

Development of the Electrostatic Clutch

The pressing demand for higher and higher operating speeds of the mechanical sections of electronic computers and data processing machines started a search for an electromechanical transducer that would be inherently faster than the traditional electromagnet. An electrostatic clutch, operating on the Johnsen-Rahbek effect, promised to fulfill this requirement.

The Johnsen-Rahbek effect is the electrostatic adhesion between a metal plate and the surface of a semiconductive material under an applied voltage. As employed in clutch form it will develop phenomenally high mechanical forces from low levels of input control energy. High torque-to-inertia ratio and a low electrical time constant assure fast mechanical response. The clutch is non-inductive, and the operating voltages and currents are within the range of medium- and low-power vacuum tubes. These desirable characteristics seemed to justify an investigation of the Johnsen-Rahbek clutch as a possible component for performing high-speed mechanical functions.

Historical background

Literature on the Johnsen-Rahbek effect is scant. Perhaps the earliest reference is contained in a patent¹ issued to Elisha Gray in 1875. Gray was a prolific inventor who pioneered in the development of the telegraph and telephone. In this patent he discloses an electric telegraph for transmitting musical tones. Reproduction of the transmitted tone is accomplished: "... upon my own discovery that such vibrations can be ... reproduced in a musical tone or pitch ... by including in the circuit animal tissue or other equivalent substance which will cause a slight resistance to the electrical current at the point of contact between such animal tissue and some resonant conductor of electricity." He further states: "... from some cause not understood or explicable in the present stage of the art ... (it) gives forth a musical tone."

Another patent² issued to Gray in 1878 disclosed a speaking telephone. The reproducer in this case was a drum with a metal diaphragm mounted for slow rotation by a hand crank. The telephonic currents, passing through the operator's hand in gliding contact with the metal diaphragm, set up vibrations which were a more or less faithful reproduction of the original speech.

Abstract: A brief historical review of the electrostatic clutch operating on the Johnsen-Rahbek effect is presented. Mechanical design of a clutch, special lubrication, and the fabrication of electronically conductive clutch facing material are described. A high-speed, high torque-to-inertia ratio test model with bi-directional shaft control is described. With the clutch operating at 2500 rpm on 30 milliamperes at 150 volts, torques over 80 inch-pounds are available. The most useful single property of the electrostatic clutch is its fast response time. It can actuate levers, interposers, print hammers, optical gates, etc., in fractions of a millisecond; it can accelerate shafts to high rpm's with moderate loads in a few milliseconds from extremely low input control energy.

Although a device disclosed in a patent³ issued to Edison in 1879 does not depend upon the Johnsen-Rahbek effect for its operation, it nevertheless resembles a Johnsen-Rahbek clutch. In this patent of a telephone receiver, a rotating chalk cylinder saturated with a solution of acetate of mercury mixed with caustic soda is used. Pressing against the surface of the cylinder is a flat spring, one end of which is attached to a diaphragm. The effect is opposite to that of the electrostatic clutch, in that with no applied voltage, the friction between the spring and the cylinder is high and tension is exerted on the diaphragm. When current passes through the spring and cylinder in a direction such that hydrogen gas is formed at the contact area, the friction is reduced and less force will be exerted on the diaphragm.

Two Danish engineers, F. A. Johnsen and K. Rahbek, contributed most to the early development of the electrostatic clutch. Their several years of research culminated in a comprehensive report⁴ published in the *IEE Journal* of July 1923. Only a few of the pertinent points will be mentioned here.

The basic clutch employed a rotating semiconductive cylinder in sliding contact with a metal band. Agate or a similar porous stone was used for the clutch wheel or cylinder. Moisture from an electrolyte within the porous stone rendered it, what Johnsen and Rahbek called, a "semiconductor." Obviously, conduction was ionic, and not electronic as in the germanium and other crystalline semiconductors used today in diodes and transistors.

The Johnsen-Rahbek clutch was used to a limited extent commercially as a telegraph repeater and as a loud-speaker driving unit. It had, however, the following disadvantages:

- (a) The use of an electrolyte and ionic conduction resulted in electrolysis and eventual erosion of the clutch surfaces.
- (b) Evaporation caused variations in electrical resistance and torque output.
- (c) Natural stone is anisotropic with the result that conductivity and torque were not uniform around the periphery.

Additional electrostatic clutch patents were issued to Edison,⁵ Winslow⁶ and Rahbek.⁷

Theory of operation

Electrostatic attraction was believed to be the mechanism responsible for the adhesion between a metal band and the clutch resistance material when voltage was applied. The force, therefore, should vary as the square of the applied voltage. Johnsen and Rahbek found this to be true only for rough surfaces. For smooth surfaces, the force was found to be proportional to the third power of the applied voltage; and for very smooth surfaces the force was proportional to the fifth power of the applied voltage. This led them to doubt that electrostatic attraction was entirely responsible for adhesion.

