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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Description and Instruction Manual for the Cylindrical Field Mill System

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BOULDER, COLORADO
February 1972

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DESCRIPTION AND INSTRUCTION MANUAL FOR THE CYLINDRICAL FIELD MILL SYSTEM

NASA, Kennedy Space Center, Contract CC-59753

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Boulder, Colorado
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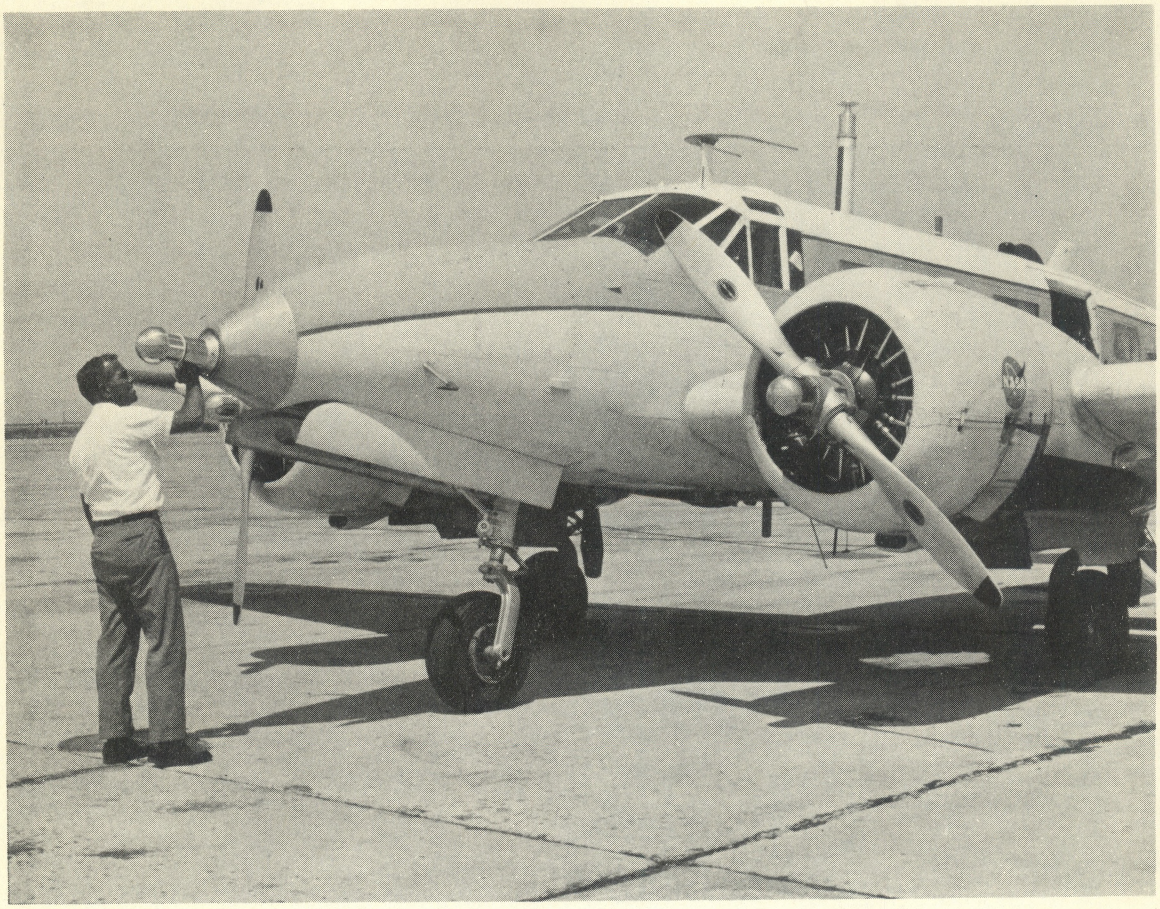
TABLE OF CONTENTS



The most recent installation of the atmospheric electric field mill system is on the NASA 6 aircraft. NASA's veteran thunderstorm research pilot, Lindy Mason, is shown in a preflight check of the nose field mill that measures two components of the electric field in a horizontal plane.

I. SPECIFICATIONS

Electric Field Range	1 V/M to 500,000 V/M
Gain Control, Fixed	1 to 100,000 in 13 Steps
Gain Control, Variable	1 to 2 by Potentiometer
Noise	1/2 V/M Maximum
Offset (at maximum gain)	5 V/M Maximum
Outputs	
Waveform Monitors	± 10V, 5 MA
D.C. Outputs	± 10V, 20 MA
Power Requirements	110V, 60 Hz, 200 Watt (Maximum)
Temperature Range (^{o}C)	-25 to +85
Lifetime, Motor & Bearings	10,000 Hr.

