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MASTER

Detailed Description of Electronic Microscope
Stage Manipulator

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Figure 1 shows the scanning pattern through which the slide is moved. The three sketches illustrate the adjustment of the motion limits to suit the desired area and the adjustment of the vertical step size to prevent underscanning or overlap when the aperture size is changed. The horizontal and vertical limits of motion, horizontal rate and vertical step size are preset by the operator. Once initiated, the scanning process proceeds automatically to completion without further attention. The completion of each horizontal sweep is registered by the Sodeco counter on the control panel.

The scanning parameters are independently adjustable over the following ranges:

vertical range	5 to 100 μ
horizontal range	5 to 100 μ
horizontal rate	0.4 to 4 μ /sec
vertical step size	0.2 to 10 μ

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Description of Stage

The mechanical principle of the stage is illustrated diagrammatically in the sketch, Fig. 2. Two control assemblies are used. One assembly is supported by and rotated 90° with respect to the other so that the horizontal and vertical positions can be controlled independently.

The 0.005 in. tungsten wires used for both horizontal and vertical control are 9.2 cm long. For the full 100 micron range the wire temperature swings from 100° C to 350° C. Over this temperature range the resistance of the wire changes from 0.5 ohm to 0.95 ohm. The relation between the wire resistance and mechanical displacement is, for all practical purposes, linear. Under average ambient conditions, the feedback-controlled dc heating current in the wire varies from about 0.5 to 1.2 amps for full displacement. The control wires are run through 5/16 in. glass tubes for mechanical protection and shielding from drafts. The entire mechanical stage assembly is shown in the photograph, Fig. 3.

Functional Description of Electronic Control System

As seen in Fig. 4, the electronic control system is divided into four basic functional parts. The horizontal and vertical wire control circuits, which are identical, produce a direct heating current in each control wire. The heating current is feedback-controlled to adjust the temperature of the wire to cause its resistance to be accurately proportional to the voltage

applied to the wire control input. Because both the resistance and the thermal expansion of the wire are invariantly related to its temperature, the position of the stage is determined by the controlling voltage.

Tungsten was chosen for the control wire because its high ratio of thermal coefficient of resistivity to thermal coefficient of expansion yields a comparatively large resistance change for a given stage displacement.

The horizontal programmer produces a triangular output voltage of magnitude and slope adjusted to move the stage through the desired distance at the desired rate. At the end of each horizontal sweep the horizontal programmer delivers a trigger pulse to the vertical programmer, causing it to add an increment to the vertical position control voltage, thus advancing the stage one step vertically. This process is repeated until the vertical control voltage reaches a preset value which represents the height of the rectangular area to be scanned. At this point the vertical and horizontal programmers are reset and the stage is returned to the starting position. An electromechanical counter on the vertical programmer panel registers each horizontal sweep and is not reset until the next scanning cycle is initiated.

Wire Control Circuits

Figure 5 shows a schematic diagram of the identical horizontal and vertical wire control circuits. The control wire is heated by dc which flows in the collector circuit of the germanium power transistor, Q_7 . A 67 ma, 10 kc, square wave

sensing current signal is applied simultaneously to the control wire by Q_5 to provide an ac voltage drop in the wire which represents the resistance and, therefore, the temperature of the wire.

A 10 kc current of the same phase is applied to the 1.5 ohm resistor, R_1 , by Q_6 . The magnitude of this current is proportional to the collector supply voltage of Q_6 which is the -8 to 15V wire control voltage. For any particular control voltage there exists a wire temperature at which the 10 kc voltages across the wire and R_1 are equal. The phase and magnitude of the voltage difference between the wire and R_1 therefore represent the sign and magnitude of the wire temperature error.

The ac error signal is amplified by the following two-stage push-pull amplifier and applied to the synchronous rectifier, Q_{12} and Q_{13} . The resulting dc signal is amplified by Q_{14} to drive the base of Q_7 to provide the required heating current.

When the stage position is run through the 100 μ range, the peak to peak value of the 10 kc voltage across the wire increases by 100 mv. The corresponding increase in error signal, measured between the wire and R_1 , is approximately 1 mv, indicating a loop gain of the order of 100 which is more than adequate to insure that the stage position is essentially independent of the ambient temperature.

