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DEVELOPMENT OF A MERCURY JET SWITCHING SYSTEM

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DEVELOPMENT OF A
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ABSTRACT

A high speed commutating and/or sampling switch for monitoring each of 120 separate circuits 60 times per second or faster is described. This switch employs a unique contacting technique. By using the switch rotor as a self-primed centrifugal pump, a jet stream of mercury is created which continuously emanates from a central pool of mercury (the pole of the switch) contained in the switch rotor. This jet stream is caused to sequentially contact pins located circumferentially around the switch stator, thereby connecting each pin in succession to the pole. Dwell times on each contact are adjustable in the region of 100 microseconds per sample. Gravity is utilized to collect the mercury from the jet in a sump in the stator, and the mercury is introduced again by 2 helical scoops to the input of the centrifugal pump, thus completing the mercury cycle.

In addition to its high sampling rate, this switch is characterized by a lack of contact bounce phenomena and by the potential of hundreds or thousands of hours of continuous trouble-free operation.

Limiting noise is due to discharge of accumulated static electricity generated in operation. By designing the switch components with this is mind, it is possible to minimize the accumulation of static charges, thus keeping the noise below an acceptable level. At an impedance level of 10,000 ohms, noise spikes of about 1/2-volt amplitude and 1-microsecond duration occur at a rate of 1 to 2 per minute.

Also described is a method of electronically synchronizing two such switches that are remotely located (that is, not mechanically coupled by virtue of a common shaft). Requirements for this type of operation exist in the telemetering system for which the switch was developed. The method used employs two single-phase

60-cycle synchronous motors which run at identical speeds. Because of a critical requirement for torque angle stability, special synchronous motors having a minimum of torque angle hunting are required.

The motors are kept in exact and particular phase match (to less than 5 microseconds) by controlling the phase of the power supplied to one of the switches. All electronic circuitry required to accomplish synchronization can be located in the vicinity of either switch.

INTRODUCTION

In order to test, operate, or control various complex systems of the types evolved in recent years, it is necessary to collect and evaluate data concerning many different parameters. It is frequently of importance either to collect data continuously, or to sample it at such a rate that no significant changes take place between one sampling period and the next. In an effort to accomplish this latter task in as efficient a manner as possible, investigators have developed, for telemetering systems, mechanical commutators sampling as many as 100 contacts at speeds up to 2000 rpm. However, because of the considerable wear undergone by mechanical parts operating in a rubbing or wiping fashion at high speeds, and also because of difficulty encountered in trying to cope with the phenomenon of contact bounce, it has long been obvious that investigation of other methods of commutating is desirable.

After consideration of several alternative possibilities, including electronic switches, the University of California Radiation Laboratory conducted a preliminary investigation of the feasibility of using a mercury jet switch in an effort to accomplish a high speed sampling function. In view of the promise shown, a contract was entered into with Detroit Controls Corporation in January of 1954, providing for development and construction of two mercury jet switches.

The concept of utilizing a jet stream of conducting liquid, such as mercury, as the pole contact in a rotary switch was mentioned in a patent as early as 1902 (1)*. From the scarcity of literature on the subject, however, it appears that in spite

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* Numbers in parentheses refer to similarly numbered entries in the Bibliography.

of early conception, not much interest was aroused until quite recently. The design and construction of a mercury jet switch at the United States Navy Electronics Laboratory (San Diego) has been described in a 1952 report (2) by H. Nathan.* Recent work of this type in connection with temperature monitoring has also been done by R. Hoff (3) at the General Electric Company in Richland, Washington. References to other work (4, 5) are included in the Bibliography.

While the purpose of this program initially involved the development of a practical switch design, it was known at the start that the untimate objective was to have two remotely located switches which could be operated in exact synchronism. Accordingly, the program has resulted in the complete design, construction, and successful test of two experimental model switches together with a system whereby the switches can be run automatically in synchronism when remotely situated, with the only qualifying condition being that a common power frequency be available at both switch locations. Complete details of the work involved in reaching this objective are contained in the following sections of this report.

*The mechanical design details of the first two switches made at this laboratory are similar to the one described by Nathan, and because of interest and cooperation provided by Nathan and NEL, the early stages of work at Detroit Controls Corporation were accelerated appreciably.

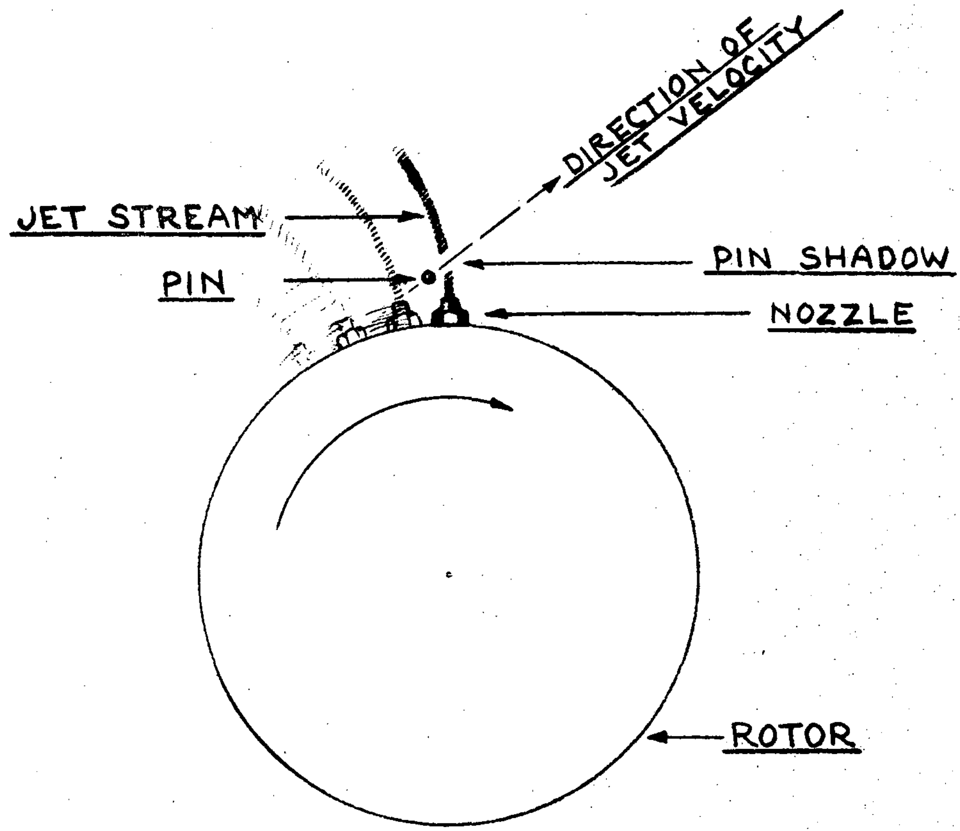
DESIGN AND DEVELOPMENT STUDIES

A. Rotary Jet Switch

Functionally, the rotary jet switch that has been developed is a single-pole multiple-contact selector switch. It must be rotating in order to provide transmission and thus has no stationary mode of operation. It differs, however, from mechanical selector switches in that it allows the possibility of being driven at high cyclic speeds, at least up to 100 cycles per second.

Basically the switch consists of a centrifugal pump primed by a screw-type scoop, which lifts mercury from a sump into an annular rotating pool from which it is ejected by centrifugal force through a small nozzle. After leaving the nozzle, the mercury impinges upon a series of stainless steel contact pins located just outside the periphery of the rotor, and then returns to the sump by gravity, thus completing the cycle. This device can be used as a switch because, during the time the jet stream is in physical contact with one of the steel pins, a low-impedance electrical contact through the mercury exists between the pin and a pole contact inserted into the sump.

Calculations indicate that the mercury in the jet stream is being ejected at a speed of approximately 63 fps, with a pressure drop across the nozzle of about 300 psi. The diameter of the jet stream is proportional to the diameter of the nozzle. Nozzles varying from 0.003 to 0.015 inch in diameter have been tried; best electrical performance was found in the range from 0.003 to 0.008 inch. Stroboscopic observation gives some indication of standing waves in the stream, and also has established that the direction of the velocity of the particles is about 45 degrees from radial and that the path of the conducting jet is slightly curved (see Figure 1).



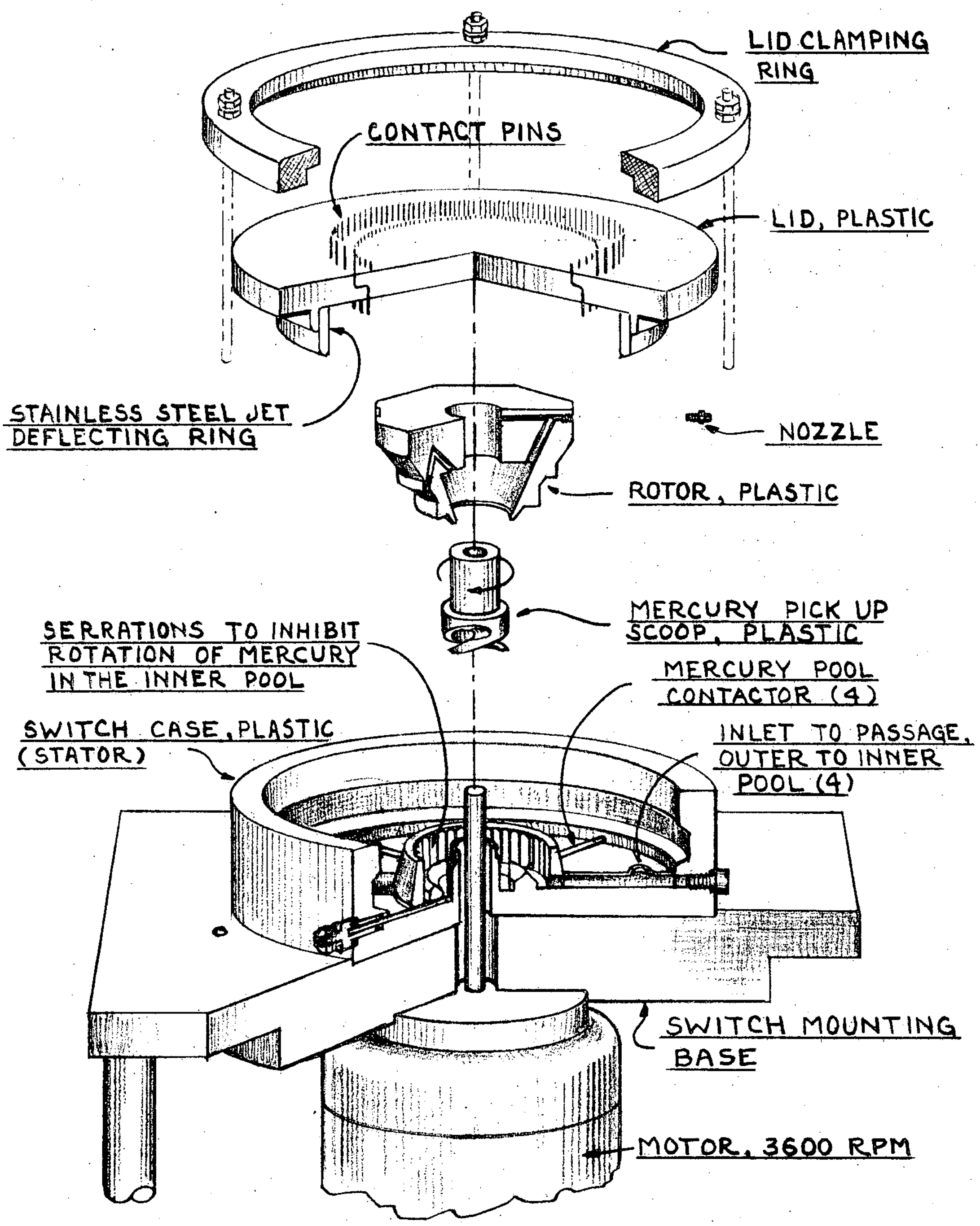
MERCURY JET STREAM

FIGURE 1

Two switches were built, both of which operate according to the foregoing description. While they differ somewhat in order to permit evaluation of different ideas, materials, and construction, both contain three major components - a case, a rotor, and a lid containing the contact pins. Figures 2 and 3 are exploded views of the two models 402-1 and 402-2, respectively.