II. THEORY OF OPERATION [1]

The field mill, in general, measures the charge induced on a conducting plate exposed to an electric field. The charge density, q, is directly proportional to the field, E, and inversely proportional to the dielectric constant ϵ, and is given by the equation:

$$E = q/\epsilon \tag{1}$$

Since ϵ is, in most cases, constant in space and time, the charge density induced on the plate will be directly proportional to the electric field. As this plate is alternately exposed to the field and shielded or grounded, the surface charge will flow to plate from ground in the exposed position and from the plate to the ground in the shielded position. The periodic shielding is accomplished by a variety of methods in different types of field mills. For example, in the shutter type mill a fixed plate is alternately exposed and shielded by a grounded rotating shutter. However, in the cylindrical field mill the sensor plates are two halves of a cylindrical mantle, as shown in Fig. 1. When these plates are exposed to a field, F_H, in the plane perpendicular to the axis of rotation, Fig. 1a, positive and negative influence charges will be induced on the two segments. As the segments rotate in this field with frequency ω, each segment is alternately charged positive and negative. The resulting alternating current is amplified, rectified, filtered and recorded. The following calculation will show that the amplitude of this current is proportional to the applied electric field.

[1] H. W. Kasemir: "The Cylindrical Field Mill," ECOM, U.S. Army, Tech Report 2526, October 1964.

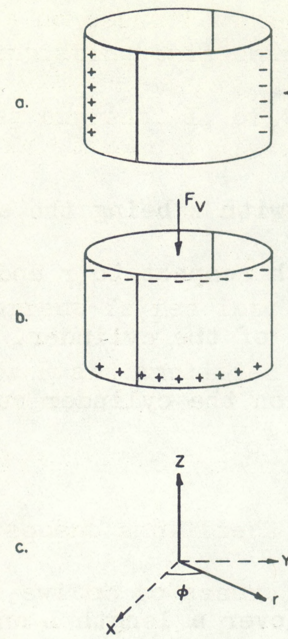


Figure 1.

To calculate the induced charge density on the sensitive plates, an infinitely long cylinder of radius, a, is substituted for the cylindrical segments. This cylinder is exposed to a homogeneous electric field, F_H, perpendicular to its axis. The error incurred by considering a segment of an infinitely length rather than of a truncated cylinder is of the order of 10% and is due to the increased field concentration at the end of the cylinder. Since in practice the field mill is calibrated in an imposed field of known strength, the simplified calculation using an infinitely long cylinder is sufficient to our purpose. It is important to note at this point that an imposed field, F_V, parallel to the axis of the cylinder, Fig. 1b, will induce the same charge density on the sensitive plate for any phase angle, ϕ. Thus for a rotating head the charge density will be constant, and the output current will be zero. This is the reason that the field mill will not measure a field along the rotational axis.

The potential function, Φ, of an infinite cylinder of radius, a, placed in a homogeneous field, F, is given by

$$\Phi = -Fr \cos \phi \, (1 - a^2/r^2), \qquad (2)$$

where cylindrical coordinates (r, ϕ, z) are used with z being the axis of the cylinder (Fig. 1c). By differentiating Φ with respect to r and setting r = a, we determine the field at the surface of the cylinder. Using this field in equation (1), the charge density, q, on the cylinder surface is given,

$$q = 2\epsilon F \cos (\phi) \qquad (3)$$

Integrating this charge density along the z axis over a length L and between the angles ϕ_1 and ϕ_2 gives the charge, Q, on such a surface segment,

$$Q = 2aL\epsilon F \left[\sin (\phi_2) - \sin (\phi_1)\right] \qquad (4)$$

Setting $\phi_2 = \phi_1 + \pi$ will give the charge of a half segment of the cylindrical mantle,

$$Q = -4aL\epsilon F \sin (\phi_1) \qquad (5)$$

Thus this would give the influence charge on one of the sensitive plates of the field mill such that ϕ_1 is the angle of the cut of the cylinder with respect to the direction of the field, F. When this plate rotates with angular velocity, ω, then ϕ_1 is advanced ωt in time t and equation (5) becomes,

$$Q = 4aL\epsilon F \sin (\phi_1 + \omega t) \qquad (6)$$

Differentiating this charge, Q, with respect to time, t, gives the charging current, I, of the rotating sensor plate,

$$I = 4aL\epsilon F \omega \cos (\phi_1 + \omega t) . \tag{7}$$

This current is fed into a current-to-voltage transducer with the input resistor R and amplified

$$U_o = IR = 4aL\epsilon RF \omega \cos (\phi_1 + \omega t) . \tag{8}$$

In subsequent amplifiers there is usually a series of gains selected by a range switch to assure maximum output signal for various applications designated G(P) where G(P) is the gain on position P.

$$U = 4aL\epsilon RG(P) \omega F \cos (\omega t + \phi_1) . \tag{9}$$

The amplitude of this voltage is directly proportional to the absolute value of the applied electric field. The direction of the field with respect to the field mill coordinates can be obtained from the phase shift between the field mill output and the output of an AC generator driven by the same motor which drives the field mill. This means that the absolute value of the imposed electric field and its direction are natural outputs of the field mill. However, it is useful to consider the electric field vector resolved in rectangular coordinates. This is accomplished by the use of a phase sensitive rectifier which gives the two components of the electric field in the plane perpendicular to the axis of rotation. One component is proportional to $F_x = F\cos(\phi_1)$, the other one to $F_2 = F\sin(\phi_1)$.