The 1.5 ohm reference resistor, R_1 , is located at the stage. Its ground return is common with that of the control wire, so

that the voltage drop in the common ground return which results from the difference between the 10 kc currents in the wire and in R_1 appears to the push-pull amplifier input as a common mode signal and is rejected. Separate potential and current leads are run out to the control wire and to R_1 to prevent the current lead voltage drops from appearing at the amplifier input.

Feedback due to the large collector-to-base capacitance of Q_7 was found to cause the impedance in its collector circuit to be so low at 10 kc as to cause serious shunting of the wire signal. This effect was eliminated by the addition of emitter degeneration via the 360 μ h ferrite-cored inductor, L_1 , to yield a high output impedance at 10 kc.

Dynamic Stability

Ideally, signals would propagate around the loop only in the normal mode in which they appear as modulation on the 10 kc carrier produced by changes in the wire resistance. Due to unbalance in the synchronous rectifier and other circuit imperfections it is also possible for signals to propagate around the loop by direct amplification. Since the tungsten wire is a very insensitive modulator a loop gain of 100 in the desired mode requires that the total electronic amplification in the loop be of the order of several thousand times. The resulting gain in the direct mode, therefore, can be of the order of hundreds.

In the modulated carrier mode the long thermal time constant of the wire sets a maximum frequency response which is at least

3 orders of magnitude below the electrical bandwidth of the system. The response extends down to dc at the low end. These conditions are ideal from the stability standpoint.

The stability situation is quite different for direct mode signals. Stability at the high end is no problem because the rectifier filter capacitor, C_3 , sets the upper cutoff frequency below the point where other circuit elements can contribute the additional 90° phase lag required for oscillation. At the low end, however, phase leads are contributed by the interstage coupling capacitors, the low frequency characteristic of transformer, T_2 , and the output capacitor of the 5V power supply. Here we have numerous time constants in the same order of magnitude, a very unfavorable situation for stability. The system was indeed observed to oscillate at about 200 cps.

It was not found feasible to separate the values of the pertinent time constants widely enough to eliminate the oscillation. The instability was finally eliminated by the addition of the low-pass filter formed by R_2 and C_5 at the synchronous rectifier output. The resulting upper cutoff frequency is much lower than the lower cutoff frequency for the direct amplification mode. The gain in this mode is therefore drastically reduced at all frequencies and no oscillation occurs.

The aforementioned filter also affects the upper frequency cutoff in the modulated carrier mode. Its time constant of about 0.03 sec (including loading by Q_{14}) is sufficiently shorter

than the thermal time constant of the wire that the stability in this mode is not affected. If C_5 is increased to the order of 200 μ f the preceding statement no longer holds and the system will overshoot seriously when the control voltage is changed quickly.

Horizontal Programmer

A schematic of the horizontal programmer appears in Fig. 6. The triangular horizontal control voltage wave is generated by a Miller integrator utilizing a Philbrick Type P-2 operational amplifier. Its gain of over 40,000 and its input current of less than 5×10^{-11} amp provide excellent linearity and stability even at the lowest scanning rates.

The feedback amplifier of unity voltage gain, comprised of Q_9 , Q_{10} , Q_{11} and Q_{12} , delivers an output voltage equal to the integrator output voltage at the 25 to 50 ma current level required to drive the horizontal wire control circuit. A loop gain of several hundred times insures that the output voltage faithfully follows that of the integrator at an output impedance of less than 1 ohm.

In the quiescent condition the integrator capacitor is shorted by R_{y3} and the output voltage is held equal to the -8V reference voltage applied to input terminal 1 of the P-2 amplifier. This voltage, which may be set by adjusting R_1 , determines the standing current in the horizontal control wire. The integrator output voltage will rise or fall according to the state of the flip-flop, Q_2 and Q_3 , at a rate determined by the setting of R_2 , the horizontal rate control.