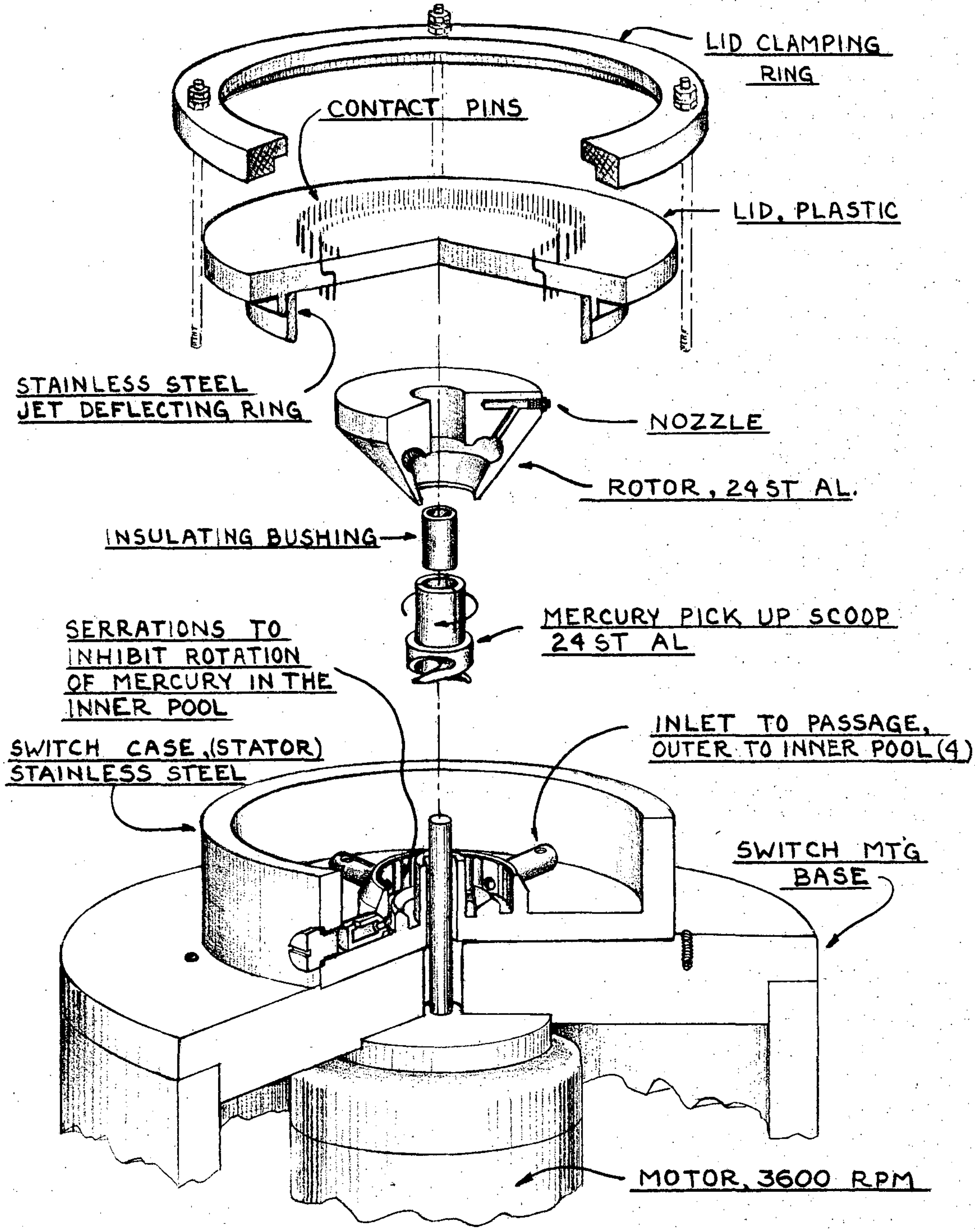
1. Case

In both models, the case provides a means of mounting the unit, a means of mounting the drive motor to the unit, and a container for the mercury. The case for model 402-1 was made of clear acrylic plastic; that for 402-2 of stainless steel. Both



MODEL 402-1

FIGURE 2



MODEL 402-2

FIGURE 3

satisfactorily provided for the three functions just outlined. In addition, the plastic case allows observation of the switch during operation.

In the course of testing 402-1, evidence indicated that electrical noise was being generated during switch operation, as a result of discharge of static electricity. For the reasons described under "Single Switch Performance," it was decided to construct the case for 402-2 of stainless steel. Various simplifications in details, such as in the mercury feeder ports, were also incorporated and proved to be acceptable.

2. Rotor

In both switches, the rotor provides the similar basic function of collecting the mercury, imparting kinetic energy to it, and ejecting it in a stream toward the pins. The first rotor was made of acrylic plastic. Various factors entered into this choice of material, such as its inert character with respect to attack by mercury, its light weight (which allowed the possibility of less dynamic instability at the high angular speeds required without the necessity of precision alignment), and its transparent nature which was an aid in machining the complicated inner passages.

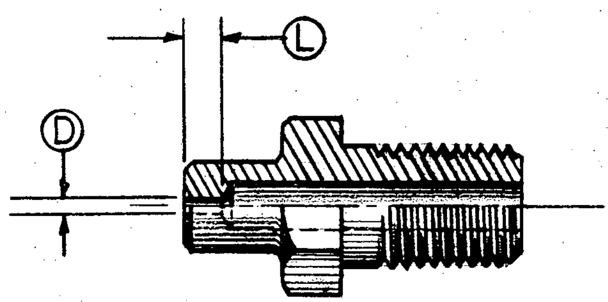
This complex labyrinth of rotor passages arose from a desire to minimize the possibility of switch malfunction due to presence of mercury scum, which consists of various solid components insoluble in mercury and non-conductive in electrical characteristics. It is made up primarily of mercury oxide generated in the course of the continual atomization and agitation of the mercury in the switch.

In the course of experimenting with the first plastic rotors, it was found that plugging of overflow nozzles, whose purpose was to flush scum from critical areas, did not cause the rotor to become clogged even after hundreds of hours of operation. It was also found that plugging of the contacting nozzles, whose purpose was to insure electrical connection between the rotating annular pool in the rotor and the sump in the stator, did not compromise the electrical connections. Furthermore, the generation of static electricity was reduced considerably by plugging these nozzles.

Since objectionable static was still being generated with a plastic rotor and a steel case, a conductive rotor was designed. By eliminating the various passages required to feed those jets found to be superfluous, a simpler rotor was obtained. Aluminum was used for light weight and ease of machining, in spite of its susceptance to attack by mercury. This was justified as allowable for the purpose of investigating quickly and easily the effect of a conductive rotor on static noise generation. It was conceded that this rotor, in comparison to one of plastic or stainless steel, might not permit as many hours of operation without becoming so contaminated that the mercury passages would become plugged.

Thus the rotor in the second switch, 402-2, is aluminum. It has operated approximately 100 hours without becoming plugged, although there is considerable evidence of scum accumulation in the inner passages. In addition, the generation of static electricity is reduced to the extent that the noise level is acceptable.

An important and interchangeable part of the rotors is the nozzle (Figure 4) through which mercury is ejected toward the pins. Nozzles with bores (D) of from 0.003 to 0.015 inch were



NOZZLE
FIGURE 4

made and tested. Best operation with the pin spacings used was found with nozzles in the range of 0.003 to 0.007 inch. The length (L), which ranged from 0.010 to 0.0562 inch, was not found to be critical, nor was the distance between the end of the nozzle and the pins in the approximate range of 0.005 to 0.050 inch. For current operation, nozzles with D = 0.005 inch and L = 0.010 inch are set at about 0.014 ± 0.002 inch from the pins.

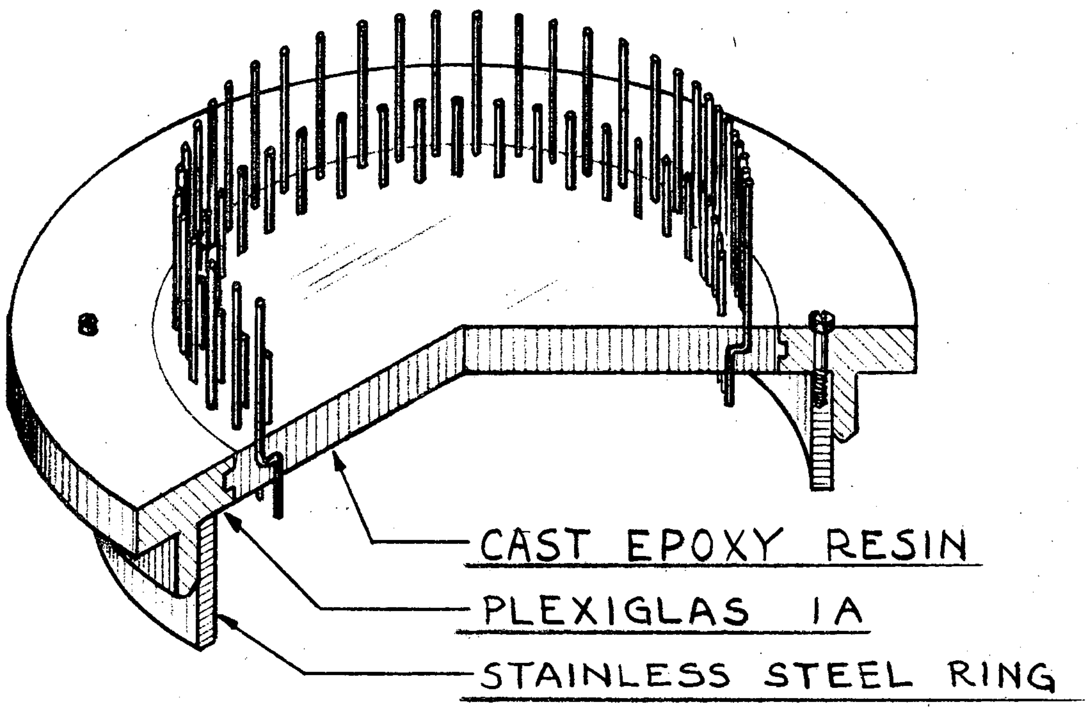
In both switches, the rotor is mounted on a shaft supported external to the case. In 402-1, this shaft is the motor shaft and thus becomes part of the rotor. In 402-2, the case is mounted on a plate containing a bearing and double extending shaft. The rotor is mounted on one end of this shaft, the motor on the other. This second arrangement was provided to facilitate flywheel experiments conducted during one phase of the program.

