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Fluid Clutches and Brakes

Fluid clutches and brakes may be divided into two groups: those containing a fluid only and those containing a mixture of fluids and solids. Those containing only a fluid rely primarily upon the mass of the fluid and secondarily upon its viscosity to transmit torque. Units containing both a fluid and a solid in a particulate form rely upon the suspended solids to provide the major bond between the components that either transmit or resist torque when under the influence of an external electromagnetic field.

The advantage of fluid clutches and brakes is that there is no lining to wear and replace. This, however, is obtained at the expense of some power loss in the transmission of torque and the distinct need for some sort of fluid cooling for both fluid clutches and fluid brakes. Moreover, occasional fluid seal replacement may also be required.

I. FLUID COUPLINGS AS CLUTCHES

Fluid couplings may serve as soft start clutches and as torque limiting clutches. A typical fluid coupling consists of an input shaft attached to an impeller and an output shaft attached to a runner, with both encased within a closed housing and oriented as shown in Figure 1. An impeller may differ from a runner in the shape of the radial vanes of the sort shown in Figure 2 and may be attached to, and rotate with, the housing that contains both the impeller and the runner. As indicated in Figure 1, the shafts are supported by bearings at the housing and by bearings at the far ends of each shaft that in turn are supported by an enclosure, as shown in Figure 3. Each impeller and

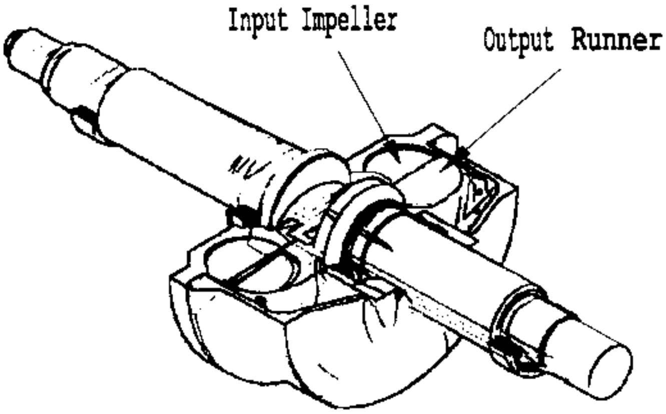

FIGURE 1 Cross section of a semitoroidal impeller and runner and their enclosure, or housing. (Courtesy TRI Transmission & Bearing Corp., Lionville, PA.)

runner consists of half of a torus, as shown in cross section in Figure 1, that is fitted with radial vanes that extend radially inward across the torus, as is evident in Figure 2. The location of the impeller and runner in a fluid coupling is also shown on the right-hand side of Figure 3 for a commercially available coupling that rests upon its oil reservoir, which is also known as a sump.

An internally driven pump located on the right-hand side of the outer housing is to pump fluid from the reservoir into the inner chamber that encloses the impeller and runner to provide a soft start over an interval of approximately five (5) seconds. Fluid from the reservoir must be circulated through a pumping and cooling system provided by the user. Standard cooling systems are generally not provided by the fluid coupling manufacturer because of the extensive variety of service conditions in which these coupling may be used.

Typically the heat to be dissipated is approximately three percent (3%) of the input power. Conversion between the power dissipated, in either watts or horsepower, and heat produced per unit time, as expressed in either large calories or Btu, is given by

$$1 \text{ Btu/sec} = 1.41391 \text{ hp}$$
$$1 \text{ kilocalorie/min} = 69.7333 \text{ W}$$

Transmitted power P is related to the input rpm (revolutions per minute) n according to the relation

