centre tap only when the stylus is deflected, balancing condensers 26 and 27 are provided between one outer plate and the inner plate, for adjustment of condensers 10 and 11 respectively. (It will be subsequently shown that no such arrangement is necessary in the case of condenser 9.)

In the preferred embodiment condensers 20* and 27* are adjustable metallicized ceramic condensers. These have sufficient capacitance, even at the “minimum” setting, to unbalance the electrical circuit. Therefore fixed condensers 26 and 27, each having a capacitance roughly one-half that obtainable in condensers 26* and 27*, are connected between the other outer plate and the inner plate of each of condensers 10 and 11 respectively. Thus by suitable adjustment of condensers 20* and 27* a fine degree of balance may be achieved between the inner plates of condensers 10 and 11 and their outer plates so that when stylus 8 is undeflected, the E. M. F. between the inner plates and the centre tap of winding 29 will be negligible. Germanium rectifiers 32, 33 and 35 with their associated choke coils 30, 31 and 32 and filter condensers 33*, 34* and 35* constitute a series or cascade rectifying circuit, somewhat similar to the voltage doubling circuit well known in the electronic art, which converts the output voltage of the balanced condensers due to deflection of the stylus in any direction into a unidirectional voltage for the
control of the milling operation, a description of which follows:

As previously stated, stylus 8 protrudes from one end of casing 7, and a seven-pin plug 37 is mounted on the opposite end. This plug carries the heater voltage and unidirectional voltage input to the oscillator tube 28, the safety circuit and the unidirectional voltage output of the rectifiers in the tracer unit.

From Fig. 3 it will be seen that the output from the tracer unit is fed to a direct coupled amplifier 38 which also contains an "overriding" manual control 43 of the machine. The control voltage from the amplifier 38 together with a unidirectional bias voltage, manually controlled by potentiometer 43, is fed to a thyratron motor control unit 39 which in turn supplies the power to direct current shunt motor 40, the magnitude and polarity of the voltage of which is a direct function of the magnitude and polarity of the voltage from unit 38. Motor 40, the speed of which is closely proportional to the control voltage, drives table 41 on which the work is mounted, as shown in Fig. 4, and the rate of feed, i.e., the speed at which table 41 moves in the direction of the arrow 41
d, is governed thereby. Pilot generator 41 is directly coupled to motor 40 and operates to supply a large degree of inverse feedback to the input of thyratron unit 39 to ensure close conformity between the speed of the motor 40 and the control voltage, regardless of load. This inverse feedback method of mechanical stabilization of rotating electrical machinery is well known in the art and need not be further described.

From the electrical circuit of the follower and control unit shown in Fig. 4 it will be seen that the control unit comprises a double triode, one section of which amplifies the output voltage from the tracer unit, and which, combined with the second triode section and with the anode lead resistors, forms a Wheatstone bridge. This bridge is balanced through a manually operated control 43 which in effect determines the basic magnitude and polarity of the control voltage fed to the thyratron power feed control tubes.

Fig. 5 shows the tracer stylus 8 in contact with a pattern 44, and the milling tool 45 in contact with a work-piece 46. The tracer unit and the tool 45 are mounted rigidly on the frame 47 of the machine, while the pattern 44 and work-piece 46 are mounted on the movable table 41. The table is traversed at a constant speed in the direction of arrow 41
d, and simultaneously it is fed toward stylus 8 and tool 45 in the direction of the arrow 41
d by the motor 40, as hereinbefore described. Indexing occurs at the end of each traverse of the machine repeats its traverse it will follow a path displaced laterally a small amount from the previous path taken.

The tracer unit provides a voltage which increases with pressure exerted on stylus 8 in any direction, by virtue of the arrangement of condensers 9, 10 and 11 in three mutually perpendicular planes. For example, direct axial pressure on stylus 8 deflects spring diaphragm 13 inwardly and causes an axial displacement of the central plate 20 of the variable condenser 9 toward fixed plate 18. As previously described, the oscillator 23 provides high frequency field between the condenser plates so that any movement of plate 20 towards plate 18 decreases the capacitive reactance between plates 18 and 20 and increases the capacitive reactance between plates 17 and 20, thereby increasing the poten-

tial difference between the central plate and the centre tap of the winding 29. This voltage is developed across choke 30, rectified by germanium rectifier 31, filtered by condenser 32 and transmitted through amplifier 38 and thyratron unit 39 to motor 40. The thyratron unit supplies a voltage to the feed motor the magnitude and polarity of which is a function of the magnitude and polarity of the voltage between terminals x, x of amplifier unit 38. The feed motor is arranged so that the speed and direction of rotation is a function of the voltage applied to its armature and so said speed and direction therefore vary as a function of the amplifier output voltage at terminal x, x. The operation of such thyratron control units is common knowledge in the art and therefore need not be further described.