To perform this phase sensitive rectification, the field mill output signal, U_o, is gated at four different phases with respect to the reference signal, U_R, produced by the signal generator. In each of these gated outputs, the signal is passed for 180^o and grounded for 180^o. The four phases of the reference signal are $0, \pi/2, \pi, 3\pi/2$, giving output voltages U_1, U_2, U_3, and U_4, as shown in Fig. 2. These gated signals are paired, U_1 with U_3 and U_2 with U_4, and filtered such that only the DC component is passed. The magnitude of this DC component can be calculated by a Fourier analysis of curves 2c through 2f. The DC output voltages U_{no} (n = 1, 2, 3, 4) of the filter network are then given,

$$U_{no} = 4aL\epsilon RG(P)\omega l/2\pi \int_{\frac{n-1}{2}\pi}^{\frac{n+1}{2}\pi} \cos(\dot{\omega} t + \phi_1) d\omega t, \quad n = 1, 2, 3, 4 \cdot$$

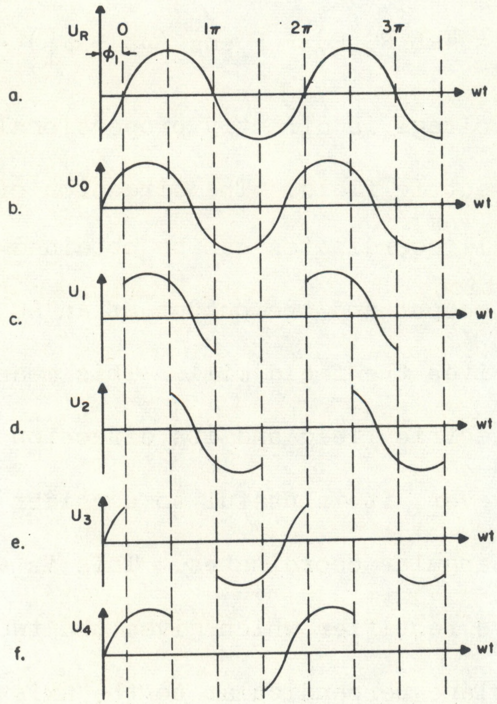


Figure 2.

Performing the integration for each n gives the following:

$$U_{10} = -AF \sin(\phi_1),$$

$$U_{20} = -AF \cos(\phi_1),$$

$$U_{30} = AF \sin(\phi_1),$$

$$U_{40} = AF \cos(\phi_1),$$

where,

$$A = 4\epsilon aL\, RG(P)/\pi \;.$$

The first two, U_{10} and U_{20}, are inverted and added to U_{30} and U_{40}, respectively, to give the final output of the system,

$$U_x = U_{30} - U_{10} = 2AF \sin(\phi_1),$$

$$U_y = U_{40} - U_{20} = 2AF \cos(\phi_1).$$

But $F \sin(\phi_1) = F_x$ and $F \cos(\phi_1) = F_y$, therefore,

$$U_x = 2AF_x \;,$$

$$U_y = 2AF_y \;.$$

These voltages are proportional to the two rectangular components of the electric field in the plane perpendicular to the rotational axis and are recorded for evaluation.

III. THE INSTRUMENT

A. The Field Mill System

The field mill system consists of three parts as shown in Fig. 3: 1) The two field mills which each includes the sensor plates, a rotating capacitator which transfers the signal from the rotating frame of the sensor plates to the stationary frame into the preamplifier, U_1, and finally a reference signal generator. 2) The control panel which receives

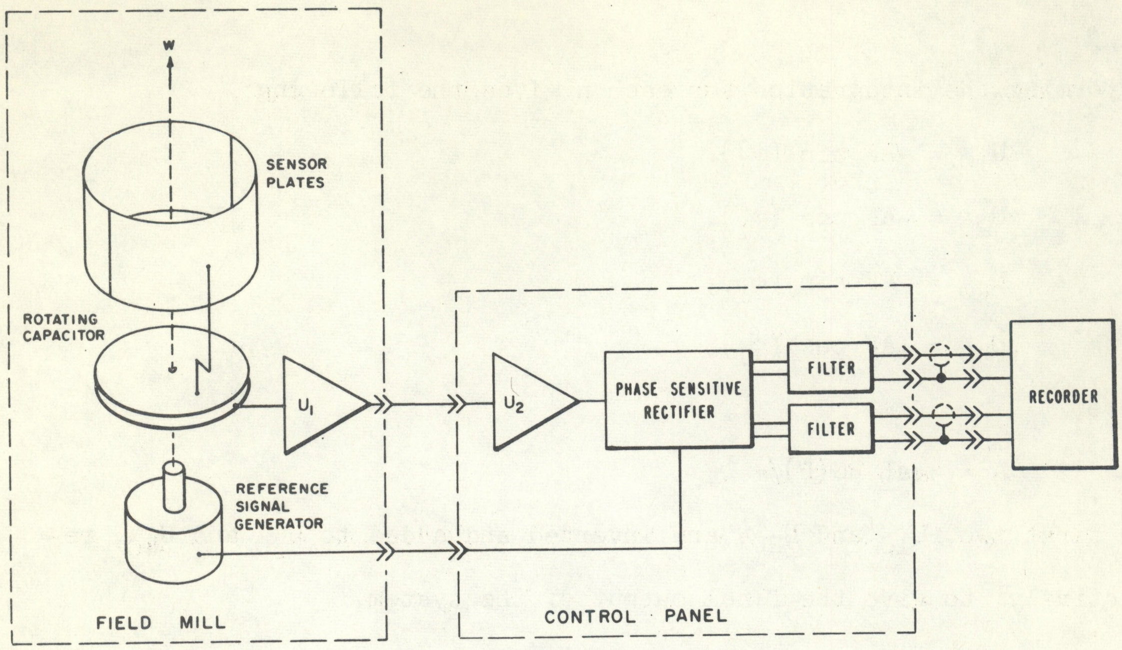


Figure 3.

the signals from the two field mills and includes for each a second stage amplifier, U_2, a phase sensitive rectifier, and a filter. 3) Devices for recording the DC signals which are proportional to the electric field components.