$$P = P_0(n/n_0)^{\alpha} \tag{1-1}$$

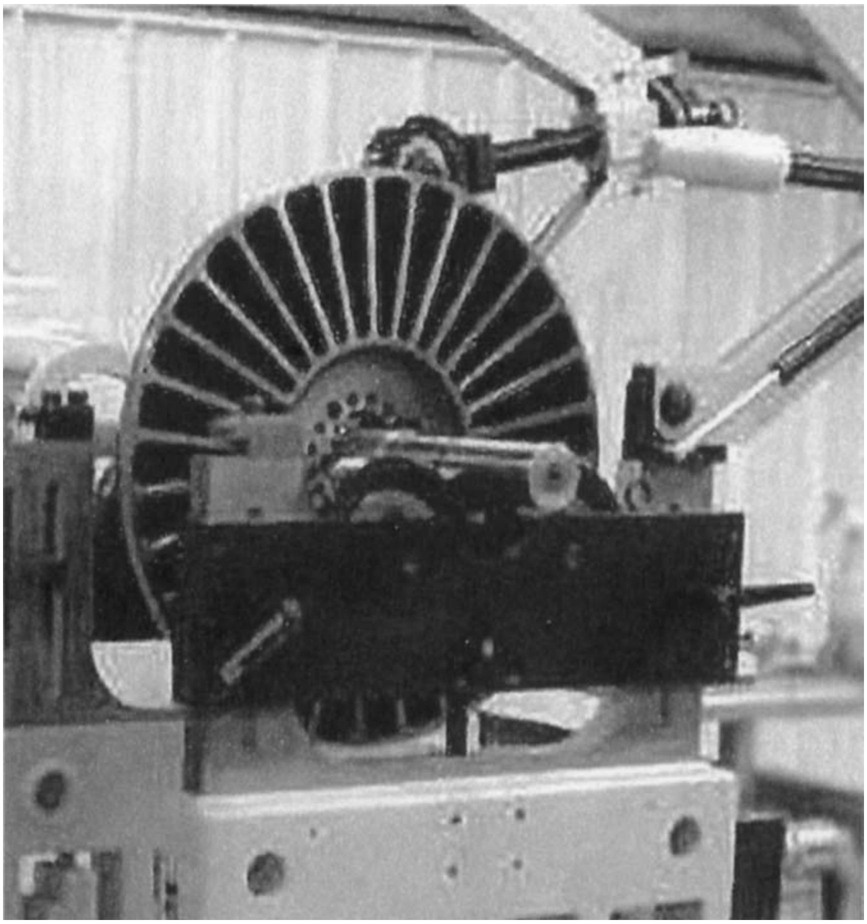

FIGURE 2 Runner and shaft in a fixture used for dynamic balancing. Not all of the balancing equipment is shown. (Courtesy TRI Transmission & Bearing Corp., Lionville, PA.)

in which P_0 is a reference power and n_0 is a reference rpm. Both of them, along with exponent α, are dependent upon the fluid drive involved. Relation (1.1) may be displayed on log-log paper, as in Figure 4, for ease of selecting an appropriate fluid coupling without the use of pocket calculator or a computer to evaluate equation (1-1).

Use of Figure 4 is straightforward. For example, to select a coupling to be driven by an motor turning at 1160 rpm that is to transmit 150 hp, merely enter the graph at 1160 rpm and read up to 150 hp. As a guide to reading the

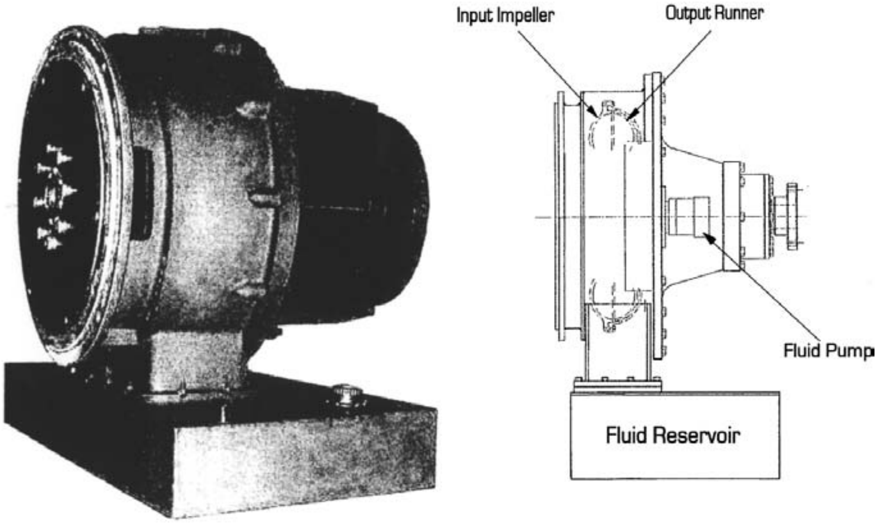

FIGURE 3 Fluid coupling designed for a sheave to be bolted to the face plate on the left. Dextron ATF, automatic transmission fluid, is the recommended fluid. (Courtesy TRI Transmission & Bearing Corp., Lionville, PA.)

logarithmic scale for power, notice that only the unlabeled 200-hp grid line lies between the labeled 100-hp and 250-hp grid lines. Hence, the point whose coordinates are 1160 rpm and 150 hp lies within the region of the model 230 coupling.