The electrostatic force of attraction between two separated metal plates when under the influence of an applied voltage is given by the formula:

$$f = \frac{1.59 KAE^2}{d^2 \times 10^{11}}$$

where f = force in ounces

K = dielectric constant, which is 1 for air

A = area in square inches

d = distance of separation in inches

E = applied voltage

From this it is apparent that the force varies with the square of the applied voltage, up to the point of ionization and breakdown of the dielectric medium.

The force of attraction also varies inversely with the square of the distance of separation. By reducing the distance, the magnitude of the force can be tremendously increased. If the distance, d , is reduced to a point where the plates touch, a short circuit occurs, the voltage is lost, and no further attraction exists. However, if one of the plates is made of a high resistance material, the distance of separation can be reduced until the plates are in contact without shorting the system; only a small leakage current will flow through the points of contact.

Ragnar Holm⁸ shows that the load bearing surface, or sum of all of the areas of points of contact of two smooth surfaces in contact, can be hundreds or thousands of times smaller than the nominal area of the surfaces. Dyson and Hirst⁹ published photographs show-

ing the points of contact between smooth solids.

Fig. 1(a) shows a magnified view of the interface between a metal clutch band and the surface of the resistance material. Even with surfaces ground and lapped to optical smoothness, contact between the surfaces will exist only at the surface asperities representing some 1% of the total surface area.

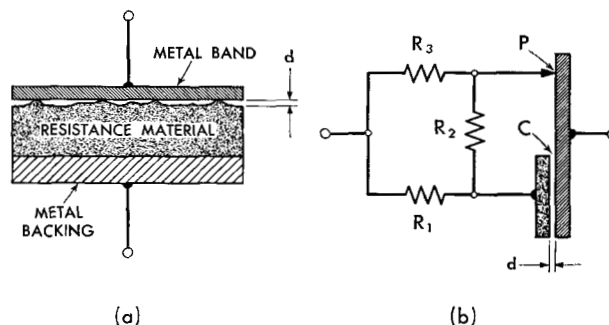


Figure 1

(a) Enlarged view showing isolated points of contact between the clutch surface material and the band; (b) electrical analogue of (a).

The electrical analogue of Fig. 1(a) is shown at Fig. 1(b). Here the resistors R_1 , R_2 and R_3 represent the bulk resistivity of the clutch resistance material. P represents the points of contact and C the electrostatic capacity of the area not in contact.

The electrical time constant of the system is equal to the product RC , R being the electrical equivalent of the network R_1 , R_2 and R_3 .

The distance of separation between the surfaces is represented by d . The smoother the surfaces the smaller d becomes and the greater the attractive force. The dielectric between the surfaces is the micro-thin air film and whatever oxide films and other surface contaminants exist. Because of the high contact constriction resistance, some 80 to 90% of the voltage drop appears at the interface and the remainder through the bulk material.

The large attractive force encountered causes the band to move physically closer to the surface of the resistance material, thereby decreasing the distance d slightly. With rough surfaces, d is large, the force is small and the relative change in distance is slight; here the force obeys the square law as observed by Johnsen and Rahbek. With smooth surfaces, d is small, the force is large, and the relative change in d is appreciable. Here the force is no longer proportional to the square of the voltage but is modified by the changing distance of separation.

An investigation of the Johnsen-Rahbek effect using a resistance material in which conduction was electronic was reported by Balakrishnan.¹⁰ He used a disc pressed from a powdered mixture of magnesium and titanium

oxides, fired and reduced by heating in hydrogen to produce suitable conductivity. One side was sprayed with metal and the other side lapped and polished to optical flatness. While results were scattered, the conclusion reached was that the simplest explanation of the attractive force is that it is the normal electrostatic attraction between the surfaces of the disc and the opposing electrode plate.

Clutch material fabrication

In setting up specifications for a clutch resistance material the following factors were considered:

1. Electronic conduction
2. Homogeneous resistivity in the order of 10^6 ohm-cm
3. Reproducibility
4. Heat and wear resistance and dimensional stability
5. Good frictional characteristics
6. Ease of manufacture

Because of the wide range of possible materials, the research facilities of Battelle Memorial Institute were engaged to aid in material selection. Although some materials excel in some of the desired properties, the conclusion reached after exhaustive tests was that the best material was rubber-base plastic rendered conductive by the addition of conductive carbon.