As the pattern 44 is brought against the stylus 8 and begins to press upon it, a voltage is produced which, at a certain pressure exerted by the pattern on the stylus, exactly balances the voltage initially applied to feed motor 40 by the manual adjustment of control 43. When this balance occurs the motor stops. Any further increase in pressure due to a rising slope of the pattern contour in the direction of traverse 41
d, will cause the voltage from the amplifier to increase again but its polarity is opposite to that of the original bias voltage as set by control 43, so that motor 40 is made to reverse, thereby withdrawing table 41 and with it workpiece 46 from the cutter 45 until balance again is restored. Similarly, any decrease in pressure due to a dip in the pattern contour in the direction 41
d will cause the motor 40 to start running again in its original sense until balance is again restored. It will be understood therefore that the pressure on stylus 8 necessary to achieve balance is dependent upon the bias voltage, the latter being manually applied and remaining constant throughout the entire milling operation. Theoretically any degree of sensitivity and accuracy of reproduction can be obtained by this means, but in practice a stylus deflection must be used which is greater than the relative movement between the tracer and the pattern due to vibration and deflection of the machine frame caused by cutter pressure. This requisite has resulted in the use of a stylus pressure of between two to four ounces which is still sufficiently small that even plaster patterns can be used time after time without excessive wear or deterioration of the surface. Previously to this invention, plaster patterns could not be used at all since the stylus pressures applied by the known types of followers which were of the order of two to three pounds, were sufficient to destroy the surface of the pattern by the time the first few passes by the stylus had been made.

In the preceding paragraph axial displacement of stylus 8 was considered as an example, but lateral displacement acting upon condenser 10 or 11 will produce a similar effect, and in fact since the unidirectional output voltages from rectifiers 33, 34 and 35 are arranged in series or cascaded by means of chokes 31 and 32, as shown in Fig. 4, the effects of lateral and axial displacement on the thyratron unit which control voltage from the tracer unit the magnitude of which is their algebraic sum. Since it is possible that the central plates of condensers 10 and 11 may be displaced in either direction, it is important that these condensers should be accurately balanced electrostatically when the
The stylus displacement is zero. This may be effected by means of adjustable condensers 26 and 27 as previously described. In the initial assembly of the traceur unit the central plate 20 of condenser 3 should be so adjusted that it is situated at an electronic close to plate 18 as to plate 17 in the mechanically neutral or "no deflection" position, and therefore, since only a positive pressure can be applied axially to stylus 8 (i.e., the stylus cannot be subjected to a pull), the necessity of a balancing condenser is thereby eliminated.

It will be understood that the form of this invention heretofore shown and described is to be taken as a preferred example of the same, suitable for the contour milling of comparatively simple shapes in which the displacements of the stylus in three dimensions can be translated into a single control voltage, which operates to withdraw the work-piece from the tool regardless of the direction or combination of directions in which excessive pressure on the stylus occurs. If it is desired to employ a more exact form of control in which the displacements in different directions are to be treated independently, for example, a profiling with constant feed rate, then a tracer unit wired as depicted in Fig. 6 may be employed. In this arrangement high frequency output voltages 47, 48 and 49 from each of the three balanced condensers 5, 10 and 11 are supplied separately to three separate rectifier and amplifier control units.

What I claim as my invention is:

1. A pressure responsive device comprising a housing, a stylus resiliently mounted thereon and adapted to deflect through limited ranges in orthogonal directions in response to pressure, a plurality of pairs of opposed insulated capacitive plates rigidly mounted in said housing in orthogonal dispositions, a center-tapped inductance connected across said pairs of plates in parallel, an electronic oscillator coupled to said inductance for establishing high frequency electric fields between opposed plates in said pairs, a plurality of intermediate capacitive plates secured to said stylus and medially disposed between said opposed plates of respective pairs along planes electrically neutral with respect to said center-tap, deflection of said stylus in any of said orthogonal directions causing movement of corresponding ones of said intermediate plates out of their respective neutral planes and the induction of high frequency voltages thereon with respect to said center-tap, and a plurality of rectifying means connected between said intermediate plates and said center-tap for providing unidirectional control voltages proportional to said induced high frequency voltages for each of said orthogonal directions.