The output voltage is sensed by two difference amplifiers, $Q_{13,14}$ and $Q_{15,16}$, used as amplitude discriminators to set the upper and lower limits of the horizontal sweep. The negative reference voltage for the lower limit discriminator, applied to the base of Q_{16} , is held 0.2 volt more negative than the integrator reference voltage by the forward drop in the germanium diode, D_1 . In the quiescent condition the output voltage is therefore 0.2 volt less than the discriminator threshold and the discriminator output current holds Q_6 in saturation. The pulse gate comprised of Q_6 and Q_4 applies positive trigger pulses, derived from the 10 kc square wave output of the horizontal wire control unit, to the collector of Q_3 , setting the flip-flop in the proper state to produce a voltage near zero at the collector of Q_5 , resulting in a positive integrator input voltage.

When the "start" button on the vertical programmer unit is pressed, R_{y3} opens, unshorting the integrator capacitor. The negative integrator output voltage increases at a uniform rate. When the output voltage, which is applied to the base of Q_{13} , exceeds the dc voltage on the base of Q_{14} , set by the horizontal range control, R_3 , in the base circuit of Q_{17} , the upper limit discriminator, $Q_{13,14}$, feeds current to the base of Q_{18} , saturating it. Positive trigger pulses are now applied to the collector of Q_2 , reversing the flip-flop to produce a voltage near -25 at the emitter of Q_5 and hence a negative integrator

input voltage. The negative integrator output voltage decreases at a uniform rate until it crosses the lower limit discriminator threshold. This discriminator and its pulse gate then reverse the flip-flop and the output voltage starts upward again. The horizontal programmer voltage thus oscillates linearly between the two preset limits as long as the integrator capacitor remains unshorted, producing a uniform back and forth horizontal motion of the stage. At each transition of the flip-flop the vertical trigger generator, Q_{19} , Q_{20} and Q_{21} , delivers a positive trigger pulse to the vertical programmer to advance the vertical position by one step. When the desired vertical limit is reached the integrator capacitor is shorted and the horizontal programmer is returned to the quiescent position.

Vertical Programmer

The vertical programmer is shown schematically in Fig. 7. When the "start" button is pressed the Sodeco counter "reset" coil is energized, clearing the counter, and the "latch" coil of latching relay, R_{y1} , is energized placing contacts 1A in the indicated position. This operation applies -25V to the upper end of the "release" coil, illuminates the "scan" light on the front panel, energizes relay, R_{y3} , in the horizontal programmer, removes the -25V inhibiting bias from the gating diode, D_1 , and de-energizes the 4 pdt relay, R_{y2} , placing its contacts in the position shown.

R_{y3} unshorts the integrator capacitor in the horizontal programmer and the horizontal sweeping process commences. At the end of each horizontal sweep, the vertical trigger pulse generated by the horizontal programmer is passed by the gating diode, D_1 , to trigger the univibrator, Q_1 and Q_2 , which produces a 50 msec output pulse. This pulse is amplified to the necessary 2 amperes by Q_3 , Q_4 and Q_5 , and delivered to the Sodeco counter "count" coil and to the combination of stepping switches, SS1 and SS2, to advance their position by one step, increasing the resistance between points X and Y (located between Q_{16} and Q_{17}) by 100 ohms. This resistance increment, by a process involving Q_{12} through Q_{22} , to be described later, increases the vertical programmer negative output voltage by an increment whose value is adjusted by the vertical step size control, R_1 , and the stage position is advanced one step vertically.

The output voltage is compared by the difference amplifier, Q_9 and Q_{10} , with a preset voltage selected by the vertical range control, R_2 (located between Q_{11} and Q_{12}). When the output voltage corresponding to the desired vertical range is reached, the dc output of the difference amplifier triggers the Schmitt discriminator, Q_7 and Q_8 , whose output current saturates Q_{16} to energize the release coil of R_{y1} , unlatching that relay and energizing R_{y2} . Relay, R_{y3} , shorts the integrator capacitor in the horizontal programmer, returning it to the quiescent state. Contacts 2A and 2B switch the stepping switches to the

self-homing mode while 2C shorts the stepping switch resistor string, returning the output voltage immediately to the quiescent value. R_{y1} may be released to initiate the "turn-off" sequence at any time before the vertical limit is reached by pressing the "stop" button (near Q_6) to energize the release coil.