Continued research in the IBM Plastics Laboratory to improve reproducibility, particularly the work of L. N. Chellis, resulted in the selection of Buna N (butadiene-acrylonitrile) synthetic rubber for the rubber portion of the material. Buna N is completely compatible with phenolics and reacts chemically to cross-link with the phenolic during curing or vulcanization. One form, available as a dry powder, is adaptable for dry blending. Table 1 gives a composition typical of some of the many tested.

Table 1 Composition of rubber-base plastic

Parts by Weight	Name
0.1	Methyl Zimate
0.5	Captax
1	Antioxidant
1	Stearic Acid
1.5	Sulphur
3	Zinc Oxide
40	Hycar 1411 (Buna N)
42.5	Conductive Carbon (Spheron C)
60	Durez 12687 (Phenolic)
100	Asbestos Fibre

Since all of the ingredients listed in Table 1 are in powder form they can be blended by dry mixing. The pre-blended material is fluxed by banding on heated rolls using standard roll milling techniques common to the rubber industry. The material is then in sheet form and may be molded by conventional compression-mold-

ing techniques. Typical curing conditions are 30 minutes at 325°F and 2 hours after baking at 275°F.

The factors found to affect electrical conductivity were: (a) carbon content, (b) milling time, and (c) molding pressure. The curve of Fig. 2 shows the volume resistivity vs carbon content, with the molding pressure held constant at 13,450 pounds per square inch.

Milling time affects resistivity in that continued milling eventually renders the material non-conductive. The milling time is a function of the batch size and the nip at the rolls. Once determined, the milling procedure must be rigorously adhered to. Small batches are milled 6 or 7 minutes and cross-blended 3 or 4 times.

Molding pressure affects resistivity as shown by the curve of Fig. 3. Variations in resistivity from batch to

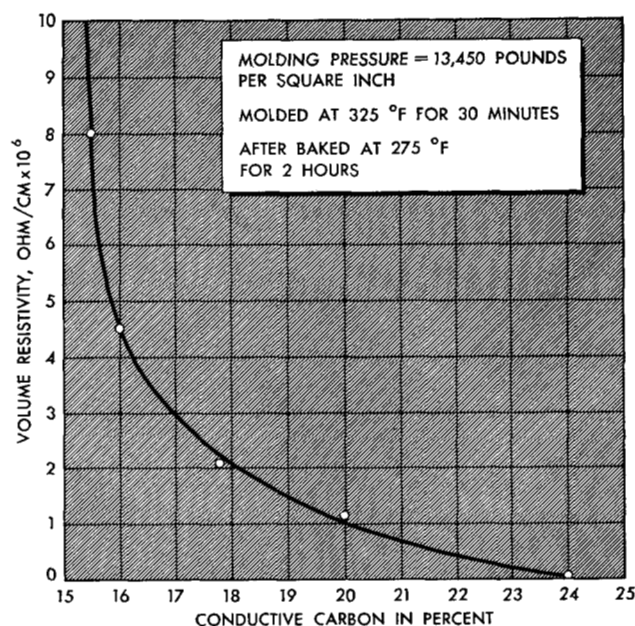


Figure 2
Curve of volume resistivity versus carbon content.

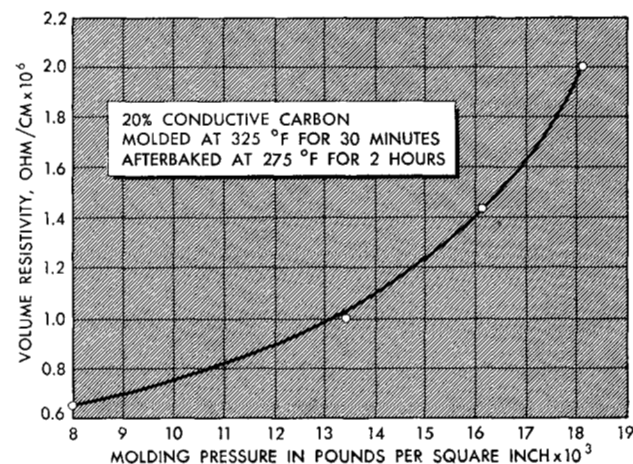


Figure 3
Curve of volume resistivity versus molding pressure.