These and similar fluid couplings are suitable for use with crushers and chippers, with conveyors and similar materials handling equipment, as well as with portable equipment. They may also be used in series with marine drives to offer propeller protection.

Not all fluid couplings control their torque limits by adjusting the amount of fluid in the impeller chamber. One coupling manufacture produces a small coupling, shown in Figure 5, that is filled with fluid at all times; no pump or reservoir is needed. The housings rotate with the input shafts in both clutch and brake applications, so in both uses the attached cooling fins rotate to dissipate the heat generated by fluid losses.

Average heat loss drops from 240% for 0.125-hp continuous duty at 600 rpm to 30% for 5.0-hp continuous duty at 3600 rpm. Simplicity gained by pump and reservoir omission has been exchanged for these losses.

Typical applications include exercise machines, amusement rides, baking ovens, valve operations, crane trolleys, reversing carriages, and winding and unwinding equipment.

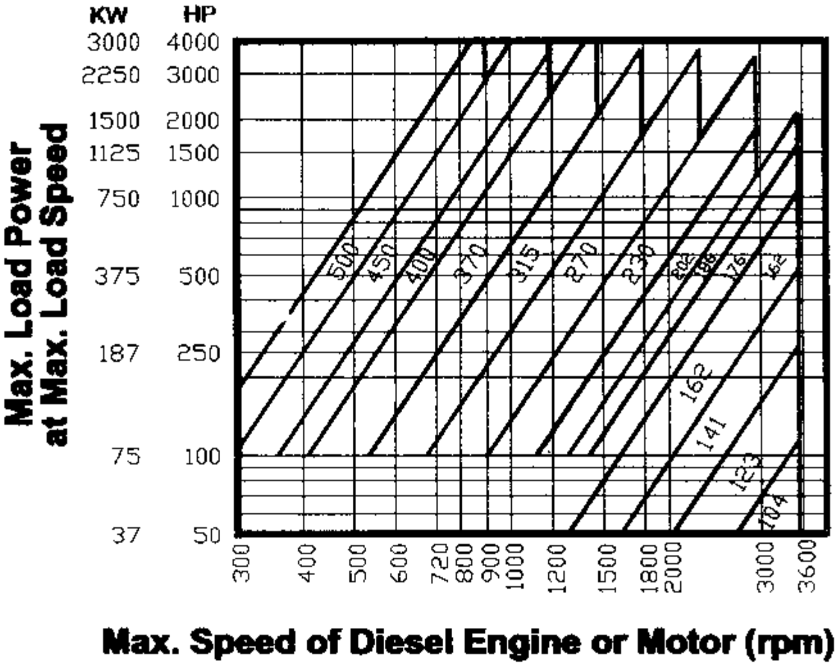

Figure 4 Output power as a function of input revolutions per minute. (Courtesy TRI Transmission & Bearing Corp., Lionville, PA.)

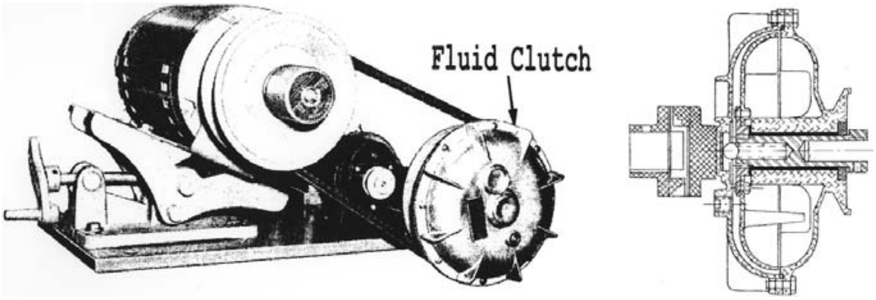

Figure 5 Photograph of a fluid clutch with input from an electric motor and a belt drive using the sheave that is a part of the right-hand side of the housing, shown in cross section. (Courtesy Fluid Drive Engineering Co., Inc., Burlingame, CA.)