B. The Field Mill

A photograph of the most recent model of the field mill is shown in Fig. 4 and a more complete electrical schematic in Fig. 5. The sensor plates are two cylindrical segments having a radius, a, of 3-1/8 inches and a length, L, of 3 inches. These plates are insulated from each other and from the remainder of the rotating cylindrical sensor assembly by Teflon pieces. One plate is grounded through the non-sensing portion of the rotating head assembly to the non-rotating case by 3 carbon-graphite brushes mounted in the cage assembly and riding on the lower portion of the drive shaft. The second sensing plate is connected to an insulated conducting core in the center of the drive shaft which is fastened at its lower end to the rotor part of the rotating capacitor. The stator portion of the rotating capacitor is connected to the field mill amplifier which completes the capacitive coupling, C_1, as shown in Fig. 5. The AC signal from the sensitive plate is coupled to the fixed frame by this capacitor and fed into the amplifier circuit through a filter network at the amplifier input. This filter network has the purpose of reducing noise caused by splashing raindrops and interference from radio communication. The operational amplifier, U_1, is used in the non-inverting mode with the feedback extended, Pin A in Fig. 5, by an interconnecting cable

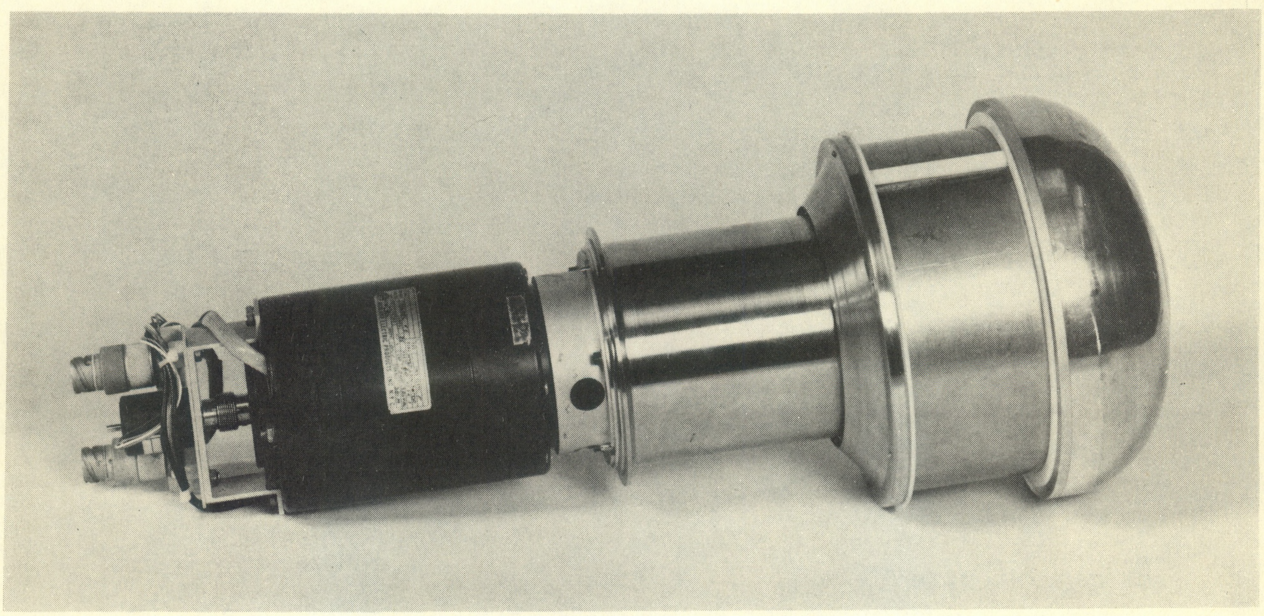


Figure 4.