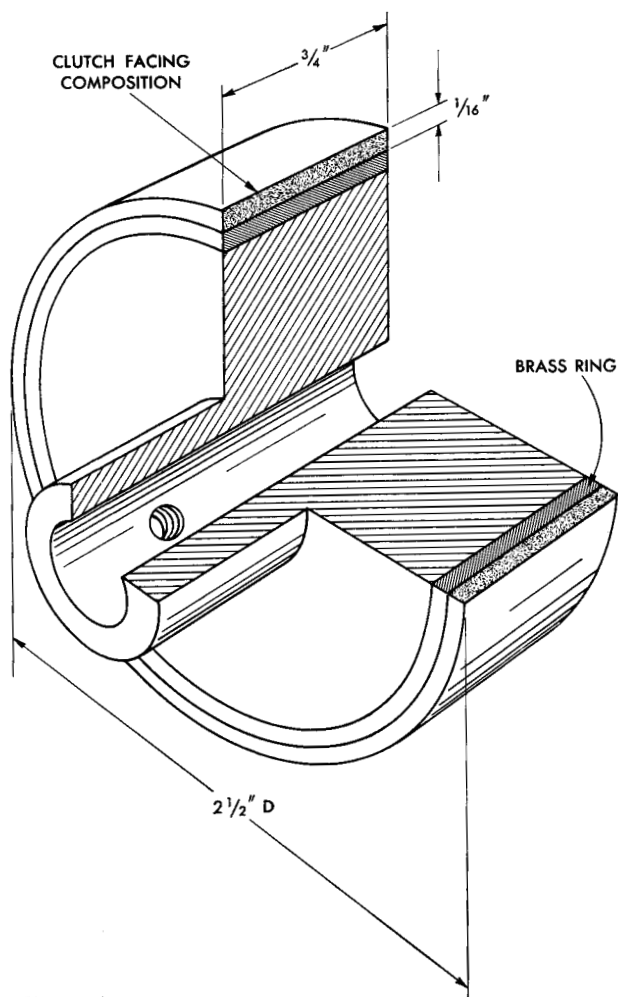


Figure 4
Standard test clutch wheel (used for gathering the data for curves of Figs. 6 and 7).

batch may be compensated for by proper selection of the molding pressure. It is interesting to note from the curve that the resistance *increases* with molding pressure.

To insure bonding of the plastic to a clutch wheel, the surface of the wheel should be sand blasted and the wheel either made of brass or brass plated. A number of sample test clutches were made by molding the material on the surface of brass rings. The material was molded slightly oversize in diameter so that it could be ground to size or preferably faced off with a diamond cutting tool to insure a smooth surface. The finished molded ring was then pressed on a steel hub arranged for attachment to a drive shaft. Fig. 4 shows the test wheel assembly.

Lubrication

Wide variations in clutch performance, even with the same clutch, at first resulted from imperceptible variations in the surface condition caused by wear, heat and abrasion. Some special type of lubrication was essential if the clutch was ever to become practicable. Johnsen and Rahbek had reported that oil on the clutch surface ruined its action. This was found to be true when ordinary hydrocarbon oils were used. Fortunately, lubricants are available today that drastically change this situation. Of the modern lubricants, both solid and liquid types have been found to be effective.

The solid lubricants include Teflon (a polytetrafluoroethylene compound) and polyethylene. A block of either of these plastics pressing lightly on the rotating surface of the clutch-facing material provided effective lubrication. In addition, a mohair brush wiper proved essential to remove gross dust particles and buff the

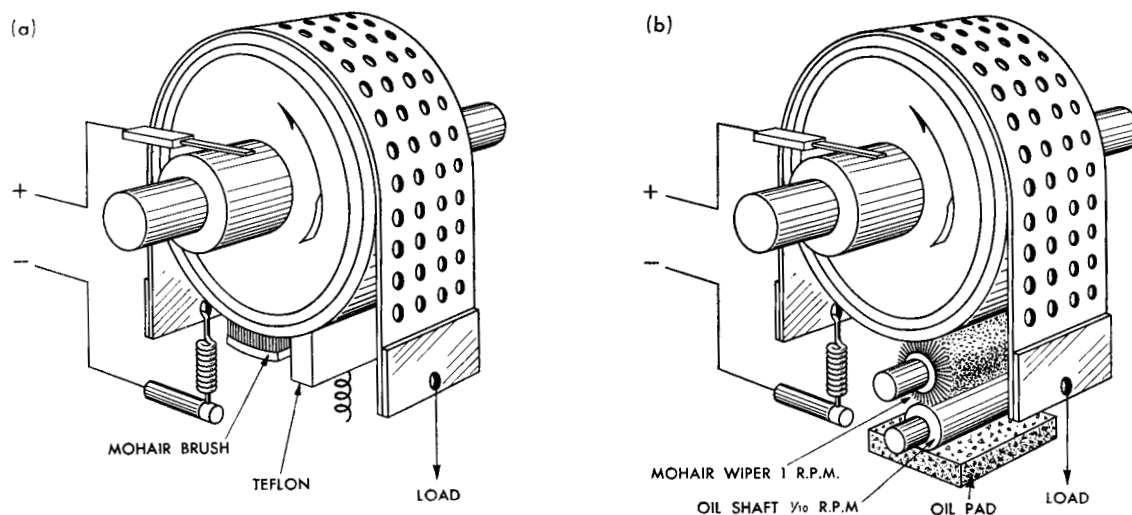


Figure 5
(a) Test clutch using solid lubricant; (b) test clutch using liquid lubricant. (Note that oil shaft and brush rotate at a low rate.)