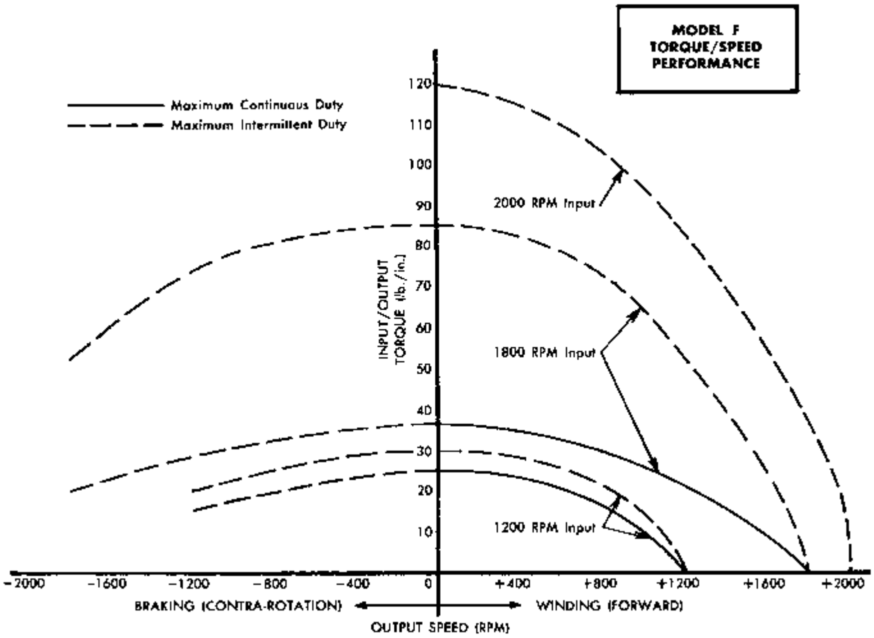

FIGURE 6 Clutch/brake torque/speed curve for the unit shown in Figure 5. (Courtesy Fluid Drive Engineering Co., Inc., Burlingame, CA.)

II. FLUID BRAKES: RETARDERS

Fluid retarders may be thought of as fluid couplings with the runner held stationary, which is, therefore, known as the stator. Figures 7(a) and (b) show opposites sides of a retarder that is equipped with a heat exchanger, an oil reservoir, or sump, and a remotely controlled valve that regulates the flow of oil from the sump into the chamber that encloses the impeller, or rotor, and the stator. The entire unit may be mounted in series with the primary shaft, as shown in Figure 7(d), for example, or it may be mounted on secondary shaft that maintains a given speed ratio relative to the primary shaft.

Removal of the bolts shown in Figure 7(b) and setting that section to the side reveals the internal construction, as shown in Figure 7(c). The rotor that rotates with the input shaft is shown on the right-hand side in Figure 7(c) and the stator is shown on the left-hand side of that figure. Both are mounted in the housing above its portion of the sump. The elbow on the lower left side of the housing section, Figure 7(c), that holds the stator carries external coolant from the heat exchanger that extends from the lower part of the housing, as shown in Figure 7(a). The flow control valve assembly also is shown at the top of the retarder in Figure 7(a).