If the vertical step size is adjusted so that the limit of 103 steps provided by the stepping switches is reached before the selected vertical range can be scanned, the turn-off sequence is initiated by the "A" circuit of R_{y2} on the last step.

In all cases the counter is not reset until the beginning of the next scanning process so that the total number of horizontal sweeps is displayed until the next scanning cycle is initiated.

Considerable difficulty has been experienced with the build-up of an insulating film on the contacts of stepping switches (and other types of relays) when the contacts were operated at low voltages and currents. The use of special contact materials greatly alleviates the problem but does not eliminate it altogether. For this reason the use of the resistor string as a simple unloaded voltage divider in which the position of the output tap is selected by the stepping switches is unsatisfactory. To draw current through the contacts would require loading the output, producing a non-linear advance in output voltage unless the divider resistors were weighted accordingly and errors might still result from residual contact resistance.

The use of the amplifier comprised of Q_{12} through Q_{16} avoids the contact-resistance problem completely. A feedback-controlled, constant output current from the collector circuit of Q_{19} flows through the stepping switch contacts, through whatever portion of the resistor string is in the circuit and through R_1 and R_3 to ground. The base, Q_{13} , which is one side of the differential input of the amplifier is connected to an adjustable reference of voltage, V_R , of approximately -8 volts, while the voltage drop across R_1 and R_3 due to the output current is applied to the base of Q_{16} , the other input terminal. The amplifier gain of several thousand times insures that the drop across R_2 and R_3 will be very nearly equal to V_R and therefore that the output current,

$$i_o = \frac{V_R}{R_1 + R_3}, \text{ where } V_R \text{ is the voltage}$$

applied to the base of Q_{13} .

The voltage at the top of the n th 100 ohm resistor, and all points above it, when the stepping switch combination is in the n th position will be given by $V_n = V_R + 100 ni_o$. V_n is independent of any contact voltage drop in the switch provided only that the drop is not so large as to prevent proper functioning of the circuit.

R_4 , which sets V_R , establishes the voltage at the bottom of the string while R_1 sets i_o and, therefore, the voltage increment for each step. The output voltage is taken from the

top of the resistor string and delivered to the vertical wire control at the necessary high current and low output impedance by the output amplifier, Q_{17} through Q_{22} . This amplifier is very similar to its counterpart on the horizontal programmer except that by the use of silicon transistors, operating at high impedance levels, its input impedance is made higher than one megohm. The high input impedance is necessary to prevent error due to voltage drop in the portion of the resistor string which is above the stepping switch tap position.

In a manner analogous to that of the horizontal programmer, the voltages which determine the quiescent stage output voltage, the vertical step size and the vertical range are all derived from and proportional to the -20V supply voltage which supplies the 10 kc reference current to the vertical control wire. The stage position is therefore essentially unaffected by supply voltage variations.

Fig. 1 Scanning pattern - The sketches A, B and C show how the vertical and horizontal ranges are adjusted to frame the desired area. Different apertures are shown with their corresponding vertical step sizes to illustrate the adjustment of step size to prevent overlap or under-scanning when the aperture is changed.

Fig. 2 Sketch illustrating the mechanical principle of the stage. The tungsten wire is held under tension by the steel leaf springs. Thermal expansion and contraction of the tungsten wire produce the stage motion.

Fig. 3 Photograph of the complete stage assembly.

Fig. 4 Block diagram of electronic control system.

Fig. 6 Schematic of horizontal programmer.

NOTES:

1. ALL TRANSISTORS ARE 2N586 UNLESS OTHERWISE INDICATED.
2. RELAYS ARE SHOWN IN "SCAN" CONDITION; LATCHING RELAY, Ry1 IS LATCHED AND 4 PDT RELAY, Ry2 IS NOT ENERGIZED.
3. STEPPING SWITCHES, S.S.1 AND S.S.2 ARE SHOWN IN "HOME" POSITION.
4. S.S.1 - 26 POS. 8 CKT. STEPPING SWITCH.
5. S.S.2 - 10 POS. 2 CKT. STEPPING SWITCH.

Fig. 7 Schematic of vertical programmer.