3. Lid

In spite of the precision required in spacing and aligning the contact pins, the switch lids have given the least trouble of the three major components. This is due in part to a novel way of casting the pins into the lid (Figure 5), requiring a single precision template for making all lids.

Three interchangeable lids have been made. Alternate pins have been removed from one and the pins adjacent to the synchronizing pin have been removed from that one and one other. Before pin removal, all lids contained 240 pins on a 3-inch circle, spaced 1-1/2 degrees or 0.040 inch apart (center to center). All pins are of 0.014-inch stainless steel wire, and are cast into the lid using an epoxy resin.

In the two lids without alternate pins removed, only alternate pins are connected to active circuits. The intervening pins "float" electrically and, by the mechanism of the mercury jet, are connected in the course of one revolution to the live pin on each side but not to both simultaneously. Thus, it has been possible



SWITCH LID

FIGURE 5

to achieve a high proportion of "on" or "dwell" time to total time between identical portions of successive live circuits without shorting adjacent live pins together.

In the lid with alternate pins removed, dwell time was limited to about 57% of the total, even though adjacent pins were separated by 0.066 instead of 0.026 inch. With the floating pins, on-time up to about 90% was achieved without bridging of live pins.

Although sufficient work was not completed to permit a correlation of the various factors and their contribution to dwell time, the following are of importance: pin spacing, pin diameter, nozzle diameter, and floating pin configurations. With all other factors held constant, pin spacing equal to 0.080 inch center to center, pin diameter of 0.014 inch and no floating pins, the nozzle diameters were varied on switch 402-2 (steel case, aluminum rotor).

The following dwell times were noted:

Nozzle Bore Diameter (inch)	Time On (microseconds)	Time Off (microseconds)	Dwell Time (%)
0.003	40	100	28.5
0.004	60	80	42.8
0.005	70	70	50
0.006	75	65	53.5
0.007	80	60	57
0.008	Contact bridging occurred		

A phenomenon which requires some comment is the shorting of adjacent pins by isolated static mercury droplets. When alternate pins were removed, almost no shorting was observed. Furthermore, some indications were obtained that less shorting occurred when the plastic near the pins was sandblasted, but time did not permit conclusive tests.

B. Synchronizing System

There are at least two ways in which telemetering can be accomplished when using this type of commutation. One method is to locate a single switch near the phenomena that are to be monitored. This switch can then be used to collect the data from the numerous channels, combine this data into a single channel, and relay the information to a remote station where it can be processed. At the remote station, the information, consisting of small time samples from each phenomenon, and coded in that adjacent time samples contain information from different circuits, can be stored in the coded condition. If this procedure were used, subsequent read-out would then require that the stored record be essentially rechopped, sorted, and regrouped so that signal bursts associated with each phenomenon could be viewed or analyzed together. This decoding procedure would of course be time consuming.

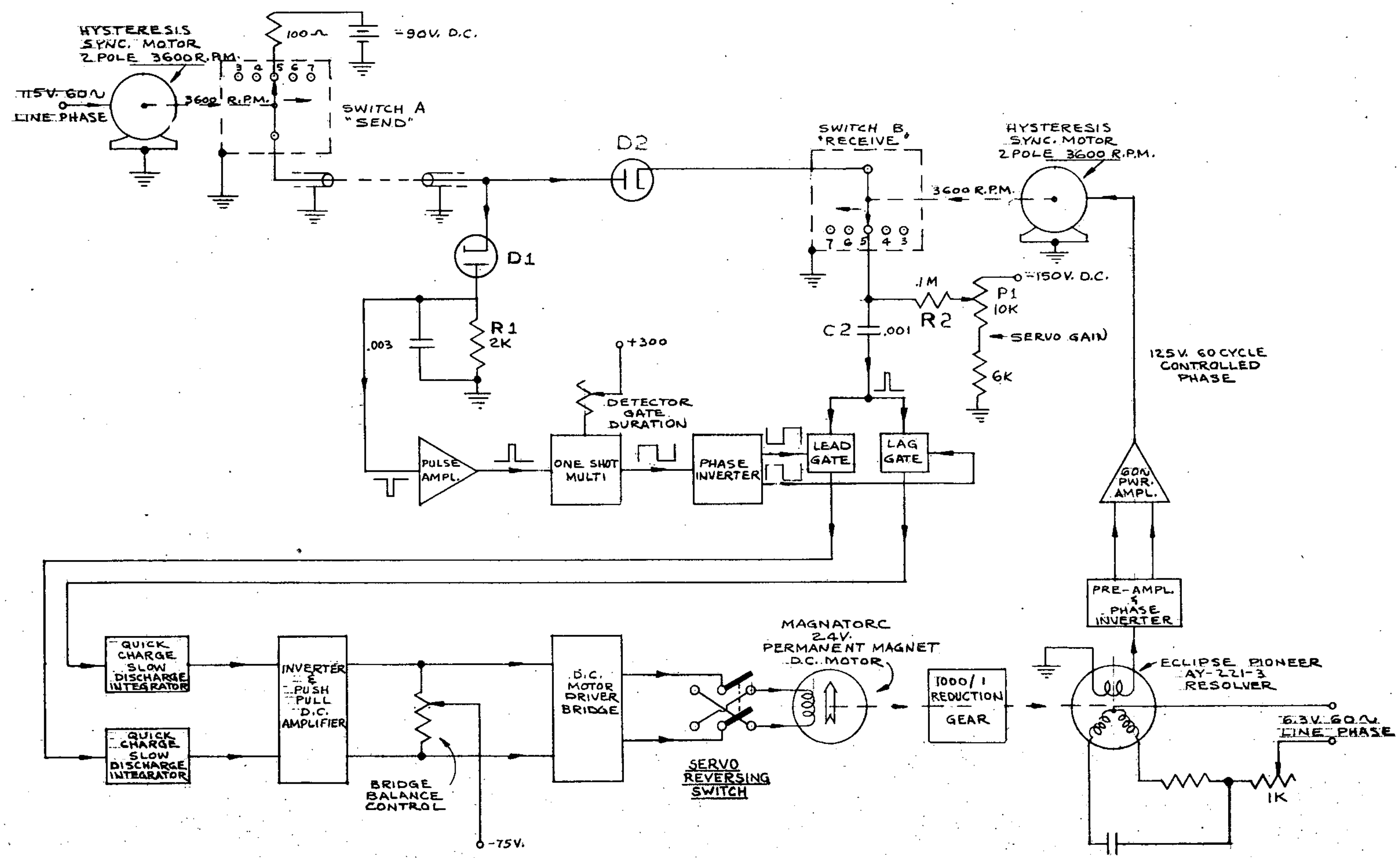
A second, simpler method of providing decoded information would be to encode all the various circuits onto one channel at the sending end as before, and then simultaneously to decode the information at the receiving end. This may be accomplished by using, for decoding, a switch which is an exact counterpart of that used to encode. Now, if these two switches are operated in synchronism, signals being transmitted on a given channel at the sending end will simultaneously be fed into the proper channel at the receiving end. With this scheme, it would be possible to assign to each signal-sending circuit a particular type of device that would be well suited to monitoring and/or recording the expected type of signal from that circuit. For the telemetering application of present interest, this type of synchronizing system was desired.

1. Basis for Synchronous Operation

Because synchronous motors run at line frequency or some integral subfraction thereof, it seemed logical to operate two switches, A and B, in synchronism merely by rotating both switches with synchronous motors driven from a common power supply, and by adjusting the phase of the driving frequency to one motor to control the relative position of the rotors. The synchronizing system that has been developed is based on this type of operation.

Two assumptions underlie this approach: 1) the torque angle of a synchronous motor driving a predominantly inertia load, such as the switch, remains nominally constant at least through one revolution of the rotor; and 2) two (or more) synchronous motors operating on a common supply frequency will, in equal periods of time after lock-in, make exactly the same number of total revolutions, with an integral relation to the number of cycles the supply frequency has undergone.

The synchronizing problem is thus reduced to knowing explicitly the difference between the phase which some chosen reference point on one rotor has with respect to a reference point on its stator, and the phase of a rotor-stator reference pair on the other switch. For sake of illustration, the jet will be considered the rotor reference point and contact pin #5 the stator reference point (see Figure 6).



SYSTEM BLOCK DIAGRAM

FIGURE 6

The phase-controlling system utilized can be explained simply. The time at which the jet on switch A contacts pin 5A is compared with the time at which the jet on switch B contacts pin 5B. This time (phase) difference is measured and utilized as an error signal to change the phase of the supply to the controlled switch B in such a direction that this difference is caused to go to zero. If no time difference exists, there is no error signal, but the latter increases proportionately as time difference increases up to approximately 20 microseconds, then remains constant.

2. Investigation of Synchronous Motors

The servo system developed is slow with respect to one revolution of the synchronous motor. It is therefore necessary that the motors themselves maintain as constant a speed and phase angle as possible. The only information available on fractional-horsepower synchronous motors indicated that both the hysteresis and the salient-pole types were very good in this regard. Consequently, motors of each type were tested. The first ones examined were an Air Marine Products two-pole hysteresis synchronous motor (1/60 hp at 3600 rpm), an Eastern Air Devices two-pole salient-pole synchronous motor (1/50 hp at 3600 rpm), and a Bodine Company two-pole hysteresis synchronous motor (1/50 hp at 3600 rpm).