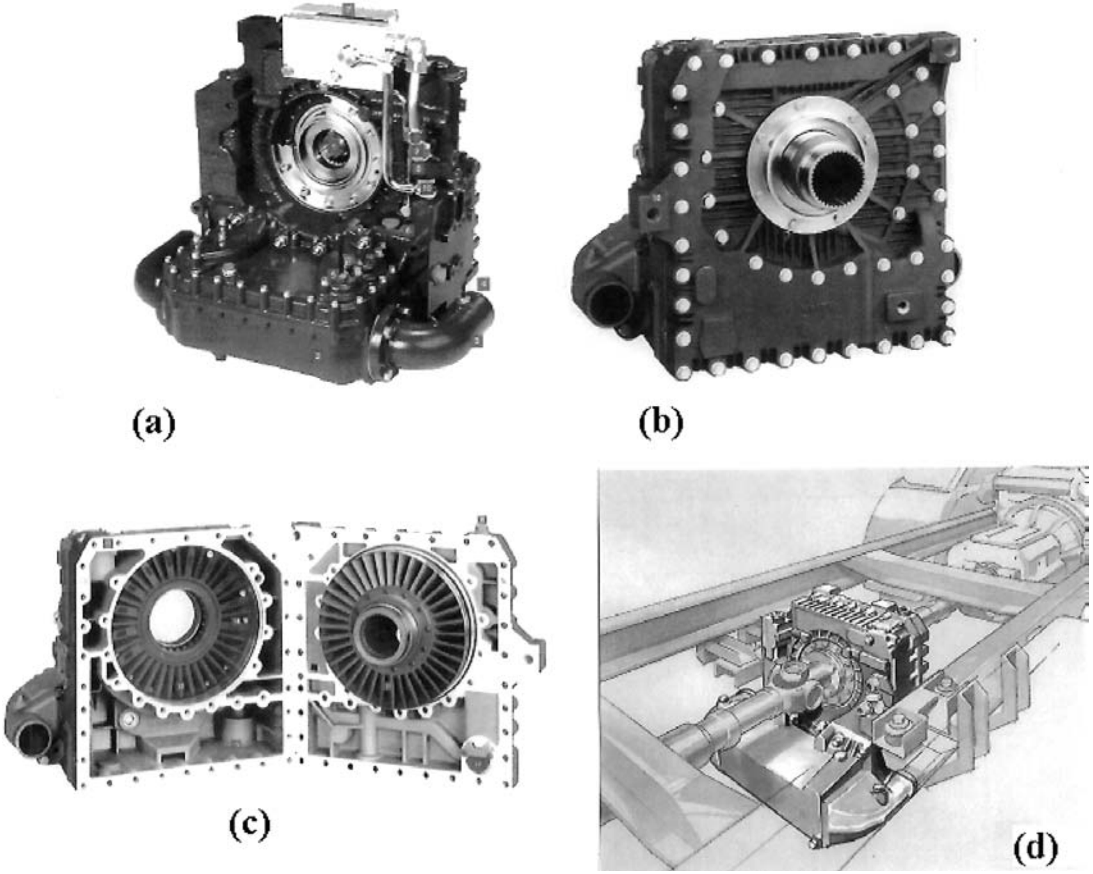

Figure 7 (a) and (b): External views of a retarder. (c) Internal construction. (d) Retarder mounted in series with the shaft upon which it acts. (Courtesy Voith Transmissions, Inc., Sacramento, CA.)

No fluid is in the rotor/stator chamber when the retarder is not in use. Activating the retarder causes fluid to be forced from the sump into the rotor/stator chamber using air from the vehicle's air compressor as regulated by the valve assembly that in turn is controlled electrically by the driver in selecting the amount of braking desired. As in the case of a fluid coupling, the torque capacity of the retarder is determined by the amount of fluid in the chamber that encloses the rotor and the stator.

Retarder performance curves shown in Figure 8, display the retarding moment as a function of the rotor speed and the amount of fluid in the rotor/stator chamber. Curves 1 through 5 that arise from the origin in Figure 8 and ascend with increasing rotational speed ω are plots of the work done on the retarder as kinetic energy is imparted to the fluid by the rotor as given by

$$W = \mathrm{KE} = \frac{I\omega^2}{2} \tag{2-1}$$

in which I denotes the moment of inertia of the fluid that is set into motion by the rotor and ω denotes its rotational speed in radians/second. Curves 6, 7,