surface [see (a) of Fig. 5]. Continued use, however, tended to build up the coating and higher operating voltage was required at the end of a long test run than at the beginning. For most applications, the liquid lubricants seemed more satisfactory.

These liquid lubricants include the silicone oils and the Kel-F fluorocarbon oils and waxes. Minute quantities of oil are used; if too much oil is applied, torque will drop off and the residual drag, at no voltage, increases. Too little oil, however, results in appreciable clutch wear.

The clutch band

Tempered spring steel, 0.003 inch thick, was found best for the 2.5-inch diameter clutch. When a metal band is curved in circular shape, the outer surface stretches and the inner surface compresses. This slightly curves the band crosswise, causing it to make better contact along the center than at the edges when flexed around a clutch wheel. For this reason, narrow bands develop more torque proportionally than wide bands. Etching rows of holes crosswise in the band, as depicted in Fig. 5, serves a twofold purpose: (1) the band flexes along the rows of holes, making it polygonal in shape and providing uniform transverse areas of contact with the clutch surface between the rows of holes, and (2) without the holes the liquid lubricated clutch would be inoperative because of the excessive residual drag. The holes allow the passage of air and relieve the partial vacuum created by the oil seal between the smooth surfaces. Narrow bands, in the order of $\frac{1}{8}$ inch or less, function satisfactorily without holes.

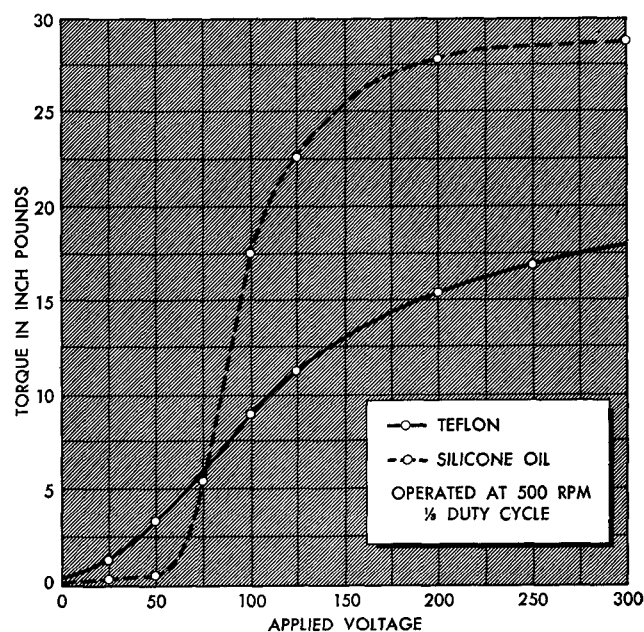


Figure 6
Curves of torque versus applied voltage for solid and liquid lubricants.

The band ends are strengthened, where needed, by sandwiching them between two reinforcing pieces soldered in place.

Test results

The curves of Figs. 6 and 7 show typical results from the test models, using a $\frac{3}{4}$ inch band with a 180-degree band-wrap angle. Tests were made by attaching the band to a long lever arm on which a sliding weight could be moved to measure the torque.

Fig. 6 shows the torque vs voltage for the Teflon and oil lubricated clutches operating at 500 rpm. Fig. 7 shows the torque vs rpm of the same clutches. The residual (no voltage torque) is also shown on this curve.

The superiority of the oiled type is apparent from these curves. Of particular interest is the comparison of the torques at zero rpm; the Teflon-lubricated one has maximum torque at rest while the torque of the oil-lubricated clutch approaches zero as the slip speed is reduced to zero. Thus, the liquid lubricated clutch behaves like a fluid drive system and requires some slip to develop torque.

The test model clutch could be operated at 500 rpm continuously on $\frac{1}{8}$ th duty cycle, at 20 inch-pounds torque. Under these conditions it would dissipate about 30 watts of heat energy without exceeding a 300°F band temperature.