2. A pressure responsive device comprising a housing, a stylus resiliently mounted thereon and adapted to deflect through limited ranges in orthogonal directions in response to pressure, a plurality of pairs of opposed insulated capacitive plates rigidly mounted in said housing in orthogonal dispositions, a center-tapped inductance connected across said pairs of plates in parallel, an electronic oscillator coupled to said inductance for establishing high frequency electric fields between opposed plates in said pairs, a plurality of intermediate capacitive plates secured to said stylus and medially disposed between said opposed plates of respective pairs along planes electrically neutral with respect to said center-tap, deflection of said stylus in any of said orthogonal directions causing movement of corresponding ones of said intermediate plates out of their respective neutral planes and the induction of high frequency voltages thereon with respect to said center-tap, and a plurality of rectifying means connected between said intermediate plates and said center-tap for providing unidirectional control voltages proportional to said induced high frequency voltages for each of said orthogonal directions.

3. A pressure responsive device comprising a housing, a stylus resiliently mounted thereon and adapted to deflect axially and laterally through limited ranges in response to pressure, three pairs of opposed capacitive plates rigidly mounted in said housing, one pair being normal to the axis of said stylus and the other two pairs normal to each other and parallel to said axis, a center-tapped inductance connected across said pairs of plates in parallel, an electronic oscillator coupled to said inductance for establishing high frequency electric fields between opposed plates in said pairs, three intermediate capacitive plates secured to said stylus and medially disposed between opposed plates of corresponding pairs along planes electrically neutral with respect to said center-tap, axial and lateral deflections of said stylus causing movement of the corresponding intermediate plates out of their respective neutral planes and the induction of high frequency voltages thereon with respect to said center-tap, and a plurality of rectifying means connected between said intermediate plates and said center-tap for providing unidirectional control voltages corresponding to said deflections.

4. A pressure responsive device comprising a housing, a stylus, an elongated quill member holding said stylus, means including a diaphragm at the stylus end and a spring at the opposite end of the member supporting it and enabling it to deflect axially and laterally through limited ranges in response to pressure on said stylus, three pairs of opposed capacitive plates rigidly mounted in said housing, one pair being normal to the axis of said member and the two other pairs normal to each other and parallel to said axis, a center-tapped inductance connected across said pairs of plates in parallel, an electronic oscillator in said housing, including an oscillator circuit coupled to said inductance for inducing high frequency oscillations therein and establishing high frequency electric fields between opposed plates in said pairs, three intermediate capacitive plates secured to said member and medially disposed between opposed plates of corresponding pairs along planes electrically neutral with respect to said center-tap, axial and lateral deflections of said member causing movement of the corresponding intermediate plates out of their respective neutral planes and the induction of high frequency voltages thereon with respect to said center-tap, and a plurality of rectifying means connected between said intermediate plates and said center-tap for providing unidirectional control voltages corresponding to said deflections.

5. A pressure responsive device comprising a housing, a stylus, an elongated quill member holding said stylus, means including a diaphragm at the stylus end and a spring at the opposite end of the member resiliently supporting it and enabling it to deflect axially and laterally through limited ranges in response to pressure on said stylus, three pairs of opposed capacitive plates rigidly mounted in said housing, one pair located
next said diaphragm being normal to the axis of said member and annularly disposed relative thereto and the two other pairs normal to each other and parallel to said axis, a center-tapped inductance connected across said pairs of plates in parallel, an electronic oscillator in said housing, including an oscillatory circuit coupled to said inductance for inducing high frequency oscillations therein and establishing high frequency electric fields between opposed plates in said pairs, three intermediate capacitive plates secured to said member and medially disposed between opposed plates of corresponding pairs along planes electrically neutral with respect to said center-tap, axial or lateral deflections of said member causing movement of the corresponding intermediate plates out of their respective neutral planes and the induction of high frequency voltages thereon with respect to said center-tap, and a plurality of rectifying means connected between said intermediate plates and said center-tap, said rectifying means being connected in a cascade circuit for integrating the unidirectional control voltages corresponding to axial and lateral deflections of said member into a single unidirectional control voltage.

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