Preliminary tests showed that in all three motors, at intervals of a few seconds, the phase angle position would of itself burst into oscillation with respect to line phase. This oscillation would last for several cycles and stop. It could also be externally excited by a sudden line voltage change or a transient externally applied torque. The exact character of the oscillation varied from motor to motor.*

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* The phase angle of the Air-Marine Products motor oscillated at approximately 2 cycles per second. The bursts would last for about 3 to 5 cycles and would occur spontaneously approximately every 5 seconds. The magnitude of the bursts was about 2 degrees peak to peak. The phase angle of the Bodine motor oscillated somewhat slower at approximately 1-1/2 cycles per second. The

The item of importance in this situation, however, is not the hunting of the phase angle with respect to line phase, but rather the hunting that exists between two separate machines, on the line, with respect to each other. A major effect of this phenomenon, of course, is a reduction of the dwell time of a particular channel being transmitted at the instant of hunting, thereby reducing the total amount of information that is being transmitted on the affected channel. By operating two switches in synchronism (Figure 7), applying signals to one, and monitoring the signals from the other, it was found that hunting reduced the dwell time from about 70 to 60% when the remote switch was run on the Bodine motor and the receiving local switch was run on the Eastern Air Devices motor.

It became apparent, after consultation with other people interested in and using constant speed drives, that motor performance required for such switch synchronizing is somewhat better than that needed for other applications. Furthermore, in most cases the motor manufacturers are not particularly acquainted with this aspect of the phase characteristics of their products. Accordingly, a program was inaugurated to determine the effect of flywheels on stabilizing the motors and reducing or damping-out the phase angle hunting. Solid flywheels had the expected effect of decreasing the frequency of the oscillations but increasing their magnitude. Compound viscous-coupled flywheels showed more promise, but considerable effort is required to design and build different models. This program was discontinued upon discovery of the availability of an electrically damped synchronous motor developed by the

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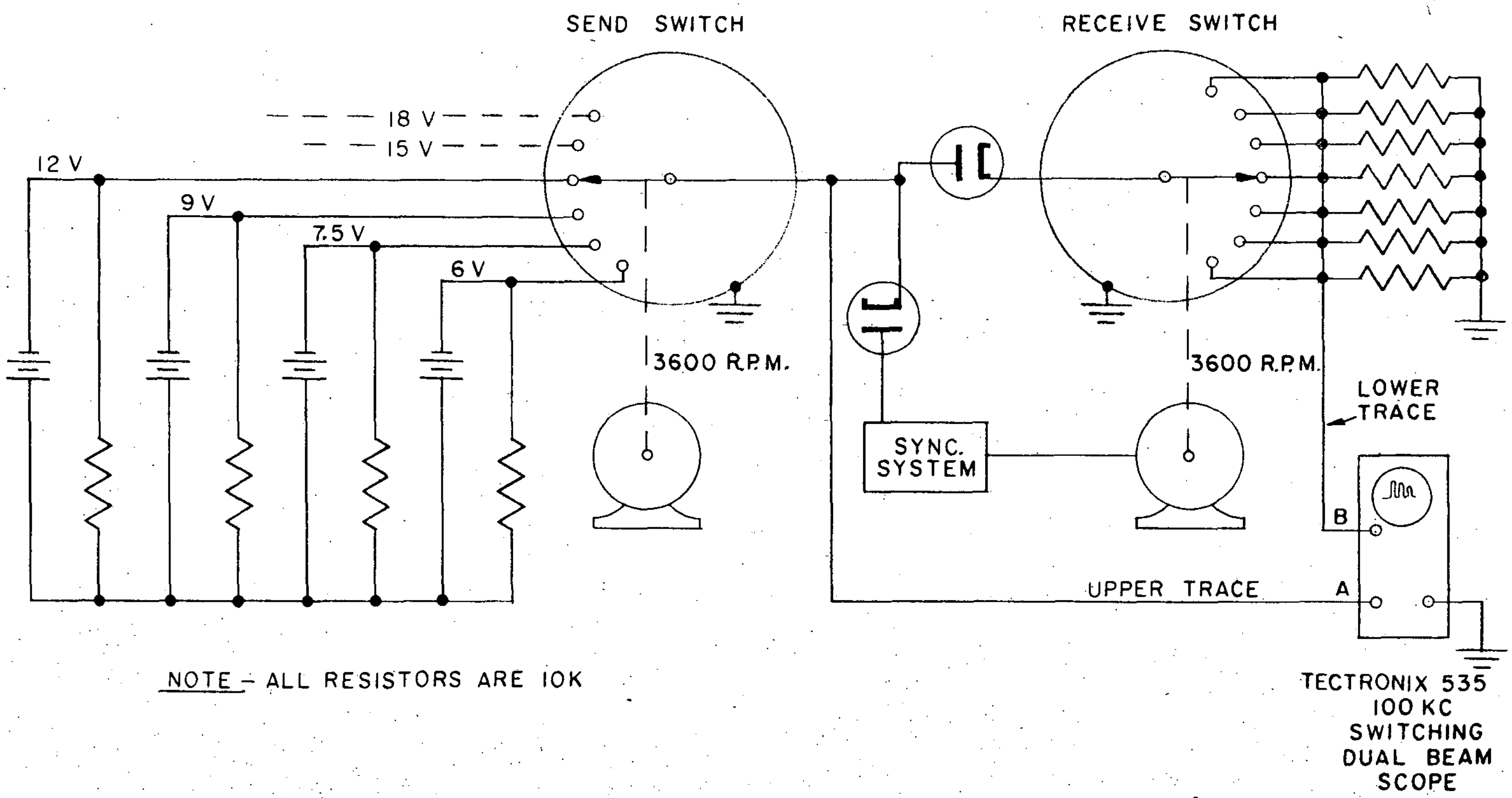
bursts lasted for about 2 or 3 cycles and would occur at approximately 10-second intervals. The magnitude was about 1 degree peak to peak. The Eastern Air Devices motor was the best of the three. The oscillation frequency was approximately 3 cycles per second, and the bursts lasted about 2 to 3 cycles. They occurred much less frequently, however, often only 2 per minute. The peak-to-peak magnitude was less than 1 degree.



SIMULATED TELEMETERING SYSTEM

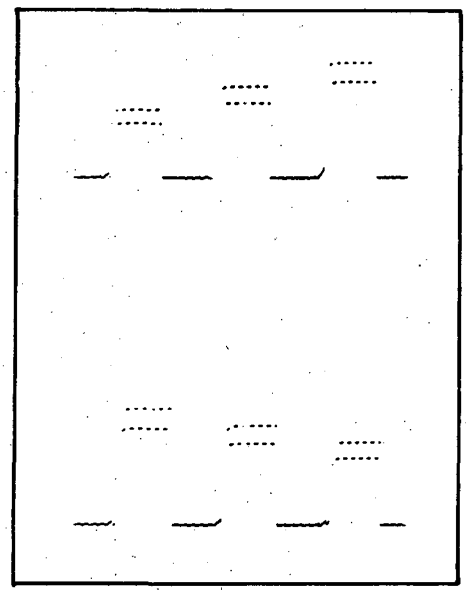
FIGURE 7

Electric Indicator Company (ELINCO), Springdale, Massachusetts.* The only motor available for immediate delivery, a two-pole machine rated at 1/20 hp, was procured, and found to have better phase characteristics than those previously tested. Hence, it was incorporated into the system, which at present is operating with this and the Eastern Air Devices (EAD) salient-pole motor. While relative hunting still exists, it is of low magnitude, and the average reduction of dwell time is only approximately 5%.

Normally, however, the system operates for some time without any disturbance of the phase angle. In Figure 8, which shows the receive signal superposed upon the send signal (refer to Figure 7),

SUPERPOSITION OF SEND AND RECEIVE SIGNALS

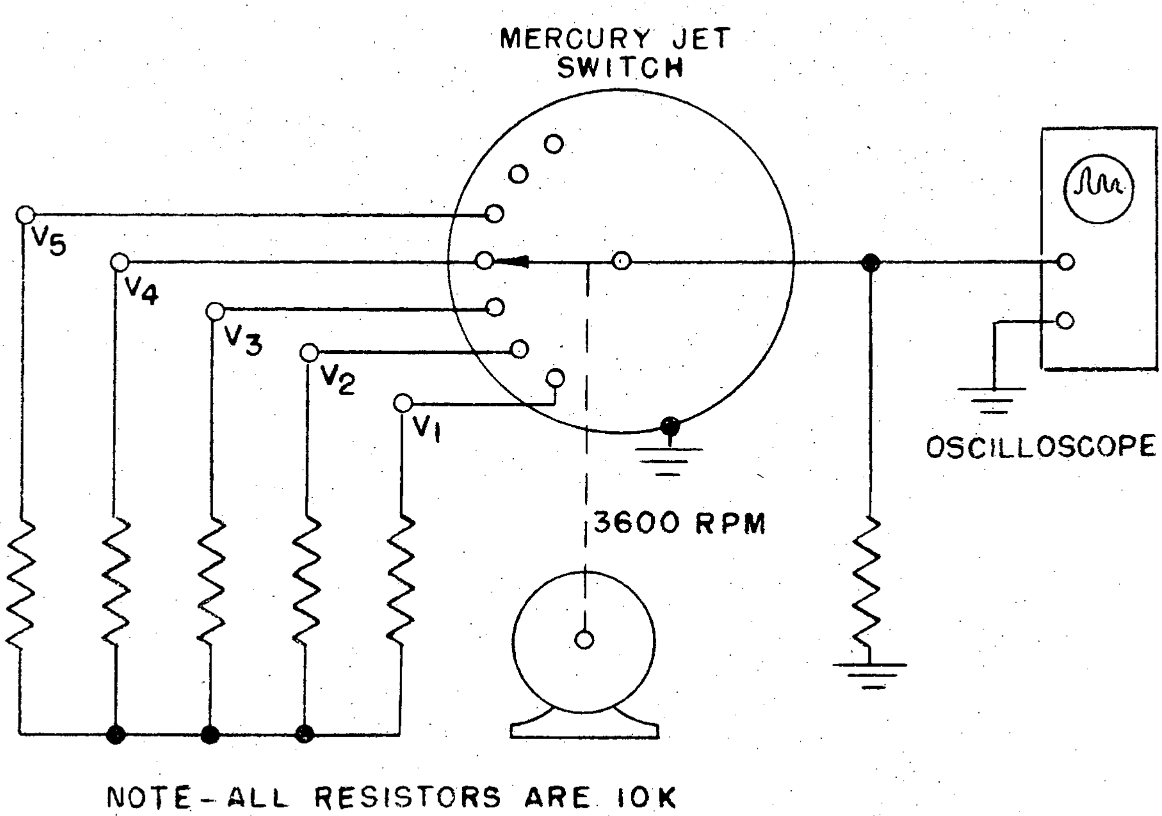
FIGURE 8



* This motor (termed a damped hysteresis motor) contains squirrel cage windings in the rotor in addition to the iron hysteresis sleeve. It was found that the effect of the squirrel cage bars was to considerably damp any phase angle oscillations. The specifications indicated that a motor which normally would have about 15 cycles of phase oscillation before the oscillation disappeared was improved by such damping so as to have only one overshoot, after any disturbance causing oscillation.

it can be seen that the on-time of the receive signal is practically identical with the on-time of the send signal. In this instance, the send switch was 402-2, driven by the ELINCO motor. Because of the lid configurations used, the send switch has a 60% dwell and the receive switch (402-1) a 65% dwell. Since dwell time of the combination can never be greater than the shortest dwell time, the maximum net dwell time that could be achieved is 60%. With average hunting, the net dwell time is never less than 55%.