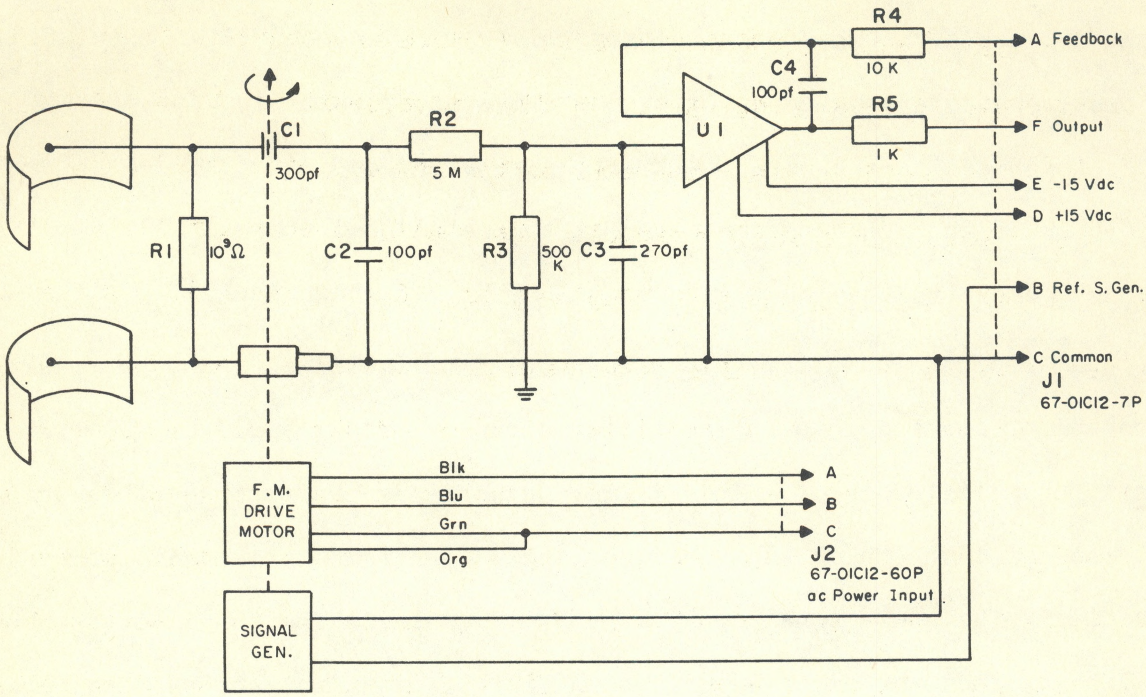


Figure 5.

to the control panel to provide a course range switching of 1:100. The output is connected through Pin F to the panel and DC power is delivered to the field mill from the panel through Pin E (-15 VDC) and Pin D (+15 VDC) with Pin C being power common. The reference signal needed for the phase sensitive rectification is produced by the signal generator and connected by Pin B (Fig. 5). The rotating assembly is driven by a hystresis synchronus, 60 Hz, 115 volt, single phase motor at 1800 rpm. Thus the frequency of the output signal from amplifier U_1, as well as that of the signal generator, is 30 Hz.

C. Interconnecting Cables

The signals are transferred from the field mill to the control panel by the interconnecting cables in Fig. 6. Note that, since the connector at the field mill end has 7 conductors and the connector at the panel end has 12 conductors, some signals do not have the same pin letter designations throughout the system.

D. The Control Panel

The control panel provides two identical but independent systems, one for each field mill. A schematic of one of those systems is given in Fig. 7.

1. <u>Gating Signals</u>

The 30 Hz reference signal is received through Pin M on J7 and is fed into a variable phase shifter. With this phase shifter the reference coordinate system can be rotated with respect to the field mill axis, so that the field components can be lined up exactly to the horizontal and vertical planes of the airplane. The reference signal is also connected

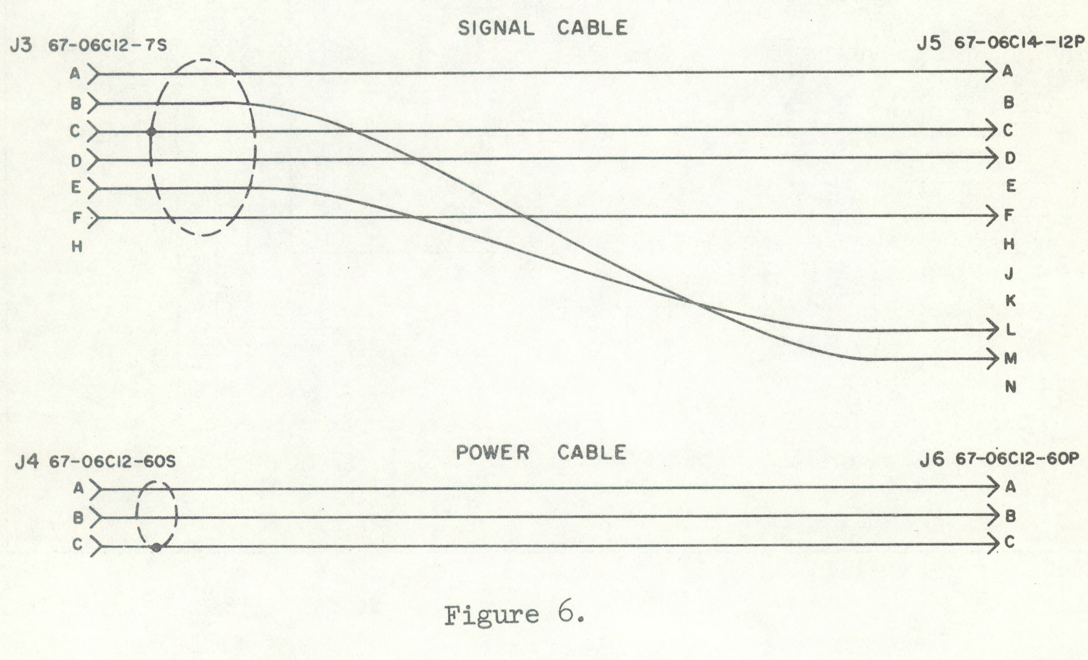


Figure 6.