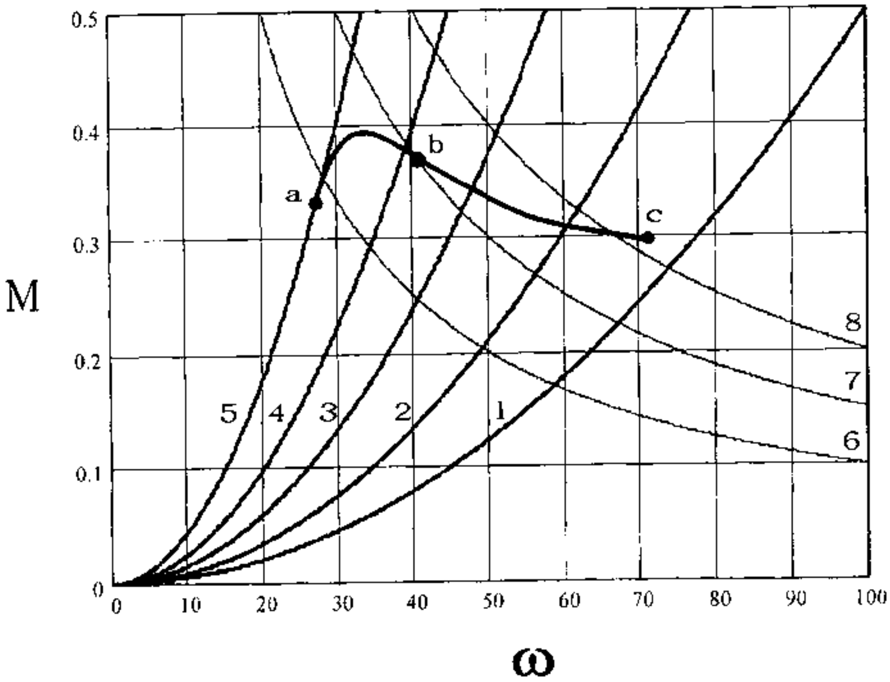

FIGURE 8 Retarding moment M as a function of rotor angular velocity ω.

and 8 that descend from the top of the figure toward the right hand side with increasing ω represent the moment M that is associated with each of the curves of constant power P according to the relation

$$M = \frac{P}{\omega}. \tag{2-2}$$

Both torque, or moment, and kinetic energy may be plotted on the same graph, of course, because they have the same units; namely, ml^2t^{-2}, in terms of the mechanical units mass m, length l, time t.

When the rotor/stator chamber is partially filled the retarding moment increases with rotor speed along a curve similar to curve 1 in Figure 8. Increasing the amount of fluid in the rotor/stator chamber causes the retarding moment to grow more rapidly with rotor speed ω, as represented by curves 2, 3, and 4 for intermediate fluid volumes. Whenever the chamber is filled the torque-speed curve may be represented by curve 5 in Figure 8.

Point a is reached on curve 1 when the rotor, which also acts a pump, forces more oil out through the stator than the air pressure on the sump can force into the rotor/stator chamber; i.e., the rotor induced pressure exceeds the air pressure in the sump that forces fluid into the chamber.

That portion of the curve that includes the maximum between a and b is determined by the design, position, and dimensions of the inlet and outlet throttles of the system.

The latter portion of the performance curve between points b and c is determined by the number and diameters of the outlet ports in the stator in combination with the flow resistance in the piping circuit to, from, and within the heat exchanger that transfers heat to the coolant that circulates through vehicle's radiator*.

Moment M is related to the resisting torque, T_r, that the retarder applies to the primary shaft according to

$$T_r = (\omega/\omega_r)M = (n/n_r)M, \tag{2-3}$$

where n represents the rotational speed of the retarder's rotor in revolution/minute and where ω_r and n_r represent the rotational speed of the primary shaft in radians/second and in revolutions/minute respectively. Clearly $n/n_s = 1$ when the retarder acts on the primary shaft directly, as in Figure 7(d).

Depending upon the model, retarders as described here may provide either a torque up to 4000 Nm (2950.4 ft-lb) at rotor speeds up to 2800 rpm or a torque up to 3200 Nm (2360.2 ft-lb) at rotor speeds up to 5000 rpm. Other

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*This explanation of retarder operation was provided by Rainer Kläring of Voith Turbo GmbH & Co. KG. Any errors in the explanation are due entirely to the author.

combinations of torque and speed characteristics are also available, as well as a retarder that uses water as its working fluid.

Energy, E, to be dissipated by the retarder in slowing a vehicle may be estimated from the work done on the vehicle and the change in kinetic and potential energy; namely,

$$E = \frac{1}{2}m(v_1^2 - v_2^2) + mg(h_1 - h_2) + W_o \tag{2-4}$$

in which m represents the mass of the vehicle plus its load, v_1 and v_2 represent the initial and final velocities during the time that the retarder is engaged, g denotes the acceleration of gravity, h_1 and h_1 represent the initial and final elevation changes during the time that the retarder was engaged, and W_o denotes the work done on the vehicle while the retarder was active.

