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MULTI-CHANNEL SLIP RINGS FOR STRESS AND TEMPERATURE MEASUREMENT

By

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Multi-channel slip rings
for stress and temperature measurement

- by -

R. Chaplin

SUMMARY

The development of the various types of slip ring are outlined in the text and the design of a brush and ring type of slip ring is discussed in detail.

It is shown that a slip ring unit of this type can be made sufficiently robust to be a permanent part of the instrumentation of any rig. A highly stable contact potential is obtained in this design making possible stress measurements below $\frac{1}{2}$ ton/sq.in. in steel and temperature measurements with errors of less than 1°C using chromel-alumel thermocouples.

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1.0 Introduction

The temperatures of parts of rotating machines such as turbine rotor blades can be measured by using temperature sensitive paints, inserted pellets of hardened steel or by optical pyrometers. While such devices are moderately accurate, either the machine must be stripped in order that the temperatures reached may be determined or extensive modification of the machine is required. Thermocouples and slip rings can give accurate instantaneous measurements of temperature and can be made a permanent part of the instrumentation of any installation. Similarly wire strain gauges and slip rings may be used to measure steady and dynamic stresses in rotating parts.

In general only the steady or fairly long term variation of temperature is required so that the instantaneous values of the resistance of the transmission system are not of interest, whereas the measurement of dynamic stress demands a slip ring having a low and stable contact resistance. The difficulty in achieving and maintaining such a contact over long periods with a conventional brush type slip ring has led to the development of other types of transmission systems. The three main systems are described in the text to justify the choice of the conventional type for development as a general purpose instrument for stress and temperature measurement on rotor blades in gas turbines.

2.0 General

An outline of the historical development of the various types of transmission systems is given in the following paragraphs.

2.1 Disc and brush type slip rings

Slip rings consisting of a metal disc and a stationary collector have been much used for measurements of temperature in parts of rotating machinery. Knoblauch[1] in 1932 measured the temperatures reached in brake drums and shoes of motor vehicles with an accuracy of 1°C. The slip rings used were of copper with radial spring-loaded carbon brushes at a maximum rotary speed of 650 rev/min the corresponding rubbing speed of the contacting surfaces was 350 ft/min.

In the standard disc and brush slip ring the contact is made between the brush and the cylindrical surface of the disc, variations have been made in which the contact is made on the face of the rotating disc or annular ring. An interesting combination of both types was used by Leist and Knörnschild[2] in measurements of disc and blade temperatures on a gas turbine. Copper discs were spaced axially along the slip ring shaft and contact was made on the faces of the discs by copper-graphite brushes attached to spring loaded tongs. These slip rings gave a satisfactory performance for short periods of time at speeds up to 20,000 rev/min or rubbing speeds of approximately 5,000 ft/min. A multi-channel slip ring was developed by Mackenzie[3] for the same purpose and to operate over approximately the same speed range. Mackenzie used phosphor bronze rings and radial spring loaded brushes of silver graphite. The highest rotational speed at which these rings were operated was 18,500 rev/min the equivalent rubbing speed being 6,000 ft/min. The brush diameter was 0.125 in. and with a brush pressure of 80 lb/sq.in. the resistance of a channel was about 0.4 ohms. The maximum steady potential measured between the ring and the brush terminal was about 60×10^{-6} volts which with a chromel-alumel thermocouple is equivalent to a temperature error of 1.5°C.

In order to eliminate the relatively high resistance of the carbon brush, Fleisner and Wiehmann[4] used a collecting brush of copper strands rubbing on a copper ring. An auxiliary brush of oiled graphite tracking with the stranded collecting brush was introduced, the purpose of this brush was to clean the disc surface so that only a small pressure was required on the collecting brush. It also provided lubrication for the contacting surfaces and contained some 6 per cent of oil by weight. The brushes were large, roughly $\frac{1}{2} \times \frac{1}{4}$ in. cross section giving a low contact resistance but a bulky slip ring assembly. With a collecting brush pressure of 2 lb/sq.in. and pressure of 10 lb/sq.in. on the auxiliary brush the contact resistance was only 0.001 ohms. Fleisner and Wiehmann were able to run for several days without any appreciable change in contact resistance (rubbing speed 2,000 ft/min).

Development has continued[5,6] to obtain reduced rubbing speeds by improvements in mechanical design and to obtain lower and more stable contact resistance by the use of more suitable materials for rings and brushes.

2.2 Mercury slip rings

Slip rings in which mercury is used as the connecting material between rotating discs and stationary rings have been in use for some time, ideally the contact formed in this way is stable and of very low resistance. A mercury slip ring assembly due to Craft, Petrick and Smith[7] is sketched in Figure 1, the rotor discs are made from electrolytic copper and are insulated from each other by spacer rings of laminated phenolic resin. The discs and spacer rings are mounted on an insulated hollow steel shaft, the insulating tube surrounding the shaft is made of phenolic resin with a fibre glass filler. The stationary collector rings are also of electrolytic copper and are held in a "built-up" assembly of plastic sheets. There is a mercury reservoir for each ring, the application of air pressure to a reservoir forces the mercury through a hole in the ring into the space between the ring and the disc so making the contact. Cold air is passed through tubes in the mercury reservoir for cooling purposes.

The users claim that the parasitic electromotive force developed in these rings is less than 30×10^{-6} volts at 20,000 rev/min. This voltage is equivalent to a temperature error of 1°F with the copper constantan thermocouples which they are using. The delicacy and bulk of this slip ring makes it more suitable for laboratory use than for direct attachment to compressors or turbines. Mercury slip rings have been used for such applications[8] with considerable success both on the test bed and in flight. In these the mercury reservoir is normally omitted and a known quantity of mercury is introduced into each section. Cooling is obtained by the circulating cold air around the outer surface of the stator ring.