The electrical response time of the clutch varies with the clutch resistance [see (b) of Fig. 1]. The resistance values of the test clutches were selected so that, with 180-degree band wrap and 150 volts, the current would

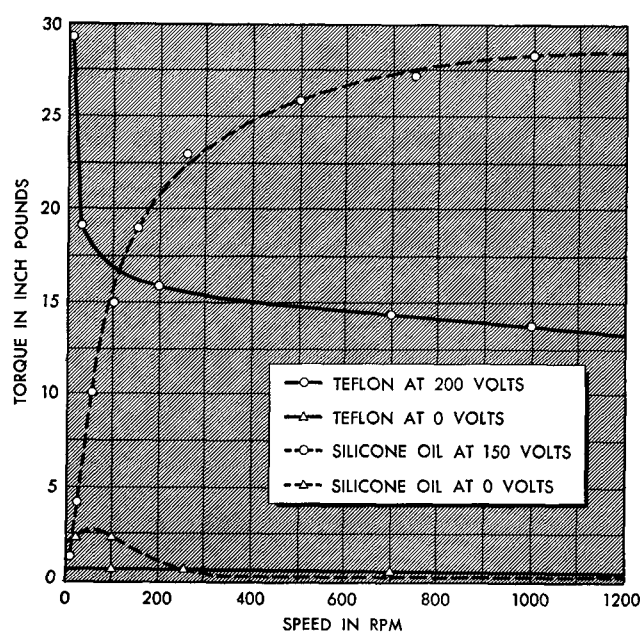


Figure 7
Curves of torque versus speed for solid and liquid lubricants.

be about 10 milliamperes. Clutches will function over a wide resistance range, but with these values the response time has been carefully measured and found to be about 150 μ sec; that is, 150 μ sec after the voltage is applied full torque is available. The time it takes to move a load, however, depends upon the magnitude of the force, the mass of the load, and the distance through which it is moved. Narrow bands, about 1/16 inches wide, will move light latches through a distance of around 0.040 inch in 500 to 700 μ sec.

There are two basic clutch designs that will fulfill almost all computer input-output machine applications: 1) a multiple band clutch in which a relatively large number of narrow bands are operated from a long cylindrical clutch rotor for actuating latches, levels, interposers, etc., and 2) a high-speed, medium-power clutch for controlling shaft rotation, for paper, tape and card feeding applications, and for an impulse type non-linear servo-control mechanism. This paper will conclude with a brief description of a practical design of a high-speed power clutch.

High-speed clutch design

The salient property of the electrostatic clutch is its fast electrical response. To utilize this feature to its full advantage a high-torque-to-inertia ratio mechanical design is essential. The design about to be described was developed with this in mind and models built for performance testing. Three clutches were mounted on one shaft, so arranged that one would serve as a brake and the other two could be used for either high and low forward speeds or for forward and reverse operation. The reproduced photograph, Fig. 8, shows the 3-clutch

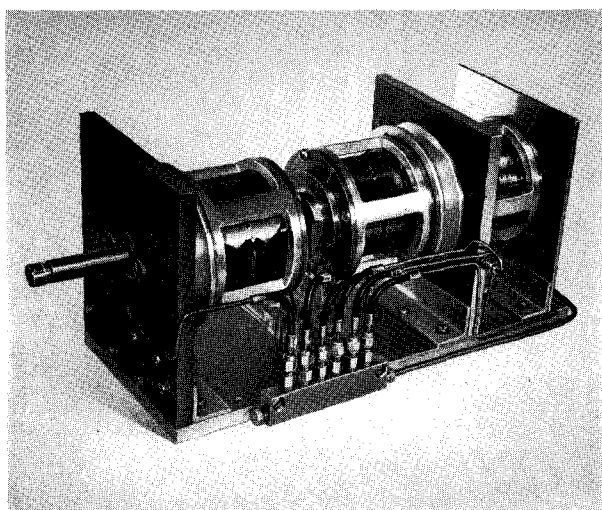


Figure 8
Assembly of the 3-clutch unit. The clutch at the rear serves as a brake. V-belts are used to drive the other two clutches at high or low speed in either direction.

assembly. The shaft, which is 1/2 inch in diameter and 13 inches long, gives an idea of the overall size.

In the design of this clutch, a primary consideration was the need for the clutch-driven member to have a low moment of inertia. Assuming uniformly accelerated motion, the accelerating time is given by the formula:

$$t = \frac{I\omega}{T}$$

where t = accelerating time (seconds)

I = inertia (in-lbs/sec²)

ω = final angular velocity (2π rps)

T = torque (in-lbs)

The accelerating time can be reduced by reducing I , increasing T , or both. The force is fixed by nature at a certain value per square inch of active clutch surface, so that the only way to increase T is to make the clutch larger. But this leads to complications. The active clutch area is proportional to r , where r is the radius of the clutch drum, and the distance from the center at which the force is acting is also proportional to r . The torque T is, therefore, proportional to r^2 .