C. Single Switch Performance



CIRCUIT FOR SAMPLING D-C VOLTAGES

FIGURE 9

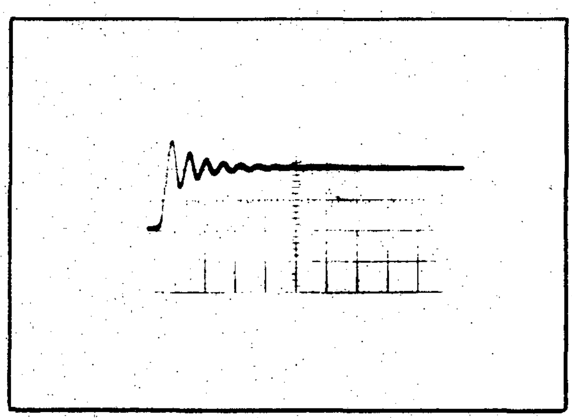
Considerable effort was devoted to operating individual switches as single-pole 120-position sampling switches, in order to obtain detailed information about such items as dwell time, contact resistance, noise level, and other associated items of interest. The impedance level of the circuit used has a considerable effect on the noise and transients involved in operating a switch, and since a nominal value of 10,000 ohms seemed reasonable, it was used as the terminating impedance for each circuit. The information recorded in the following sections was accumulated by using essentially the circuit outlined in Figure 9, with signals generated by a dry cell battery.

1. Dwell Time

An item of interest is the exact detail of the making of the jet-to-pin contact. It will be useful in the following discussion to bear in mind that since the switch was always operated at 60 cycles, and since there were 120 separate circuits on the switch, the time between identical portions of successive contacts is essentially 140 microseconds. Thus a contact with 50% dwell time is connected for 70 microseconds.

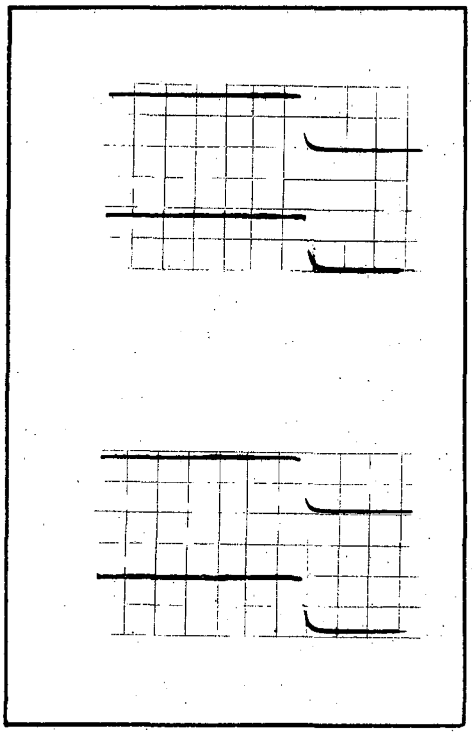
In observing the square waves generated by d-c voltages on successive pins, it appeared that the leading edge was indeed very square. In order to study its fine structure, experiments were undertaken utilizing a sweep speed of 0.2 microsecond per centimeter. In Figure 10, which shows the leading edge of a typical pulse, it

CONTACT-MAKE RISE TIME
Sweep Speed
0.2 microsecond/division
FIGURE 10



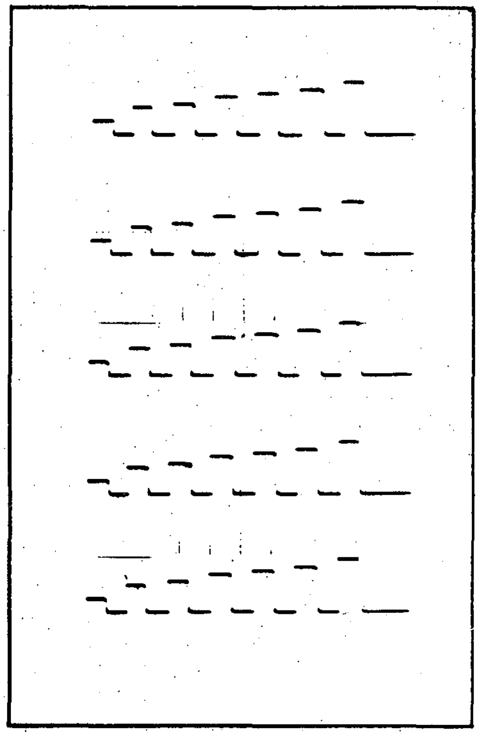
can be seen that the signal rises from 0 to 100% in approximately 0.05 microsecond and then undergoes a damped oscillation which continues for about 5 cycles at a rate of approximately 7 megacycles, resulting in the total switching transient being over after about 0.8 microsecond. In the course of these experiments, it was found that the exact frequency of the "ringing" could be changed by varying the lengths of the leads in the monitoring system. It is thus believed that this ringing is due to the external circuit and not inherent in the switch.

Typical performance for the remainder of the dwell is characterized by a very flat noise-free signal, with the following exception. When the final 5 to 10% of the on-time is reached, uncertain operation is encountered in some cases. Two distinct possibilities exist. The first is that the contact will break at different times on the same pin from one cycle to the next. This is evidenced by the fact that when an oscilloscope monitoring the signal is synchronized to the 60-cycle line, the leading edge starts at the same place for each succeeding cycle, whereas the trailing edge flutters back and forth a slight amount. The second possibility is that the last portion of the signal just preceding the contact break will have, at times, a "jitter" or noise superposed upon it. This noise, which can last anywhere from 5 to 10% of the total signal length, has an appearance very similar to that of contact bounce found in mechanical switches. However, it is confined to the trailing edge, and its maximum magnitude is of the order of 10%. In an enlarged picture of typical pulses (Figure 11), this phenomenon can be clearly observed, but in a picture showing several successive pins or contacts (Figure 12), it is hardly noticeable. Only in extreme cases, which occur about



TYPICAL CONTACT-BREAK
CHARACTERISTICS

FIGURE 11



IDENTICAL SAMPLES OF
SEVEN D-C VOLTAGES

FIGURE 12

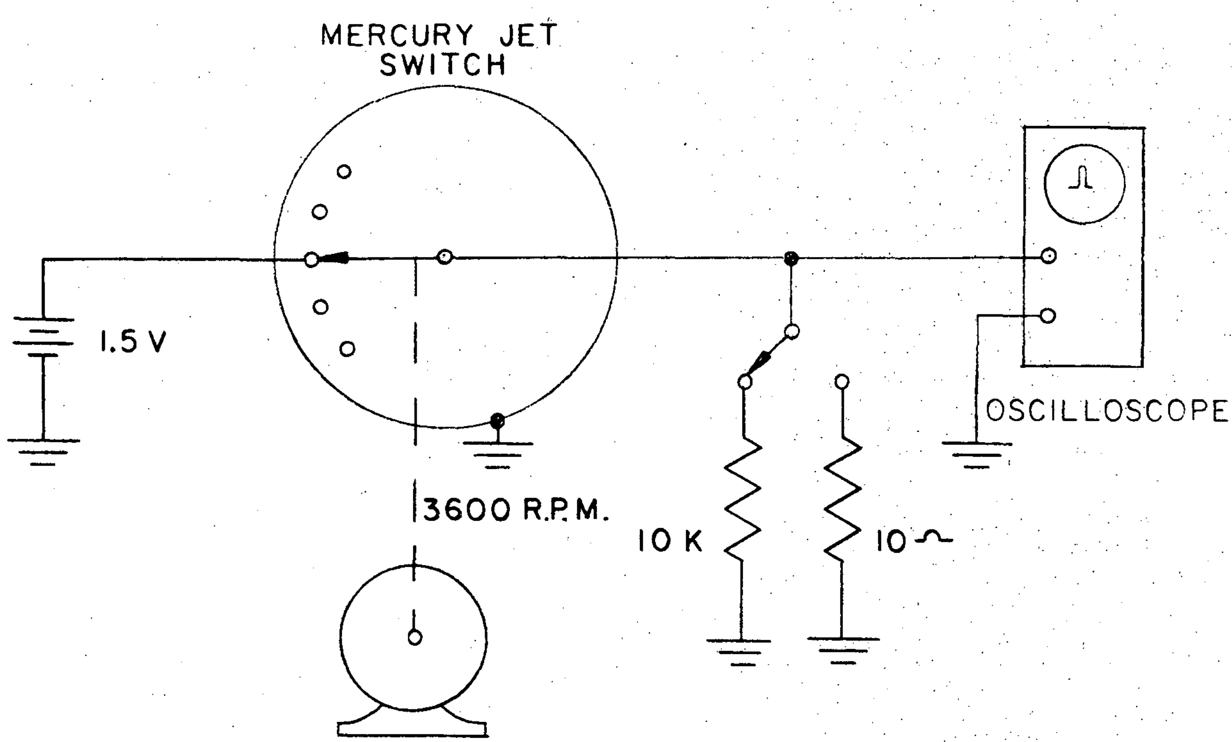
once in 50, can this phenomenon be noticed in a group of pulses. Another distinguishing feature that can be seen in Figure 11 is the considerably longer break time evidenced by the rounded character of the signal as it approaches the base line.

Figure 12 shows a series of single-shot photographs of seven successive pins or contact circuits. A different d-c voltage was placed on each pin, thus giving the stair-step effect. The sweep speed for this picture is 100 microseconds per centimeter, and the over-all impression is one of a very clean square wave, examination of which reveals that the dwell time is slightly over 50%. In these pictures, the synchronizing signal which initiated the scope sweep was always the 60-cycle line frequency, and it can be seen that each signal burst lines up very well with that above it.

These bursts are separated by several hundred switch revolutions, which were not monitored because of the time required to move the camera to a new position and trigger the sweep again.

2. Contact Resistance

An item of considerable interest to anyone using a contacting switch is the effective resistance between the pole and the contacts. By utilizing a circuit similar to that shown in Figure 13, the contact resistance of this switch was measured and found to be approximately 1.4 ohms.