2.3 Coupled stationary and rotary circuits

If mutual coupling exists between two circuits then changes occurring in the impedance of one circuit will be reproduced in the second circuit. Fleisner and Wiehmann[4] refer to Gnam and Kuehl as having measured the temperature of a piston in an internal combustion engine by using the electromotive force developed by a thermocouple to produce a magnetic field in a rotating coil and hence a proportionate electromotive force in a linked stationary coil.

More recently the rotating transformer system has been used for strain measurements on compressor and turbine rotor blades. An installation consisting of two channels is sketched in Figure 1, the strain sensitive element on the blade is connected to the outer coil which rotates with the shaft, the inner stationary coil is connected to the measuring apparatus. The system is fed from a high frequency oscillator and if the impedance of the strain element changes there will be a corresponding change in the current in the stationary coil. This current change can be detected and amplified in the usual way. Alternatively, it is possible to use a frequency modulated system by making the complete channel of stationary and rotating circuits govern the frequency of an oscillator.

The coils must be spaced a sufficient distance apart to reduce the coupling between adjacent channels to an acceptable value, the wiring must be of low capacity to avoid shunting the sensitive element and to reduce stray couplings.

Slip rings, in which the capacity between a rotating and a stationary ring is used to couple the rotary and stationary circuits, have been made. The same considerations apply, namely the axial spacing of the rings must be large compared to the radial clearance and the wiring must be of low capacity.

3.0 Discussion

When temperature measurements on rotating parts are undertaken, in general only the steady or the fairly long term variations of temperature are required so that only the mean potential across the ring is of interest. If a potentiometer can be used then the variation of the contact resistance can be neglected provided that it remains finite. The measurement of dynamic stress on a rotating part using wire resistance gauges requires a slip ring with a low and stable contact resistance, as the instantaneous value of the resistance of the gauge must be measured. Hence the requirements for a slip ring for stress measurements are usually more severe than for temperature measurement.

The voltage changes to be transmitted through the slip rings are of the same order in the two cases. The electromotive force per unit temperature difference is about 40×10^{-6} volts/°C for a chromel-alumel and about 55×10^{-6} volts/°C for an iron-constantan thermocouple. For a conventional wire gauge of 100 ohms resistance attached to a steel specimen, the resistance change for a change in stress of 1 ton/sq.in. is approximately 0.015 ohms, if the gauge is carrying the normal current of 0.010 amperes this corresponds to a voltage change of 150×10^{-6} volts.

One of the causes of error in the measurement of stress or temperature through slip rings is the thermo-electric potentials generated by temperature differences within the slip ring. Temperature differences such as that across the sliding contact cannot be avoided in either conventional or mercury slip rings but are absent from the coupled circuit type. The thermo-electric effects can be reduced by reducing the temperature differences within the slip ring, by the choice of materials and by the siting of terminals etc.

The major disadvantage of the brush and ring type slip ring is the nature of the contact between the ring and the brush. The resistance across the contact surfaces is that of the film between them, this film consists of oxides, graphite scales, oil and water. The thickness and composition of the film are variable as the film is being continuously worn down by abrasion and reformed by oxidation, brush wear and by fresh depositions. The current passes through this film with interruptions similar to those in the electrical breakdown of insulators, the electrical "noise" generated in the measuring circuit by these interruptions must be more small in comparison with the signal voltage if accurate instantaneous measurements are desired. The thickness of the film is dependent on the brush pressure, ring and brush materials and operating temperature. To maintain a steady brush pressure the rings must be made concentric to fine limits and the inertia of the brush reduced to a minimum.

The contact in a mercury slip ring is also complex in character, the copper disc is coated with amalgam of variable thickness and runs in a turbulent annular pool of mercury. The advantage lies in the fact that these materials are very good conductors and therefore, the absolute value of the resistance variation is small. The rotating disc gives rise to a spray of mercury droplets, there must be an efficient seal between adjacent rings to prevent the passage of this spray. If this is not prevented a considerable amount of electrical noise will be generated and finally a complete short circuit between the rings. Efficient seals imply accurate machining of both stator and rotor assemblies and the maintenance of concentricity in the rotor, otherwise rubbing will take place at the seals and hot spots will develop with local distortions.

The coupled circuit type of transmission system avoids the difficulties of deterioration of the contacting surfaces and of achieving and maintaining rotor concentricity.

The disadvantages of this system are that the bulk and spacing of each coil severely limits the number of channels that can be accommodated, and the strain sensitive element and the measuring apparatus are not at present available commercially.

For the reasons above the mechanically simple and robust conventional slip ring was chosen for development.

4.0 Design of a brush and ring type slip ring

The design details of a general purpose slip ring designed to operate at speeds up to 10,000 rev/min and in a low ambient temperature are given in the following paragraphs.

4.1 Materials

Because of the film between the contacting surfaces it is essential to use a metal for the rings which does not form a hard and stable oxide immediately after exposure. Silver fulfils this requirement and has the advantages of being cheap, easily machined and of low resistivity. A substantial tyre of sterling silver allows for machining after assembly and for resurfacing of the ring after use. To reduce the rubbing speed at very high rotational speeds a silver ring may be painted[9] on to an insulated shaft, making possible a smaller overall diameter.

Development of metal-graphite conductors with silver or copper forming 80 to 90 per cent (by weight) of the whole has produced brushes of very high conductivity. The graphite in these brushes acts as a binder and lubricant. The proportions of silver to graphite in the brush must be selected on the basis of rubbing speed, the higher the rubbing speed the greater must be the proportion of graphite otherwise the wear will be excessive.

The choice of insulating materials is governed by the ambient temperature in which the rings are to operate, and by the mechanical strength required. For high temperatures porcelain, 'syntox' or steatite can be ground to shape after firing, for lower temperatures steatite in the "green" state is easily machined and for temperatures below about 70°C a phenolic resin with a fabric filler is adequate.

4.2 Brush design

To maintain a constant film thickness between the rubbing sufaces a constant brush pressure is necessary. The surface of the ring will not be truly circular or concentric so that the brush will be forced to oscillate radially if contact is maintained between brush and ring. Consider a brush-ring combination with the following properties.