Since the inertia $I = mr^2$, and m , the mass, is proportional to r^2 , the inertia I is proportional to r^4 . The accelerating time, t , would, therefore, be proportional to r^2 . Summing up,

$$T \approx r^2$$

$$I \approx r^4$$

$$t \approx r^2 \text{ (provided } \omega, \text{ or the rpm, does not change)}$$

(Note: r may be thought of as the radius of a cylinder whose moment of inertia is equal to the sum of the inertias of all the accelerating members in the system.)

Reducing the radius r will increase the torque-to-inertia ratio and decrease the accelerating time. This, however, has its limitations in that the torque may be reduced to a point where there will be insufficient left over to do the required work.

Maximum mechanical efficiency is obtained when the inertia of the clutch system equals the inertia of the load. If the load inertia is greater or less than that of the clutch, gearing may be employed for matching. In other words, the output impedance of the clutch should equal the input impedance of the load. Since ω , or the final angular velocity, will be inversely proportional to r when the match to the load is maintained through suitable coupling, the accelerating time of the whole system, clutch plus load, becomes directly proportional to r . To elucidate: given a fixed load and load rpm, a large clutch would operate at a lower angular velocity or rpm to maintain a match.

These general rules hold under ideal conditions; practical design considerations, however, may favor one clutch size over another for any given application. For example, the formula indicates that one way to increase the torque without reducing the torque-to-inertia ratio is to make the clutch longer; that is, increase the size of the clutch in the dimension parallel to its axis of rota-

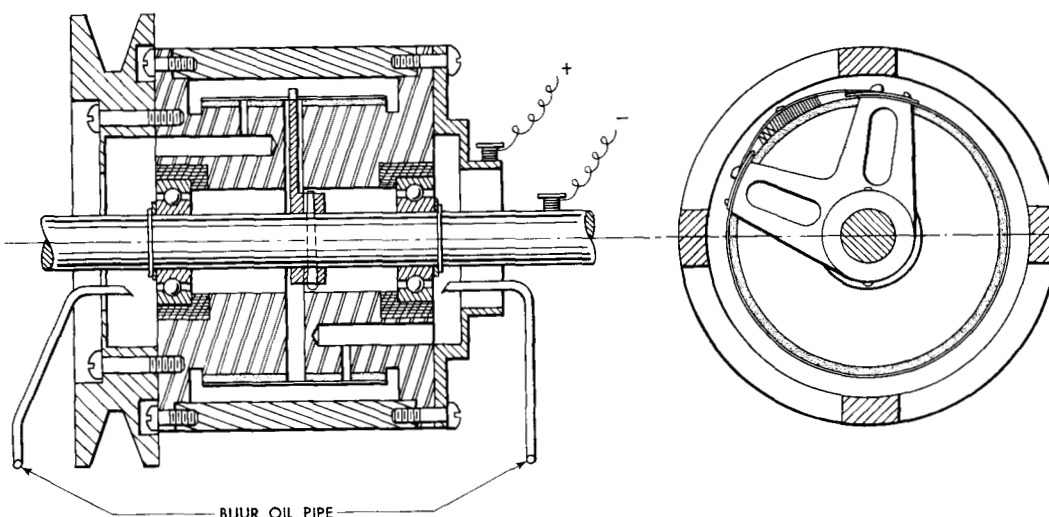


Figure 9

Sectional views of the high-speed clutch. Note that the shaft and ball bearings are insulated from the clutch wheels.

tion. This is equivalent to operating two or more clutches in parallel on one shaft.

The basic components of an electrostatic clutch are the clutch wheel and the band. One or the other must be the driven member. The band, which is the lighter of the two, obviously should be the driven member. In order to drive a shaft, the band must be attached to the shaft. The sectional drawing of Fig. 9 shows how this is accomplished. The photograph of Fig. 10 shows another view. Here the three bands used in the 3-clutch assembly are shown. Incidentally, this shaft and band assembly represents the total inertia of the triple clutch unit, which is calculated to be 0.0004 in-lb/sec².

The band is held to the arms by a spring clip which dovetails into place. This clip carries a polyurethane sponge plastic wiper, cemented in place. A coil spring from one end of the band to the center of the wiper clip holds the band taut. A spring may be placed on either or both ends of the band, depending on the direction of rotation and whether or not it is used for the brake for stopping the shaft from either direction.

The photograph of Fig. 11 shows the two clutch wheels, drive pulley and cage for joining them together. The band, spring clip and wiper, and spring, are also shown in the foreground.