III. MAGNETORHEOLOGICAL SUSPENSION CLUTCH AND BRAKE

Magnetorheological suspensions have been referred to as magnetorheological fluids even though the fluid itself is not magnetorheological. It is the suspension of magnetically susceptible particles, such as carbonyl iron, in the fluid that causes the mixture to become a magnetorheological suspension, or a magnetorheological fluid. The first magnetorheological suspension was demonstrated by Rabinow and Winslow in 1948 and termed a *magnetic fluid clutch*, made from a suspension of carbonyl iron* in silicone oil and kerosene [1]. Application of a magnetic field causes the iron particles to converge along the lines of flux, which in turn increases the flux density. In the case of a brake, the braking action is due to increased magnetic attraction between stator and rotor. The same principle applies to a clutch, except that the attraction is between the input rotor and the output rotor. The concentration of particles along the flux lines also may retard fluid motion to some extent, and thereby aid somewhat in both the braking and clutching actions.

Settling of the suspended material is apparently not a problem because the suspended material is remixed by the motion of the clutch or brake. However, having a fluid that displays a low viscosity when the clutch or brake is disengaged is important in order to reduce operating losses when they are inactive.

Subsequent development of the magnetorheological fluids seems to have been concentrated in the area of finding or developing fluids whose

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**The Handbook of Chemistry and Physics* (CDC Press) lists three forms of carbonyl iron. $FE(CO)_4$, $FE(CO)_5$, and $FE(CO)_9$.

viscosity does not change due to high shear stress, and perhaps compressive stress, over time. (Some earlier fluids were reported to have reached the vis cosity of shoe polish due to stress over time.) This thickening was thought to be due to spailing of a thin, brittle surface layer on the carbonyl iron. Presently available magnetorheological fluids that have been developed to ameliorate this problem are said to be able to sustain 10^7 J/cm^3 before becoming unusable [2].

A small, commercially available, brake that employs a magnetorheological suspension is shown in Figure 9. Its maximum torque is approximately 5.6 N-m (about 50 in.-lb), and, because it contains a fluid, it provides a small torsional load that is less than approximately 0.3 N-m (2.7 in.-lb) when the brake is not engaged.

The requisite magnetic field is supplied by an electric current of 1.0 A or less in a circular coil that induces the magnetic field shown in the schematic cross section of the brake and coil in Figure 10. This excitation produces a linear relation between the braking torque and the electric exciting current within the range from 0 to 1.0 A, as shown in Figure 11.

The operating temperature range of the brake is from about −30°C to 70°C, corresponding to −20°F to 160°F. Notice that a residual torque capability of 0.3 N-m is available at zero curent, probably due to fluid viscosity as augmented by either the suspended or precipitated particles.

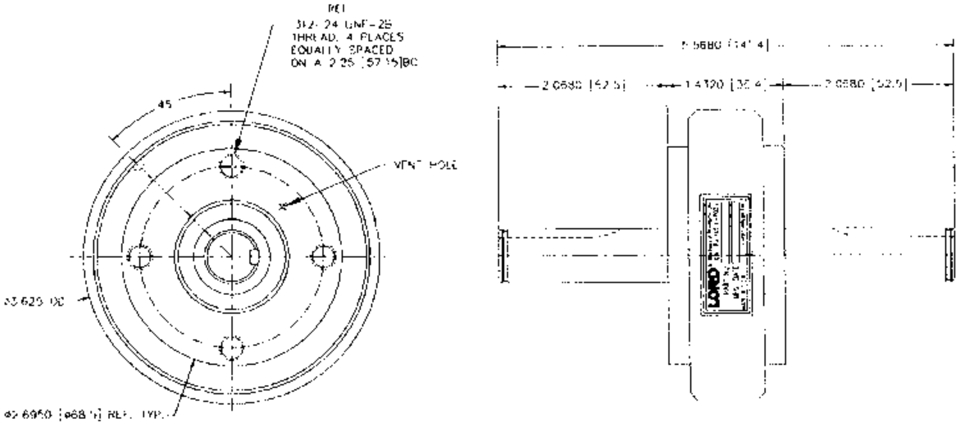

FIGURE 9 Magnetorheological brake. Omitted: power cord attached to housing. (© 2002 Lord Corporation. All rights reserved. Lord Corp., Materials Division, Cary, NC.)