Ring speed = 12,000 rev/min

Eccentricity = 0.001 in.

Brush weight = 1 oz.

Cross sectional area = 0.0625 sq.in.

The radial acceleration of the brush if contact
is maintained = ±4g approximately.

Equivalent variation in brush pressure = ±4lb/sq.in.

To reduce this variation, brush weight and ring eccentricity must be small.

Brushes operated by compressed air need only be in contact with the rings when measurements are required, thus reducing the quantity of conducting dust produced at the rubbing faces. All brushes in use are at the same pressure which is virtually independent of brush wear and the pressure can be adjusted to suit the state of the ring surface.

The design of brush and brush holder shown in Figure 2 reduces the moving parts to the silver graphite brush and the attached pigtail. The brush slides in a brass cylinder which is pressed into the bakelite holder. The connection from the brush is passed through the hollow brass rod, which forms a terminal post, and soldered at the top of the post. Sufficient slack is left in the pigtail to allow the brush to move freely. A hole is drilled from a circumferential groove into the central cavity of the holder, when the holder is fitted into the stator casing, this hole allows compressed air from an axial channel in the stator casing to force the brush on to the ring. When the pressurising channel is open to atmosphere, the pressure in the slip ring due to the cooling air is sufficient to lift the brush off the ring.

To stabilise the location of the brush a small trail was given by setting the axis of the brush holder at 10° from the radial (Figure 3). Further stabilisation was found necessary and brushes of square cross section (4 mm × 4 mm) were used.

4.3 Rotor design

The rotor assembly of the slip ring is shown in Figure 4. The silver rings are pressed on to the annular insulators and, with the spacer discs, are pushed on to the shaft between the flingers F_1 and F_2. F_1 is fixed to the shaft and F_2 screws on a threaded portion of the shaft to clamp the rings together. This arrangement avoids any disturbance of the rings when the bearings are renewed. The connecting leads are disposed in two or more axial slots, S. These slots continue under the inner race of the bearing at the drive end, allowing the leads to terminate on the insulated brass screws, T. The disc carrying the terminal screws and the drive pins, P, is keyed to the slip ring shaft and locked in position by the screw B. A driving disc of the same dimensions is attached to the end of the driving shaft; on assembly the drive pins fit into holes lined with soft rubber in the driving disc. Terminals are placed at the same radius and in similar positions on the driving disc as on the driven disc. Corresponding terminals are then bridged with flexible wires, thus carrying the slip ring connections to the main rotor.

As it is necessary to grind the rings while the shaft is rotating in its own bearings, this operation is facilitated by the use of bearing housings which are not integral parts of the stator casing. To allow for axial growth of the rotor or stator, the outer race at the free end of the shaft is made a sliding fit in the bearing housing. The bearings are grease-packed on assembly; the labyrinth seals, which are shown simplified in the figure, prevent movement of the grease on to the ring surfaces.

As radial movement of the slip ring shaft cannot be tolerated, bearings without radial clearance are used. To obtain a reasonable life, the bearing loads must be made very small or rapid wear will result. The machining of the bearing housings and of the stator casing must be sufficiently accurate for there to be negligible side loads on the bearings when assembled. Axial or radial movements of the driving shaft must be prevented from placing any loads on the slip ring bearings by the use of a highly flexible coupling between the driving shaft and the slip ring shaft.

4.4 General assembly

The complete assembly is sketched in Figure 5 in which two longitudinal sections of the stator casing are shown; the stator casing is split longitudinally along the line of the cooling air exit holes (Figure 3) to allow the rotor to be inserted. The stator is drilled and tapped to take the 36 brush holders in four rows of nine holders, the rows being spaced at 90° intervals around the casing.

Each line of brushes is pressurised from an axial compressed air channel; the four channels are fed from a common source through a manifold which is not shown. Cooling air is taken from the two axial channels shown in the cross-section in Figure 3, and directed on to the rings through radial passages; the cooling air is allowed to escape to atmosphere.

Metallic dust produced at the rubbing surfaces is partly carried away by the cooling air but some is deposited on the inside surface of the stator casing and a small proportion between the silver rings. These deposits may form a conducting path between the brush and the casing or between adjacent brushes, giving rise to spurious readings. The path length for such a deposit to become effective is increased in this design by the attachment of a thin sheet of insulating material to the inner wall of the stator casing.

5.0 Performance

Two slip ring units as described except for the arrangement of the brushes in eight rows of alternately four and five holders have been manufactured and tested. Prior to running, the eccentricity of the rings was less than 0.0001 in. and the surface roughness was 5 micro-in.

The slip rings were put on test at a speed of 7000 rev/min with a brush pressure of 15 lb/sq.in. (gauge) and cooling air at approximately 5 lb/sq.in.(gauge). After running for 40 hours under these conditions the rings were dismantled for inspection owing to the deterioration of the insulation resistance between adjacent channels. The decrease in insulation was due to the metallic dust deposits which are shown in Figure 7. The eccentricity was measured and found to be between 0.0002 and 0.0003 in. and in the track of the brush the surface roughness had increased to 40 micro-in. The average brush wear was approximately 0.0625 in. and the rings had been worn down by approximately 0.0004 in. in diameter. When the dust had been removed the rings were reassembled and found satisfactory.

Over the period of 40 hours the potential difference across the ring-brush contact was continuously monitored and the mean steady potential difference and the fluctuations of the mean level were recorded. At a fixed mean current through the contact surface little change was observed in either level until the breakdown of the insulation occurred.

The variation of the steady potential difference with current density and the variation from ring to ring at a fixed density are tabulated below.