CIRCUIT FOR MEASURING CONTACT RESISTANCE

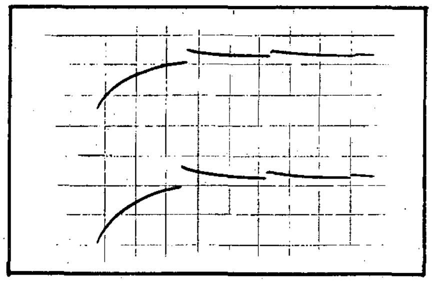
FIGURE 13

3. <u>Noise Level</u>

Although very little of the noise commonly classified as contact bounce is involved, there is noise that is peculiar to this type of switch. As nearly as can be determined, the noticeable noise is due to an accumulation and subsequent discharge of static electricity, apparently generated by the breaking up of the liquid mercury stream. This phenomenon was observed many years ago and was first described as "waterfall electricity" (6-9).

There are at least two methods of observing effects of this type of static discharge. One method is to operate the switch in a completely darkened room and observe the inner pool through a transparent acrylic plastic lid. Under these conditions it is possible to see the luminous flashes from the discharge. These discharges are particularly noticeable in the switch with the plastic components. In a switch with a stainless steel case and a plastic rotor, the static discharge level is nearly as high; on the other hand, the effect is reduced by use of a plastic case-aluminum rotor combination. The least spark discharge of all is noticed in a switch containing an aluminum rotor and a steel case. Whereas for an all-plastic combination, practically continual static discharge is observed, in the switch with the aluminum rotor and steel case, evidence of static discharge was noted only once or twice in a period of 2 or 3 minutes.

Another way of observing the effects of noise is to remove the battery from the circuit shown in Figure 9 and observe the oscilloscope trace, allowing it to trigger on noise only. The noise observed is found to depend very much on the impedance level that the noise voltage is working into, with a high noise level existing at high impedance and a low noise level at low impedance. In the steel case-aluminum rotor switch working into a 10,000-ohm impedance, noise spikes of about 1/2-volt amplitude and 1-miscosecond duration occurred at a rate of 2 or 3 per 2-minute interval. When the impedance was increased to 1/2 megohm, noise spikes of 1-volt amplitude and 10 to 20-microsecond duration occurred at intervals of approximately 1 second. Figure 14 is an oscilloscope trace of several typical noise spikes generated by the aluminum rotor-steel case switch when working into 500,000 ohms.



STATIC DISCHARGE NOISE INTO 0.5 MEGOHM
(Sweep speed = 50 microseconds/division,
sensitivity = 0.5 volt/division

FIGURE 14

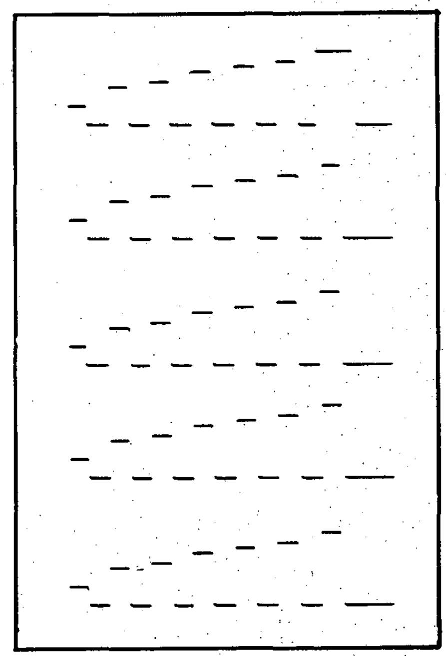
In addition to "waterfall electricity", there is also the possibility of static charge generation by rubbing or wiping action of the mercury flowing past the plastic. Regardless of which effect is predominant, it seems reasonable to expect that the switch with the plastic components would produce more trouble because the nonconductive properties of the plastic allow the static charges to accumulate to high potentials and then discharge. On the other hand, when the component surfaces are of steel and aluminum, the static charges, even though created, would immediately disperse and be drained to the mercury pool. Thus the static discharge noise phenomenon would not be observed.

4. <u>Contact Bridging</u>

A shortcoming in the switches that have been built to date is occasional bridging of two pins or supposedly isolated channels (see upper right hand square wave in Figure 15). It is almost certain that this phenomenon occurs when a drop of mercury becomes lodged between the two adjacent pins. It is believed this can be

EVIDENCE OF CONTACT BRIDGING

FIGURE 15



eliminated by proper lid and rotor design. For example, there is evidence that a sandblasted lid, as opposed to a very smooth lid, inhibits the tendence of mercury droplets to cling to the lid, thus greatly reducing the possibility of bridging. Another possibility might be to put a fiber or some type of insulating brush on the rotor to wipe the pins adjacent to the plastic base. It is also possible simply to separate the pins farther, or to use the floating or buffer pin technique mentioned earlier in this report.

It should be noted that even in situations where occasional contact bridging occurs, malfunction of the system does not necessarily follow. For example, given two synchronized switches, one of which is a remote encoding switch and the other a local decoding switch, shorting together of two contacts on either switch will not appear as a short at the output end unless both switches experience bridging between the corresponding two pins simultaneously.

The possibility of this happening is remote, and such an effect has not been observed to date.

In make-before-break type operation, shorting of adjacent pins occurs as a proper function. Random shorting, however, even in this situation, could be detrimental if not corrected because it would allow the possibility of three isolated circuits being connected together simultaneously, instead of only two.

5. <u>Current-Carrying Capacity</u>

The current-carrying capacity of individual connections is affected by at least two system parameters: the spacing between contact pins and the impedance (or voltage) level of the circuit.

One phenomenon that is enhanced by excess current is the formation of an ionized path between adjacent pins by arcing at the instant of break. This ionized path allows shorting of adjacent circuits, which can be undesirable. Increasing the pin separation can prevent a complete ionized path, and, for a given current, low impedance (or low voltage) inhibits the initial arcing.

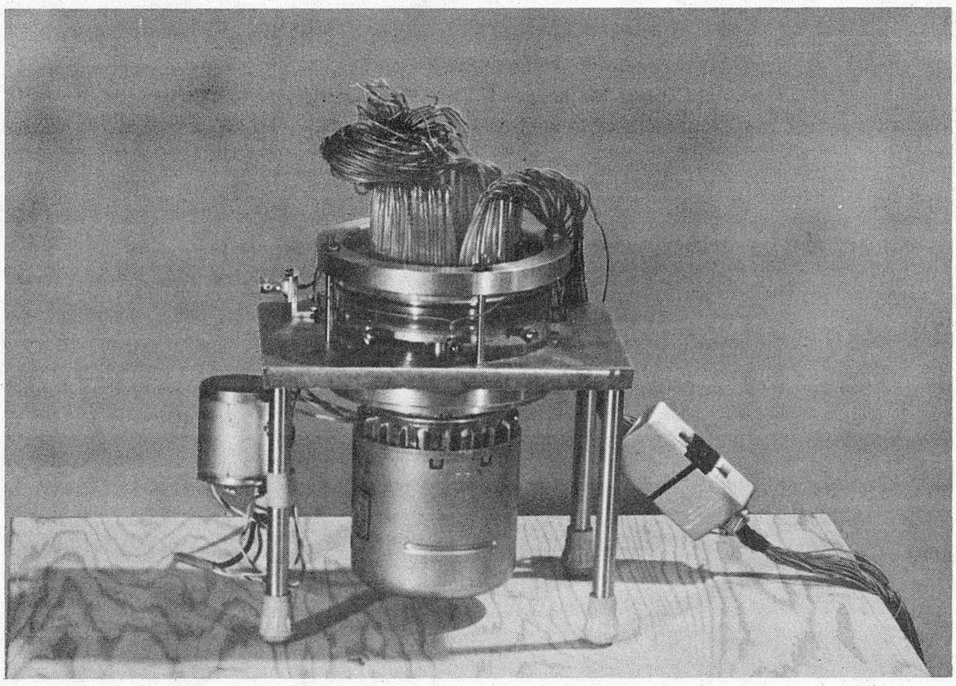
Currents as high as 60 milliamperes into 2000 ohms (120 volts) can be handled in the present switch by removing adjacent pins, but a maximum of 35 milliamperes at 2000 ohms (70 volts) is advisable with the standard pin separation. When operating at 1.5 volts into 10 ohms, no arcing was noticed while 150 milliamperes were being switched. At 300 volts with 20,000 ohms in series, 15 milliamperes were switched with no arcing. While these are not necessarily limits, they indicate the order of magnitude that can be expected.

DESIGN DETAILS AND OPERATING PROCEDURE

This section contains the design details of the particular synchronized switching system delivered under the requirements of the purchase order providing for this over-all study. It has been prepared and included in such form as to serve as a complete descriptive and operating manual for the reference of individuals concerned with applying the system to practical switching problems.

A. Switches

1. Model 402-1 (Figure 16)



MODEL 402-1

FIGURE 16

This switch is recognized by its acrylic plastic case and octagonal rotor. An integral part is an Eastern Air Devices 2-pole salient-pole synchronous motor rated 1/50 hp at 3600 rpm, for operation on 115-volt 60-cycle single-phase power. The following switch data apply.

Sampling rate	60 per second per circuit
Number of poles	1
Number of contacts	118 (with original lid)
Contacting interval	140 microseconds
Mean dwell time	80 microseconds
Size (including motor and mount)	7 inches x 8 inches x 10 inches high
Weight (including motor and mount)	10 pounds

This switch is designed to rotate clockwise (viewed from above), and is filled with clean triple-distilled mercury. When the mercury level is adjusted to be approximately 1/8 inch above the "pickup-pool" inlets with the switch at rest, the switch should begin to function within 1 to 2 seconds after being started. It is not necessary to level the switch, because it will operate properly when tilted to a 10 to 15-degree angle. (In the original design, there were "Sealol" shaft seals between the motor and the switch. These seals were removed to eliminate all possible drag on the motor, which might contribute to phase angle oscillation. No trouble has been experienced with mercury leakage since removal of the seals.)

Although little trouble is expected from stoppage of the jets by reason of scum formation and/or contamination, the switch can be cleaned by a complete disassembly, including removal of the nozzle from the rotor. All components should be washed with warm (135 F) water and detergent, followed by copious rinsing with warm water. All passages must then be blown out with dry air. Wire may be used to remove any obstruction from the jet (music wire, gage 6/0, 0.004 inch). As the slightest burr prevents entrance into the hole, nippers or cutters cannot be used to cut the wire. Instead, it should be parted by a straight pull.