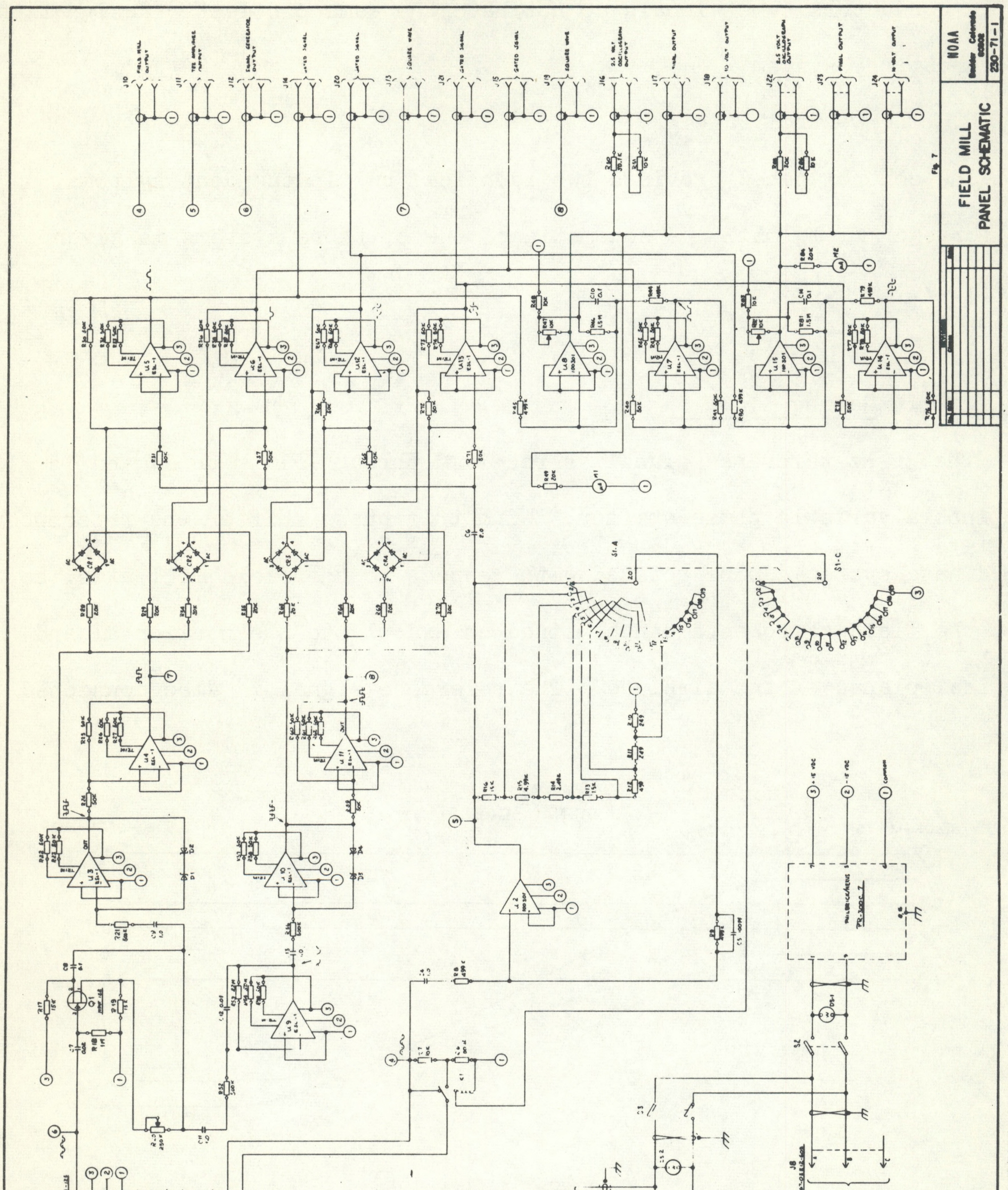

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Figure 7.

to test connector J12 for monitoring. The amount of phase shift is determined by potentiometer, R20, and is adjustable from 0 to about 170 degrees. This phase shifted reference signal is fed into two amplifier networks, first an integrator, amplifier U9, which produces a 90^{o} phase shift for the second field component, and second a flip-flop, amplifier U3, giving a 30 Hz square wave. This square wave together with its inverted counterpart, output of amplifier, U4, is used in a gating circuit (to be described later) to produce the first field component. The output of U_4 is available for monitoring at J13. The reference signal which was shifted 90^{o} is also converted to a square wave by amplifier U10 and this square wave inverted by amplifier U11. The output of amplifier U11 can be monitored at J19. These square waves will also be used in a gating circuit to be described below to produce the second field component.

2. <u>AC Gain</u>

The output of amplifier U1 is received through Pin F and the feedback through Pin A both of connector J7. When the position switch, S1, is on positions 1 through 6, the relay, K1, is not activated, and the amplifier in the field mill, U1, is operating in a follower configuration giving a voltage gain of one. However, if the position switch S1 is on positions 7 through 13, the relay will be energized (through S1-C). This changes the feedback configuration of the amplifier U1 in the field mill to that of a simple Tee network (resistors R6 and R7) yielding a voltage gain 100. The output of the field mill amplifier U1 can be monitored at J10 and is fed into the circuit of amplifier U2 which also applies a Tee network in its feedback for further subdivision of the coarse gain. When switch, S1, is in position 1, the Tee network is bypassed, and amplifier U2 is in the simple inverting mode. The gain of U2 is 2.5, 5, 10, 25, and 50 for positions 2, 3, 4, 5, and 6, respectively. When the switch S1 is set to position 7, amplifier U2 is returned to unity gain, but the field mill amplifier, U1, is set into the configuration giving 100 to 1 gain because relay K1 is energized. Thus the effective gain at the output of U2 for position 7 is 100. Amplifier U1 continues in the gain of 100 mode through position 13,while the amplifier U2 is again stepped through its fixed gains thus giving effective gains of 250, 500, 1000, 2500, 5000, and 10,000 in position 8, 9, 10, 11, 12, and 13, respectively.