Current amps.	Current density amps/sq.in.	Potential difference volts	Equivalent resistance (ohms)
0	0	0.000004	0
0.0026	0.105	0.000066	0.025
0.0055	0.222	0.000127	0.023
0.0080	0.323	0.000185	0.023
0.011	0.444	0.000277	0.025
0.022	0. 87	0.000545	0.025
0.046	1.85	0.001725	0.037

Ring No.	Potential difference volts	Equivalent resistance ohms
1	0.000350	0.032
2	0.000330	0.030
5	0.000307	0.028
6	0.000305	0.028
9	0.000295	0.027
10	0.000255	0.023
13	0.000248	0.023
14	0.000240	0.022
17	0.000283	0.026
18	0.000190	0.017
Mean	0.000280	0.026

The above values were obtained at a speed of 7000 rev/min with a brush pressure of 15 lb/sq.in. (gauge) and a current density of 0.444 amp/sq.in. except where stated.

No appreciable variation of contact resistance could be found when the brush pressure was varied between 10 and 30 lb/sq.in. Below about 5 lb/sq.in. the contact resistance rose rapidly and the contact became unstable.

It can be seen from the tables that the equivalent contact resistance is independent of current density over a wide range. It is unlikely that current densities above 0.5 amp/sq.in would be required for either temperature or strain gauge work. The variation of contact resistance from ring to ring is fairly large, say ∓30 per cent of the mean but as the absolute value of the mean is small, this variation will not introduce any appreciable errors.

The fluctuations in the contact potential difference were analysed and are expressed in figure 6 in terms of the equivalent root mean square series resistance. This figure shows the mean overall level as 0.0032 ohms, and that the major constituents of the fluctuations are the first and second rotational orders. In terms of dynamic stress measurements using a 100 ohms gauge attached to a steel specimen, the overall background noise is equivalent to an r.m.s. stress of 400 lb/sq.in. and, using filters, this level can be reduced to at most 200 lb/sq.in. over an octave span.

Further use of the slip rings has shown that adequate life can be obtained from the bearings provided that the precautions mentioned are taken, namely, that sufficient flexibility is provided in the coupling to isolate the slip ring shaft from the main shaft.

6.0 Conclusions

Brush and ring type slip rings for the measurement of temperature or stress on rotating rigs can be made with high performance and a life sufficient to be made a permanent part of the instrumentation.

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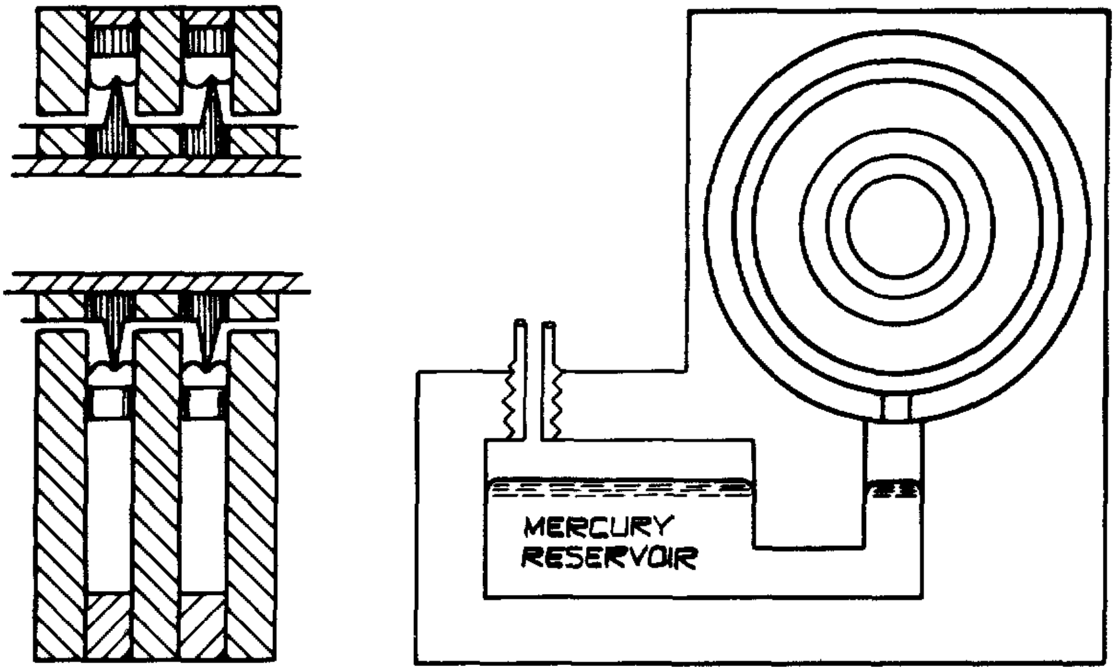
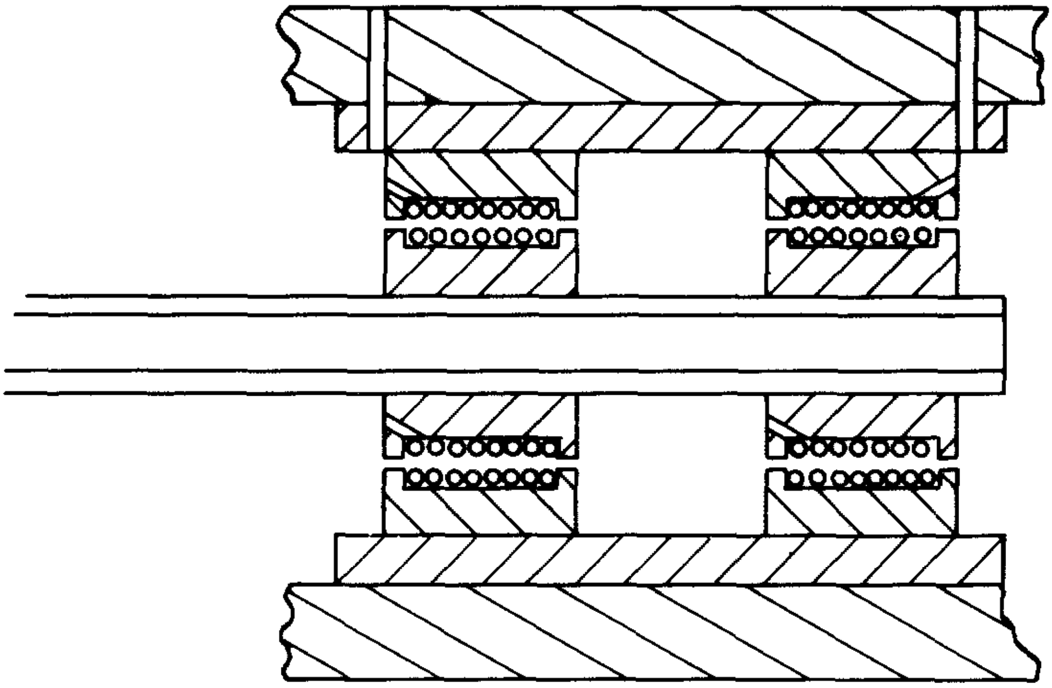
FIG.1