In reassembly, some care will be required to align the switch case with the motor shaft and the lid with the case. Clearances between mating parts were established with due regard to the large relative coefficients of thermal expansion of the materials used. Hence, the following procedure is recommended for complete realignment of the switch parts.

a. Check concentricity between switch case and motor shaft by mounting a dial indicator on the shaft and sweeping the inside diameter of the case when both are assembled on the mounting plate. This should be within 0.003/0.004-inch total indicated runout.

b. Install rotor and check for height by using a straight edge across the switch case. The rotor should be flush within ± 0.005 inch of the top of the case.

c. Install contact lid, using the Teflon washer supplied. Center the lid by carefully rotating the motor shaft by hand and feeling or listening for contact between the rotor and the pins in the lid while shifting the lid to find the best position. Clamp the lid down and make a final check before turning on the power.

d. In reinstalling the nozzles, it is advisable to use new Teflon washers each time. A leak around the nozzle results in erratic switch action and can best be detected by visual examination with a Strobotac.*

2. <u>Model 402-2 (Figure 17)</u>

This switch is recognized by its stainless steel case and round aluminum rotor. As currently assembled, a laminated plastic

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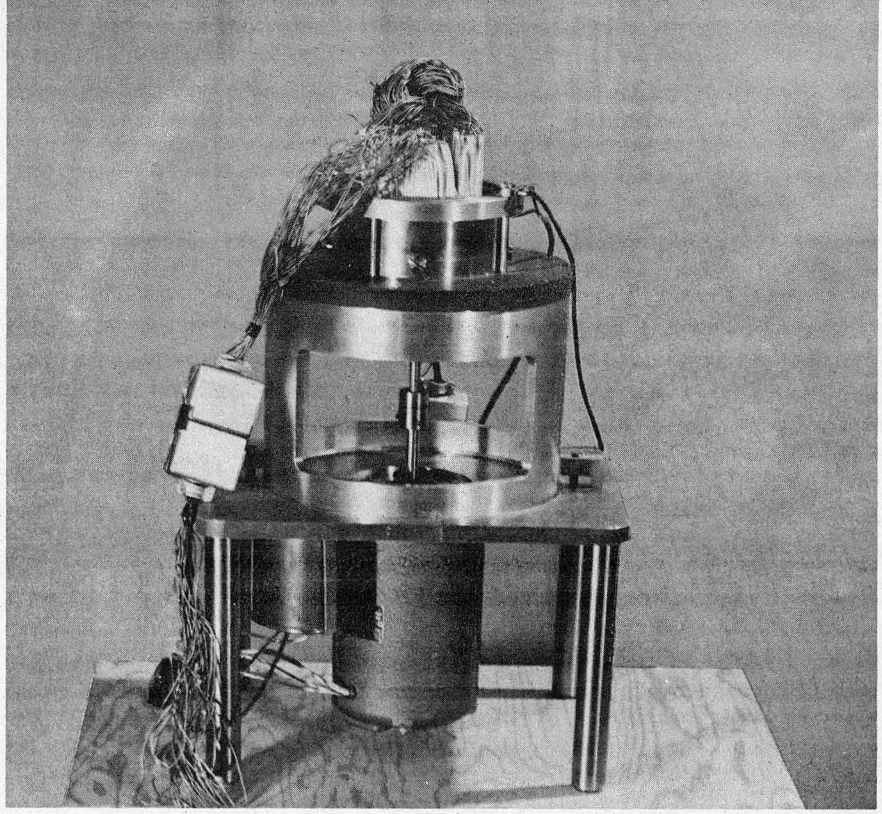
* The cast epoxy lids are not sufficiently transparent to allow a visual examination of the jet stream. For this purpose, a clear acrylic plastic lid is furnished with the switch.



MODEL 402-2

FIGURE 17

base contains a bearing with shaft. The switch rotor is mounted on one end of this shaft, and the drive motor is coupled to the other. Although the motor is not integral with the switch as in 402-1, this is the only other motor supplied. It is an Electric Indicator Company 2-pole hysteresis synchronous motor rated 1/20 hp at 3600 rpm when operated on 115-volt 60-cycle single-phase power.

The following switch data apply.

Sampling rate	60 per second per circuit
Number of poles	1
Number of contacts	236 total 118 active (with original lid)
Contacting interval	140 microseconds
Mean dwell time	75 microseconds
Size (including motor and mount)	10 inches x 12 inches x 18 inches high
Weight (including motor and mount)	35 pounds

This switch differs from model 402-1 in several details. The internal configuration of the case is slightly different, although functionally the same. The rotor is made of aluminum instead of plastic and thus contributes less to static generation. The mechanical configuration was altered with the objective of improving pumping action, and more precise machining provides a truer running rotor with improved dynamic balance. In addition, the stainless steel case is mounted on a laminated plastic base, which insulates it from the motor, the bearing and shaft, and the spacer tube.

Although no trouble has been experienced with switch stoppage due to scum formation caused by reaction between the aluminum rotor and the mercury, it is expected that this ultimately may take place. As described in a previous section, the choice of aluminum alloy was one of expediency.

Maintenance of 402-2 is substantially the same as that required for the 402-1. The switch is designed to rotate clockwise (viewed from above) and the mercury level (though not the amount) should be identical. Concentricity between the various parts is improved by a "unitized" form of construction. The switch case, mounting plate, and an auxiliary bearing cartridge containing the rotor shaft are assembled into a unit. The motor and its mounting plate form a second unit, which is separated from the switch and joined only by a shaft coupling; heat transfer from the motor to the switch is thus kept to a minimum. Reassembly is less exacting; however, precautions should be taken to check concentricity before running the switch under power. With the exception of the nozzles and the lids, there are no parts of the two switches which are completely interchangeable.

3. Description of Lids

A total of four lids are provided with the switches, as described below.

a. The first is of cast epoxy resin containing 240 stainless steel pins, each 0.014 in diameter. Pin spacing is 0.040 center to center with alternate pins electrically dead but acting as guard or buffer pins to the mercury stream.

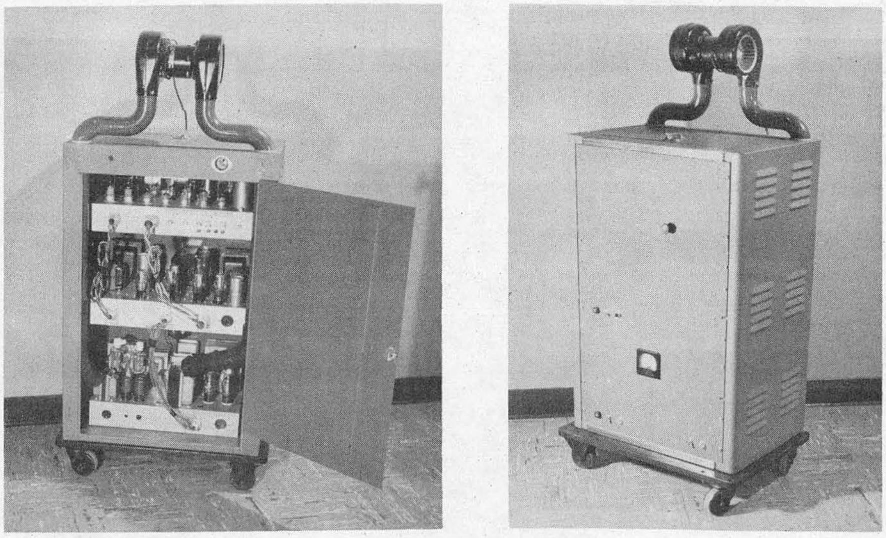
b. The second, also of cast epoxy resin, is substantially the same as a., but contains 236 pins. Pin "X" (Winchester plug designations) is isolated by the removal of 2 pins on each side and should be used for the transmission of the reference signal necessary in the synchronizing system.

c. The third, an experimental cast epoxy resin lid, differs from a. and b. in that alternate (floating) pins have been removed. This creates a spacing of 0.080 inch between centers with 120 pins. Pin "X" is isolated as in b., leaving 118 pins. Some areas of the inside surface of the lid are sandblasted, while other areas are sandblasted and have a thin coat of epoxy resin flowed on and cured.

d. The fourth lid is of clear acrylic plastic to allow visual examination of the jet stream by stroboscopic methods.

B. Synchronizing System

The circuits for the synchronizing system are contained in 3 separate chasses mounted in a 36-inch relay rack (see Figure 18). Their operation can best be understood by referring to Figure 6, the system block diagram.



SYNCHRONIZING CIRCUITS AND POWER SUPPLIED

FIGURE 18

For proper functioning of the synchronizing scheme, it is necessary that some method of identifying the signal from the remote (switch A) reference contact (5A) be established. Since all the information to be monitored can be introduced with a positive polarity or bias, thus pin 5A can be recognized by maintaining it at a negative potential.

1. Reference Generator

Considering for the moment switch A, diode D1, and resistor R1 only, it can be seen that a negative voltage will appear across R1 at that time when the jet is in contact with pin 5A. At no other time can switch A cause a voltage of either polarity to appear across R1.

The voltage across R1 will thus appear to be a negative square pulse of about 100-volt magnitude, occurring once per rotor revolution and having a duration of less than 140 microseconds (that is, 16,667 divided by 120, the number of stator contacts). This pulse, after being amplified and inverted, is used to trigger a one-shot multivibrator that stays flipped for approximately 8.33 milliseconds and then flops to await the trigger again. The multivibrator thus produces a 60-cycle square wave whose leading edge is tied exactly to the first incidence of the jet on pin 5A. This square wave is then inverted and used as a phase reference in a gated detector to be described later.

2. <u>Error Generator</u>

Consider now that part of the circuit consisting of R1, C1, diodes D1 and D2, switch B, R2, and C2. Normally C2 is negatively charged to that value set by potentiometer P1, about -100 volts. When jet B contacts pin 5B, the potential at 5B will rise from -100 volts to about -2 volts. The other side of C2 will simultaneously rise 98 volts. It will stay at this value as long as R1 continues to short out R2 through contact 5B.

If, however, due to the function of switch A, there is a potential of -100 volts across R1 during any of the time that 5B is connected to jet B, then R2 will not be shorted and the voltage on 5B will remain at -100 volts. Thus, the length of the positive pulse appearing on pin 5B depends upon that length of time that 5B is connected to jet B while 5A is not connected to jet A. When there is exact time coincidence between the contacting of jet A with 5A and jet B with 5B, the error pulse duration will be zero and no pulse will be generated. For phase differences (errors) greater than that corresponding to the contact pin separation, the length of the error pulse is still only as long as the dwell time of jet B on 5B. This can have a maximum of about 140 microseconds, and in the present switches, with their 60% dwell time, is about 85 microseconds.

3. Phase Comparator - Gated Detector

Phase comparison is necessary in order to decide whether jet B is leading or lagging jet A. If jet B reaches 5B before jet A reaches 5A, a leading situation is said to exist.

Two gates are provided, one driven by the 60-cycle square wave generated by the reference generator, the other by an inverted version of this square wave. These are diode gates which allow transmission only during the positive dwell of the reference square wave. Thus, only one is open at a time. The error signal is fed to the input of each of these gates, but appears at the output of only one. A part of each gate is a clipper which allows only the error pulse to be transmitted, and eliminates effects of cross coupling and feed through of the reference square waves. By this means, the error signal is isolated as either leading or lagging. If jet B leads jet A, then there will be a positive pulse (of about 60 volts magnitude after clipping) having a duration of 85 microseconds or less in channel A. Conversely, if jet B lags A, there will be a pulse in channel B. It is thus apparent that channels A and B do not work simultaneously, but in an either/or fashion.