3. Phase Sensitive Rectification

This amplified sinusodial output of U2 is available at J11 and is fed into four gating networks, amplifier U5, U6, U12, and U13. Each has a diode bridge in parallel with the feedback resistor. When the proper combination of square waves is fed into points 2 and 4 on any diode bridge (CR1, CR2, CR3, CR4), the path from 1 to 3 will be non-conducting. Then the equivalent feedback resistance (R30 for U5, R36 for U6, R66 for U12, R72 for U13) will be 50 K, and the amplifier will be in the inverting mode with unity gain. When this combination of square waves is inverted and fed into points 2 and 4 on any diode bridge,then the path between 1 and 3 will be conducting. Then the feedback resistance will be virtually zero and the amplifier gain zero. Thus the output of any one of the gating amplifiers will resemble curves c, d, e, or f of Fig. 2 and will be directly dependent on the relative phase between the field mill signal and the reference signal. It should be noted that the square waves fed into the diode bridge, CR2, in the feedback of amplifier U6 are inverted with respect to those square waves fed into corresponding points on the diode bridge, CR1, in the feedback of amplifier U5. Therefore, whenever amplifier U5 is in unity gain or conducting mode, amplifier U6 is in zero gain or blocking mode. The output of these two amplifiers would thus resemble curves c and e, or d and f, of Fig. 2. In order to obtain an analog of full wave rectification, the output of amplifier U6 is inverted by amplifier U7. The signals from amplifier U5 and U7 are fed into a final stage network of amplifier U8, which adds these signals, filters the resultant sum leaving a DC output, and with a Tee network affords a fine gain adjustment. The filtering is due to the large capacitor C10 in the feedback of amplifier U8 and C14 in the feedback of amplifier U15. It should be noted that amplifiers U12, U13, U14, and U15 perform the same functions as U5, U6, U7, and U8, respectively, however, with the gating square waves shifted 90°. The gain of each final DC output can be adjusted by R47 for amplifier U8 and R82 for amplifier U15. This fine gain adjustment covers about a factor of two and serves to compensate for the form factors of the different field components introduced by the geometry of the installation. This is accomplished by setting the potentiometers such that the meters (M1 and M2) or the recording devices read in some even values of electric field for a given installation (i.e., set R47 such that M1 reads 50 v/m full scale on P13).

4. DC Outputs

The final DC outputs from amplifiers U8 and U15 are monitored through the meters M1 and M2, respectively. These are DC 500-0-500 micrometers with a full scale deflection of ±500 microamps, corresponding to a full scale output of ±10 volts from the final stage amplifiers (amplifiers U8 and U15). There are two direct outputs for each of these amplifiers (see Fig. 8). These are J17 and J18 for U8 and J23 and J24 for U15. Each amplifier also has a 2.5 volt output used for oscillograph monitoring (J16 and U8 and J22 for U15). Both amplifiers U8 and U15 are capable of supplying 20 milliamps output current which should not be exceeded by additional loads such as a tape recorder or telemetry transmitter.

5. Input Power

The AC input power is received through J8 (Fig. 9). When switch S2 is closed, the 60 Hz power is delivered to the power supply having outputs of +15V DC and -15V DC. When S3 is closed, the 60 Hz power is delivered

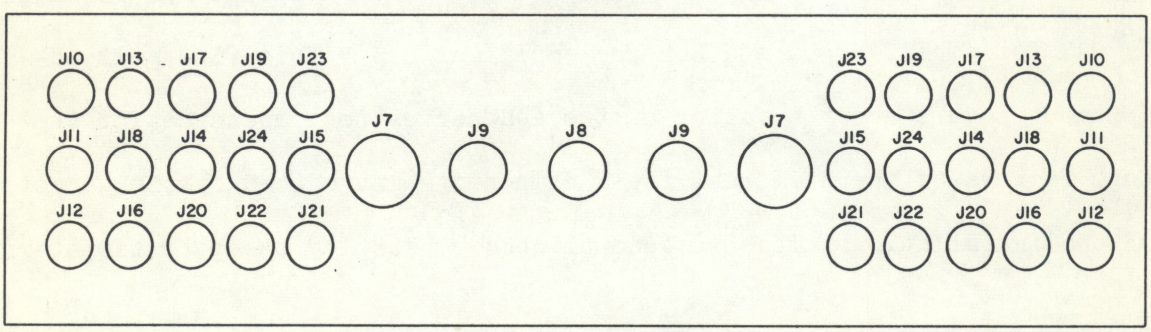

Figure 8.