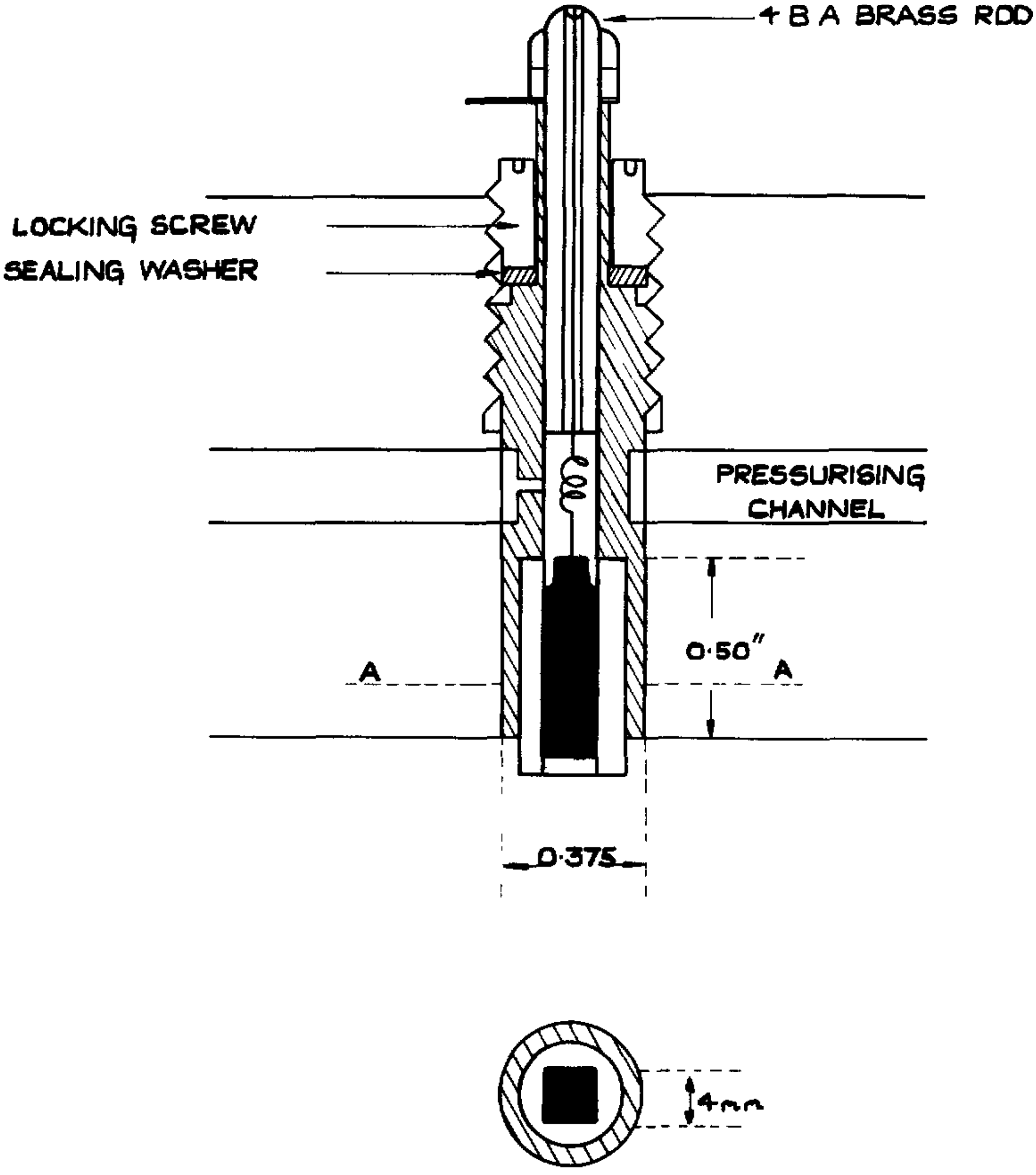


MERCURY SLIP RINGS.



TRANSFORMER TYPE SLIP RINGS.