4. Integrators

In order to utilize these pulses to control the supply power phase to the motor of switch B, a circuit using a d-c motor-driven phase shifter is incorporated. In order to provide a smoother signal to the d-c motor, the error pulses are integrated in a quick-charge, slow-discharge type integrator. This circuit charges a capacitor toward the pulse amplitude through a 5-microsecond time constant but allows the capacitor to discharge through a 5-millisecond time constant. Thus, any pulse lasting 20 microseconds (4 time constants) or longer, charges the capacitor completely. This creates a roughly proportional range for the phase servo of up to 20 microseconds on each side of null. For time (phase) errors greater than this, no increase in integrator output is achieved. For error pulses of less than 20 microseconds duration, the capacitor does not charge all the way to the full pulse amplitude, and a proportionately smaller signal emerges from the integrator.

Two identical integrators are employed, one in the lead (A) and one in the lag (B) channel. The output appears in the form of pulsating direct current of positive polarity at a 60 pulse per second rate. Output will exist on one integrator or the other, but not simultaneously on both.

5. D-C Amplifier and Motor Drive

The isolation of the lead and lag channels ends with the quick-charge integrators. The output of each channel is at this point introduced on the separate grids of a push-pull d-c amplifier. By this means, a pulsating d-c with a net d-c component is placed on a power amplifier bridge that contains a small 24-volt permanent-magnet d-c motor armature in the cross arm of the bridge. The polarity of the bridge voltage and, thus, the direction of motor rotation, depends upon which push-pull grid receives the positive signal.

A balance potentiometer is included between the cathodes of the push-pull amplifier to adjust the motor to standstill for zero signal input.

6. Phase Shifter

By placing 60-cycle voltages of equal magnitude, but with a 90-degree time phase difference onto the space quadrature excitation windings of a resolver, a 60-cycle voltage of constant magnitude, but adjustable phase, can be obtained from either of the output windings. The phase of the output will depend upon the position of the rotor. As the rotor is advanced one revolution, the phase of the output voltage advances from 0 to 360 degrees. If the two resolver inputs are of exactly equal magnitude and exactly 90 degrees out of phase, the output voltage from the resolver will not vary in magnitude as the phase is advanced.

Should this ideal situation not prevail, and a slight magnitude variation be observed at the resolver output, it is not particularly significant in this system, as can be seen by considering the following. The variable phase 60 cycles from the resolver is amplified by a push-pull power amplifier capable of delivering about 200 watts, which is sufficient to drive any of the synchronous motors used. This drive is applied to the motor of the receiving switch. Adjusting the resolver rotor adjusts the phase of this synchronous motor. Furthermore, as the resolver is rotated 360 degrees, the phase of the synchronous motor is similarly advanced (or retarded) 360 degrees. It is apparent that, irrespective of the exact voltage on the synchronous motor at any particular setting, the synchronous motor must take on every phase position in a continuous fashion. Thus, there is a position of the resolver rotor which will cause the phase of the receiving switch to have the exact phase of the sending switch, and this position can be approached in a continuous fashion from either direction.

7. Over-all Operation

Proper operation of the send switch with its reference pin excited by an appropriate stiff (low impedance) negative voltage source causes a negative reference pulse to be generated in the synchronizer. This pulse establishes a 60-cycle square wave reference (gating) voltage.

Proper operation of the receive switch (at any arbitrary phase with respect to the send switch) with its reference pin connected to a non-stiff (high impedance) voltage source causes a positive error pulse to be generated. This error pulse is detected as occurring in the half cycle either before or after the reference pulse. The error pulse is then integrated and applied to a d-c motor. This motor drives, through a 1000 to 1 reduction gear, the resolver phase shifter until the phase of the receiver switch is such that pin 5B is being contacted by jet B at the same time 5A is being contacted by jet A. This causes the error signal to disappear and the d-c motor to stop running. The resolver phase shifter is thus locked to the proper phase position.

The d-c motor will not move again until some line transient comes along that affects the receive-switch motor differently than it does the send-switch motor. In this case, the error pulse will reappear and the necessary correction will take place.

In actual operation it has been observed that, if the error signal is removed after the switches are synchronized, the two switches will remain in synchronism for several minutes without any noticeable relative drift. This means that for purposes requiring only a few minutes of operation, a manually operated control on the rotor of the resolver phase shifter could be used to accomplish the initial lock-in, and the system could be run open ended without the necessity for the servo amplifier. Also, certainly situations requiring operation for several seconds could be handled in this fashion, because the servo system as presently constructed requires several seconds to re-zero when an error is introduced.

8. Operation of Controls

There are 4 potentiometer controls on the synchronizer, all of which are labeled. The most conspicuous is the servo gain control, the only one on the front panel. This is a 10-k potentiometer that fixes the bias level of the error pulse. It is possible to adjust the pulse height by this means from about 65 to 150 volts. A nominal setting is about 85 volts.

A very important control is the excitation for the synchronous motor. This is a 1-k potentiometer, which adjusts the amount of 6.3 a-c filament voltage excitation that is applied to the phase shifting resolver, and thus the magnitude of the voltage to the receive switch synchronous motor. The meter on the front of the power amplifier chassis indicates the RMS voltage to the motor and is thus controlled by this potentiometer. IMPORTANT - This control should be set so that the meter reads approximately 125 ± 5 volts with the motor load on the power amplifier.

The detector gate duration potentiometer, which is in the second grid of the 60-cycle reference multivibrator, allows the multivibrator to be adjusted so that it will produce a symmetrical square wave. The reference pulse triggers the multivibrator each cycle, and the length of time required for the multivibrator to reset is controlled by the potentiometer. The adjustment is not critical since the servo nulls at the triggered edge. The return edge, which the potentiometer controls, merely determines the exact point of distinction between a leading and a lagging phase error for 180-degree errors. Exact symmetry is not important, because lack of symmetry merely allows, for example, a 200-degree leading error signal section compared to a 160-degree lagging one, instead of 180 degrees for each. This does not affect the servo operation around null in any way.

The remaining potentiometer control is the balance potentiometer for the d-c motor bridge. This control allows adjustment for tube differences in the bridge circuit, and should be set so that the d-c voltage across the motor is zero for zero error signal. This condition can be achieved by removing the error signal coax from the chassis jack on the rear. The voltage across the motor is available at the two pin jacks labeled "D.C. Motor" on the back of the chassis. Caution should be exercised in this measurement since the potential of these jacks can both be about 300 volts above that of the chassis.

Aside from the on-off switches on the power units and blower, the only other manual control is the d-c motor reversing switch. This is provided to allow the servo to lock onto the reference square wave at the reference pulse edge and not at the reset edge. With one rotor configuration, it is possible to run one of the switch motors counter-clockwise, thus necessitating this switching provision. Normally it will remain set in the same position.

9. Power Supply

The power supply contains all the d-c supplies except the high voltage source used for the power amplifier. In the power supply are three fixed +300-volt supplies, a -20-volt bias supply for the 6AG7's, a -75-volt bias supply for the 6AS7's, and a -150-volt source for the error pulse generation.

Of the three +300-volt supplies, one is used to drive tubes V_1 - V_{12}, V_{15}, and V_{16} of the synchronizer, and its 0-volt side is grounded to the chassis. The second furnishes power to the two 6V6's in the power amplifier, and its 0-volt side is also grounded. The third 300-volt supply is used to drive the 6AS7 bridge; its 0-volt side is common with the 0-volt side of the -75-volt bias supply. They are, however, floating with respect to the other supplies.

10. Power Amplifier

This unit is a straightforward high power amplifier. The filament power switch on this unit should be turned on for a few seconds for warmup before the high voltage is turned on.

IMPORTANT - The high voltage switch should not be turned on unless a motor or equivalent (light bulb) load is connected to the amplifier output. The 811A output tube plates will become very hot if they do not operate into a reasonably good load match.

CONCLUSIONS

In reviewing the work on individual rotary jet switches and the synchronous system, it is now possible to make certain definite statements of a summary nature, relating to the performance and applicability of the equipment which has been developed.

A. <u>Switch Characteristics</u>

1. The switches which have been constructed allow sampling or commutating of as many as 120 different circuits in a sequential fashion at a rate of 60 samples per circuit per second and provide a sampling rate of 7200 items per second. The speed at which the switch is run is not critical, a speed from as low as 20 or 30 cycles to over 100 cycles per second being feasible. The number of contacts could also be varied over a wide range.

2. By varying the size of the orifice through which the jet stream is forced, the size of the jet stream can be effectively changed, and in this fashion the on (dwell) time which the contacting pole makes with each separate circuit can be varied. If the floating pin technique of utilizing only alternate pins as live contacts is used, a range of dwell time can be achieved from approximately 20 to 90%.

3. The switch is characterized by a lack of contact bounce phenomenon.

4. The make portion of the contact requires less than 1 microsecond. The break is characterized by a trail-off which requires approximately 5 to 10 microseconds. In addition, the break time has a degree of uncertainty, thus causing the pulse to have a slightly varying width of the order of 5% of the total.

5. Nominal contact resistance is approximately 1.4 ohms.

6. The switch generates static noise pulses during operation. When working into a 10,000-ohm load, these pulses appear at a rate of 1 or 2 per minute, with a magnitude of approximately

1/2 volt and having a duration of about 1 microsecond. This noise level is below that which would interfere with observation and recognition of usable signals.

7. The switch utilizes gravity in part of the mercury recirculation scheme and thus must be operated not more than 20 or 30 degrees from the vertical.

8. The switch appears to be satisfactory for almost all commutating or telemetering applications.

9. Life of the switch is unknown, but should be thousands of hours without servicing.

B. Synchronizing System

1. The phase synchronizing system is essentially a position servo. The phase angle position of the receiving switch synchronous motor is caused to match the position of the phase angle of the sending switch motor. Inasmuch as both motors are run from a common supply, this servo system is characterized by a zero velocity error. Position errors occur when either switch receives some external torque or supply voltage variation which causes a shift of its phase or torque angle relative to that of the other switch. A shift of either torque angle with respect to the other is detected by the error detection system, and correction is sent to the phase-controlling portion of the receive switch power supply, thus correcting the phase of the receive switch.

2. For optimum operation, this phase synchronizing requires high quality synchronous motors, characterized by a minimum of phase angle oscillation. Motors for fulfilling these requirements are currently manufactured by the Electric Indicator Company and designated as damped hysteresis synchronous motors.

3. The method of phase synchronizing, or running two switches remotely situated in synchronism, appears to be fully workable and practical, maintaining synchronism to within 5 microseconds.

4. For many operations, a manual phase adjustment for bringing two remotely situated motors into synchronism might be acceptable, because of the tendency for the damped synchronous motors, in particular, to retain the same phase relationship, with respect to the line frequency, that is initially established.

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