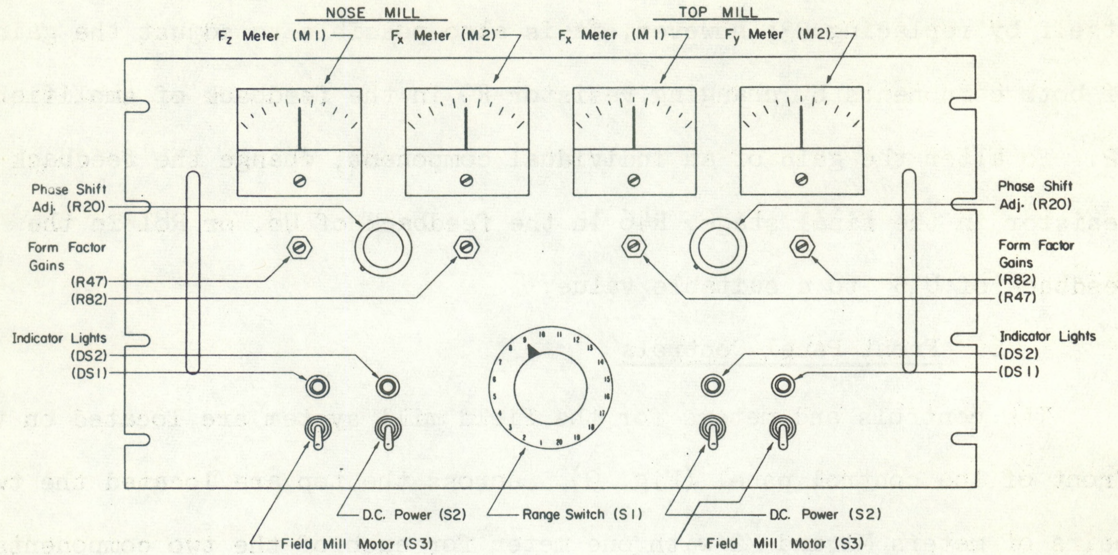

Figure 9.

through J9 to the field mill. It should be noted that the motor start and run capacitor, C15, is located in the control panel.

As was stated earlier the above description applies to the electronics for only one field mill. The typical control panel for aircraft installation contains the electronics for two field mills. Except for the input AC power, J8, which is shared and the range switch, S1, the electronics for each field mill in the control panel will be nearly identical and completely separate. Range switch S1 has 4 decks denoted S1-A, S1-B, S1-C, and S1-D, with S1-A and S1-C used for one field mill as shown in Fig. 7 and S1-B and S1-D performing the same function as S1-A and S1-B, respectively, for the second field mill. Thus the gain of both field mills is controlled by a single range switch, S1. The only differences which might occur between the two electronic systems are in the gain settings for the various field components which are beyond the range of the fine gain adjustment in the final stage amplifiers (U8 and U15). It is recommended that such adjustments in gain be made in the field mill itself by replacing R3; however, it is also possible to adjust the gain of both components by changing resistor R9 in the feedback of amplifier U2. To alter the gain of an individual component, change the feedback resistor in the final stage, R46 in the feedback of U8, or R81 in the feedback of U15 to a suitable value.

6. Front Panel Controls

The controls and meters for the field mill system are located on the front of the control panel (Fig. 9). Across the top are located the two pairs of meters M1 and M2 with one meter for each of the two components of each of the field mills. Located directly under each meter is the control for the form factor gain of that component being monitored by the meter (i.e., R82 or R47). Between the controls for R82 and R47 on each side of the panel is located the phase adjustment control for R20. Lower and in the center is located the range switch S1. To each side of the range switch are the power switches S2 (DC power) and S3 (Field Mill Motor Power), each with the indicator lights DS1 and DS2, respectively.

7. Rear Panel Connectors

All cable connections are mounted on the back of the control panel (Fig. 8). In the center is the AC input connector J8. To each side are the connectors J9 which deliver AC power to the field mill motors. The two field mill signal connectors are J7. The remaining connectors, J10 through J24, are the output and waveform monitor connectors, as shown in Fig. 8.

E. Recorder

The third part of the field mill system is the recorder. For each field mill there will be two final outputs from the control panel proportional to the two components of the electrical field. Ideally these signals should be recorded on both a multichannel oscillograph and a magnetic tape recorder for optimum data evaluation. The voltage dividers furnished in the control panel, R50 and R51 for J16 and R85 and R86 for J22, are designed to deliver 2.5 volts to an oscillograph (typical of Clevite Brush Oscillographs). In addition to the 2.5 volt output there are two 10 volt outputs for each component; J17 or J23 denoted FINAL OUTPUT and J18 or J24 denoted 10 VOLT OUTPUT. The final output is usually reserved for waveform monitoring, and the 10 volt output is provided for a second recorder such as a tape recorder. If the input voltage range of such an instrument is less than ±10 volts, a voltage divider must be built either in the control panel or at the instrument input. It should again be noted that the total effective load resistance should be more than 500 ohms since the maximum output current of the final stage amplifier, U8 or U15, is 20 milliamps.

IV. MAINTENANCE

The minimum lifetime of the motor is 10,000 hours, continuous duty. Thus the motor should be replaced after it has run 10,000 hours. The lifetime of the bearings exceeds 10,000 hours, but it is recommended that they also be replaced after this length of time. The three carbon-graphite brushes (see drawing 230-16) should be checked periodically and replaced when necessary.