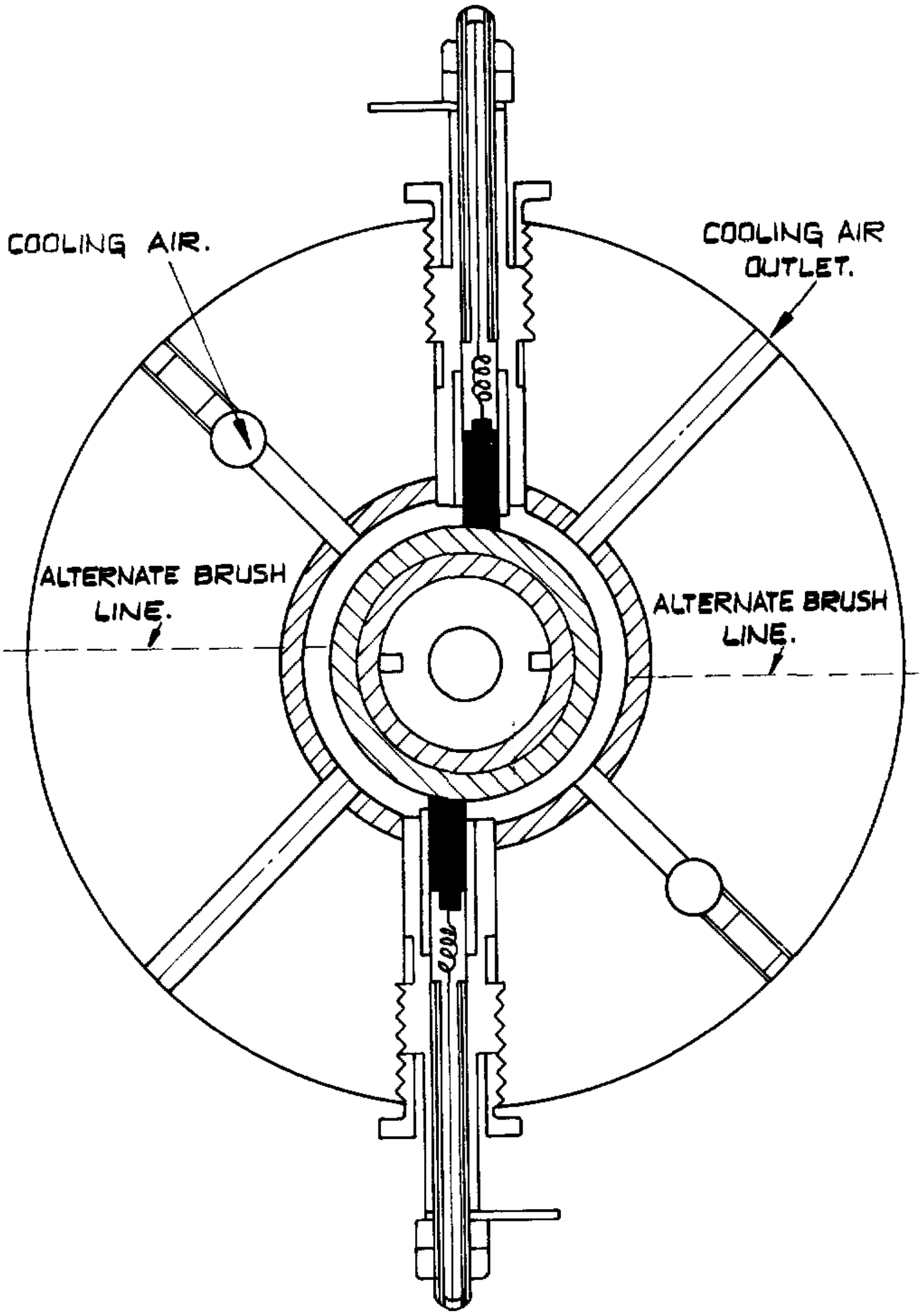
FIG. 2



SECTION ALONG A.A

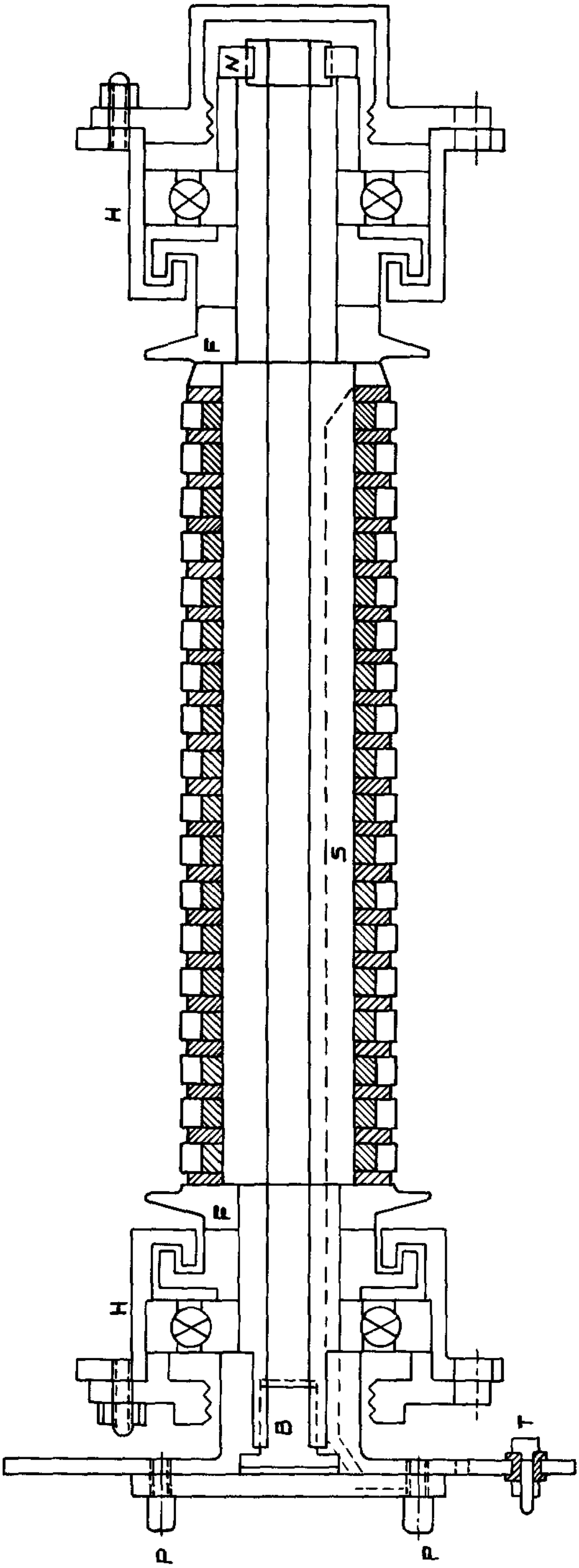
DETAILS OF BRUSH HOLDER.