A band wrap angle of 270° is used. With two clutch wheels, each the size of the sample test models described earlier, double the torque shown on the curve of Fig. 6 is obtained plus the additional torque resulting from the larger wrap angle. From 80 to 100 in-lbs is possible.

An outstanding advantage of this design is the good heat conduction from the clutch wheels to the outer

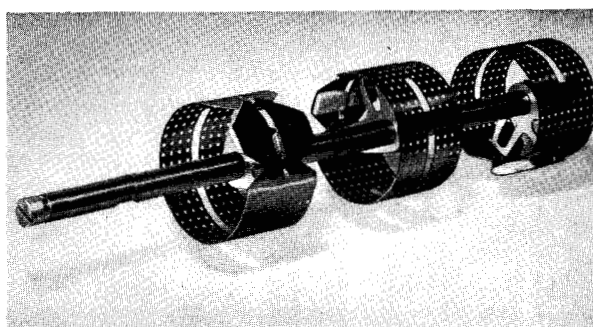


Figure 10

The shaft and clutch band sub-assembly.

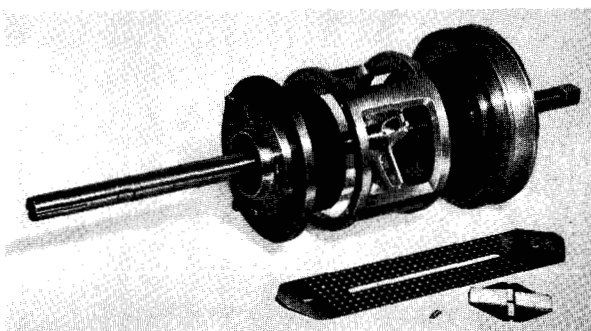


Figure 11

View of one of the clutches disassembled, showing the drive pulley, two clutch wheels and cage for joining them together. The clutch band, spring clip and wiper, and spring are shown in the foreground.

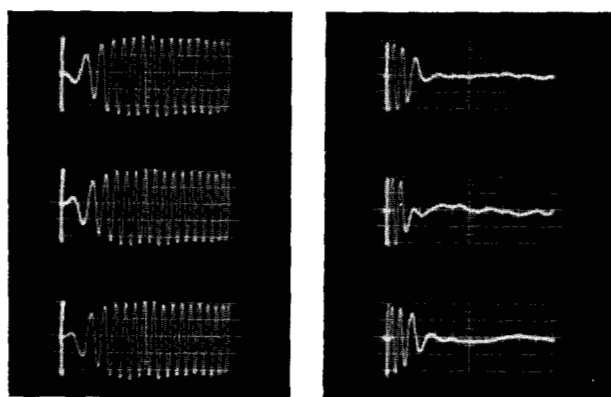


Figure 12
Oscilloscope traces of the acceleration and deceleration of the clutch shaft.

frame. The clutches run cool under high-speed and high-work-rate conditions.

A Bijur oil pump is used to pump about one drop of oil per clutch wheel per hour inside the clutch wheel, as indicated in the drawing of Fig. 9. The oil pipes can also be seen on the assembly photograph, Fig. 8. Centrifugal force and gravity in the brake clutch cause the oil to migrate to the clutch surface through holes in the periphery. Oiling is not critical, as excess oil is thrown off by centrifugal force.

The clutch has been operated at speeds up to 2500 rpm, and the shaft changed from forward to reverse without using the brake. Under these conditions the slip speed is equivalent to a speed of 5000 rpm.

Accelerating and decelerating tests were made by mounting a 69-tooth gear on the shaft and recording the impulses generated by the teeth passing the pole tips of a telephone receiver with the diaphragm removed. Table 2 gives the test data, and the oscilloscope traces in Fig. 12 show the results obtained. Since the angular gear tooth spacing is known (5.217°), an accelerating curve can be plotted, showing angular rotation vs time. It is interesting to note that the shaft attains full speed (1600 rpm) and can be stopped, within an angular distance of 3 gear teeth, or in a time interval of about 3 milliseconds. The inertia of the gear was almost equal to that of the clutch system.

It seems probable that the electrostatic clutch will find a wide range of applications—from driving a "woofer" in a Hi-Fi sound reproducing system to being used in servo controls of automatic processing systems.

Table 2 Performance Data

Scope calibration	Horizontal: 1 msec/cm Vertical: none
Shaft speed	1600 rpm
Speed indicator	Reluctance pick-up, 69-tooth gear
Angular rotation	5.217° per cycle
Inertia of clutch system	0.0004 in-lb/sec ²
Inertia of load	0.00037 in-lb/sec ²
Clutch voltage	150 volts
Clutch current	30 ma
Lubrication	Kel-F #10 oil

Acknowledgments

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