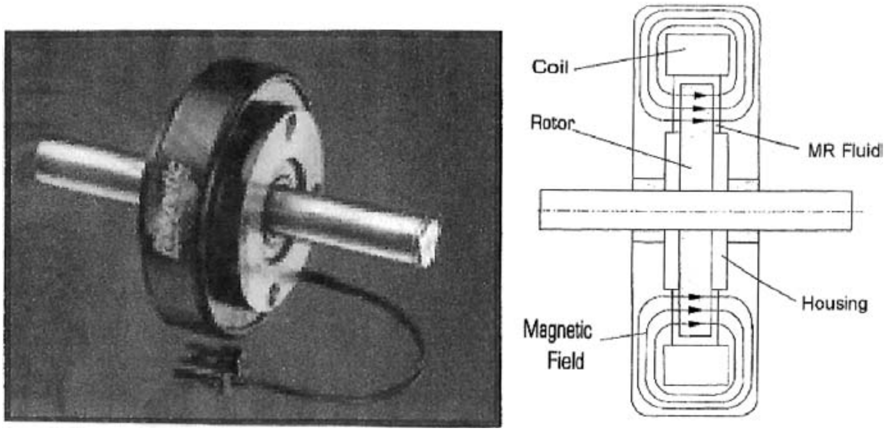

FIGURE 10 Photograph and schematic cross section of a magnetorheological brake. (© 2003 Lord Corporation. All rights reserved.)

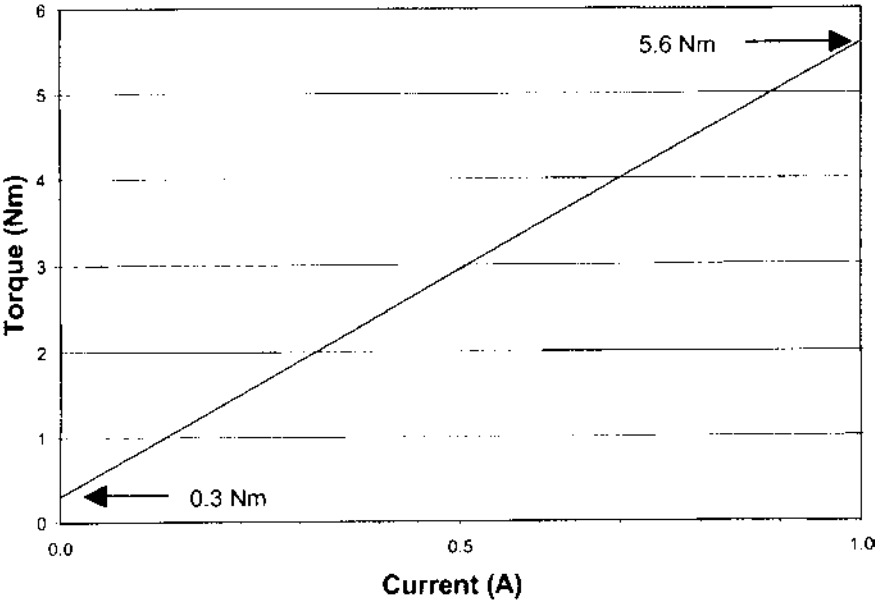

FIGURE 11 Typical torque in newton-meters vs. electric current in amps. It should not be used for specifications. (© 2002 Lord Corporation. All rights reserved. Lord Corp., Materials Division, Cary, NC.)

IV. NOTATION

g	acceleration of gravity (lt^{-2})
h	height (l)
KE	kinetic energy (ml^2t^{-2})
m	mass (m)
n, n_0	rpm (t^{-1})
P, P_0	power (ml^2t^{-3})
PE	potential energy (ml^2t^{-2})
t	time (t)
v_1, v_2	velocity (lt^{-1})

V. FORMULA COLLECTION

Power transmitted:

$$P = P_0\left(\frac{n}{n_0}\right)^{\alpha}$$

Energy dissipated:

$$E = \mathrm{KE} + W_0 + \mathrm{PE} = \frac{1}{2}m\left(v_t^2 - v_2^2\right) + mg\,\Delta h + W_0$$

Power dissipated:

$$P = \frac{\mathrm{KE}}{t}$$

REFERENCES

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2. Carlson, J. D. (July 9–13, 2001). What Makes a Good MR Fluid, presentation at 8th International Conference on Electrorheological (ER) Fluids and Magnetorheological (MR) Suspensions, Nice, France.