FIG. 3



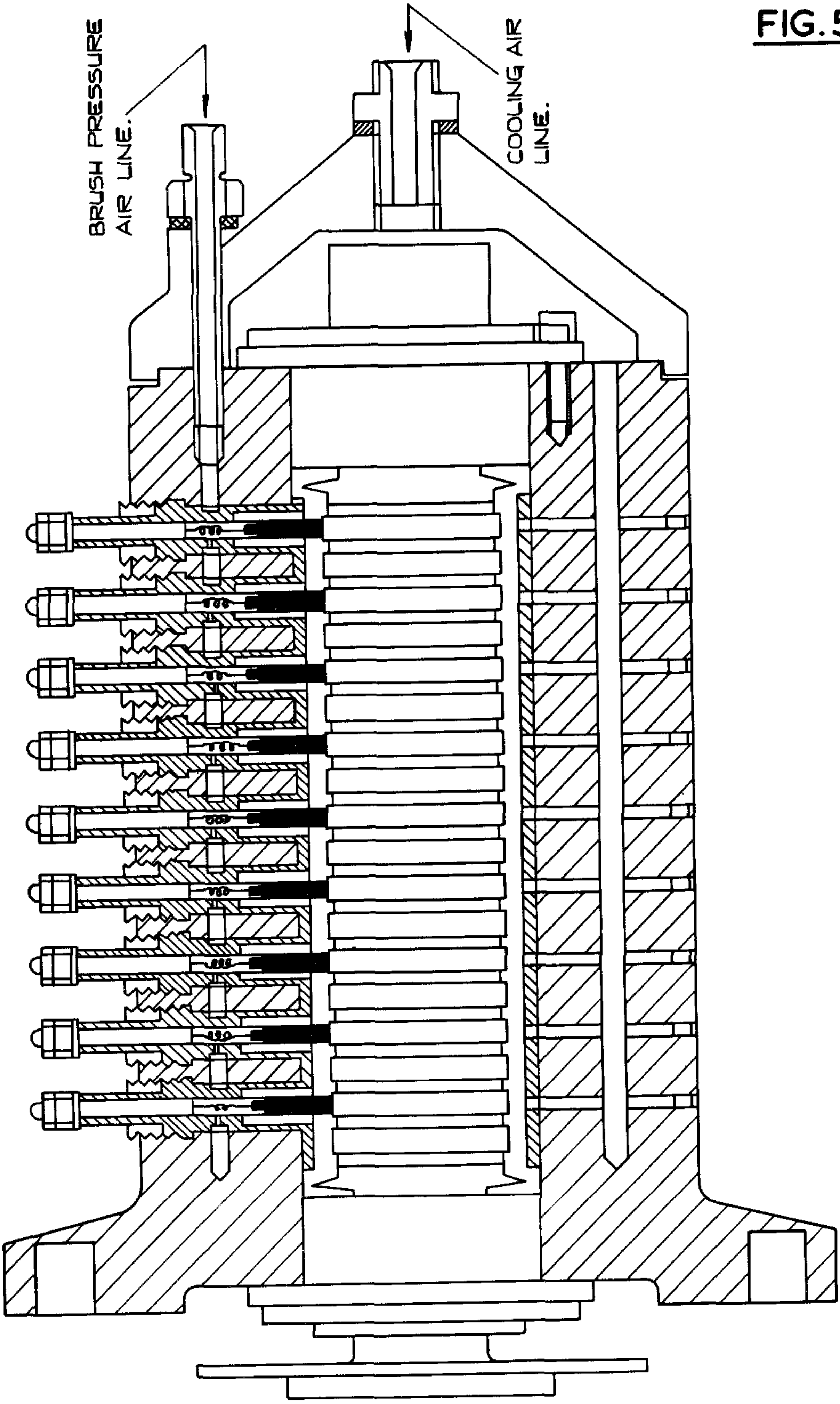
SECTION THROUGH SLIP RING.

FIG. 4



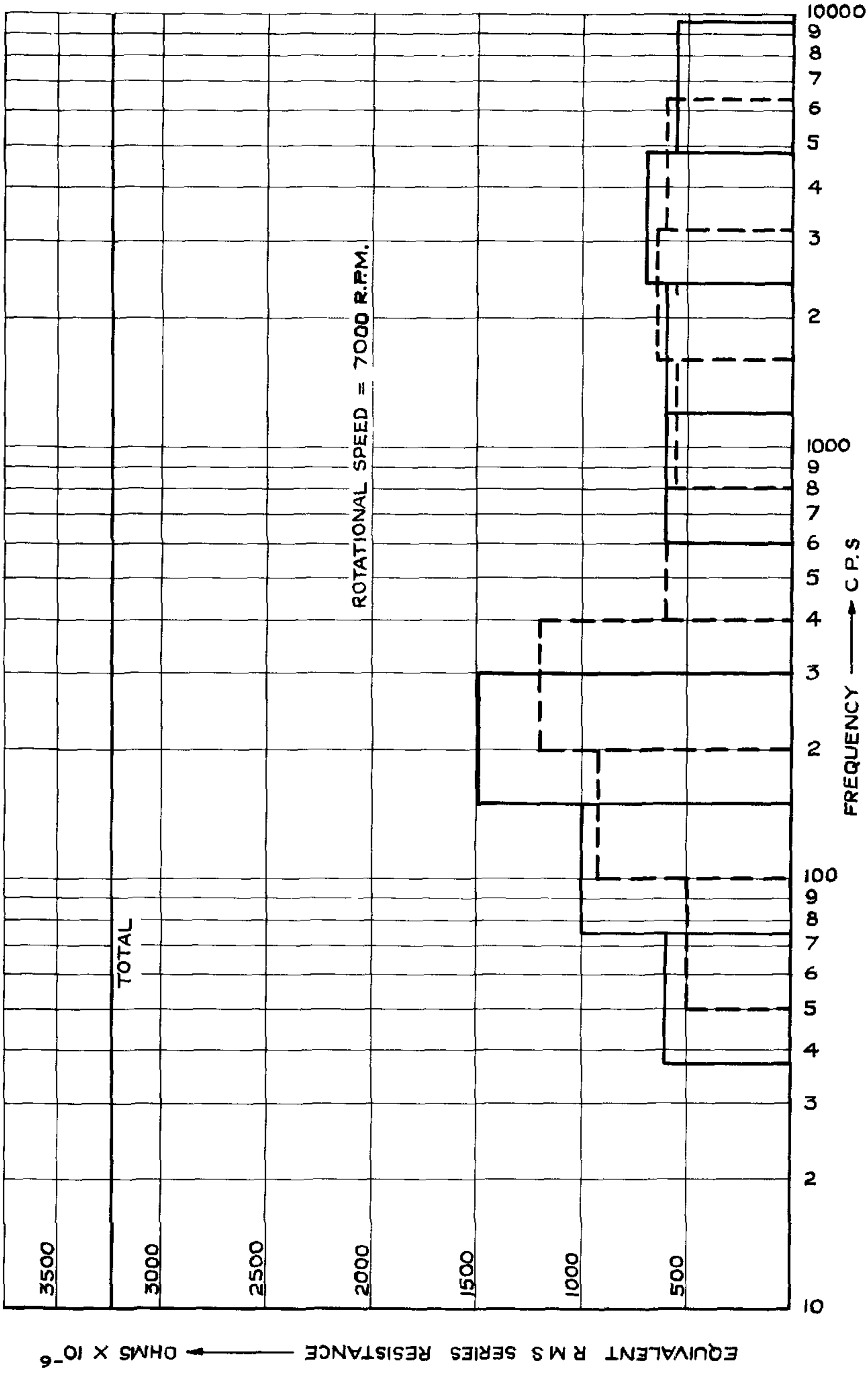
SLIP RING ROTOR ASSEMBLY. (FULL SIZE)

FIG. 5



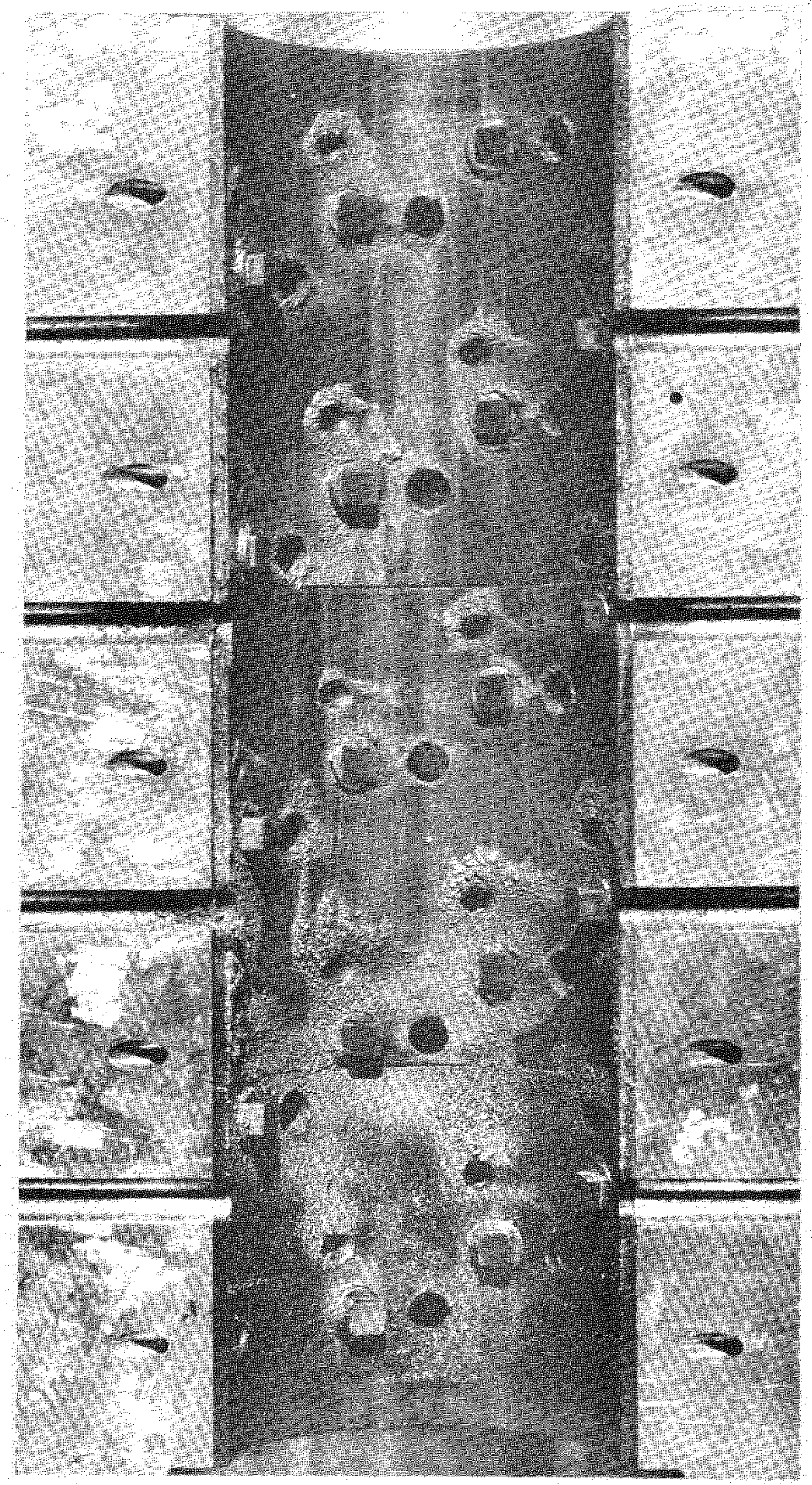
SLIP RING – GENERAL ARRANGEMENT.

FIG. 6



OCTAVE ANALYSIS OF RESISTANCE VARIATIONS

FIG. 7.



DUST ACCUMULATIONS

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