Principles of Active Vibration Control: Electrorheological fluids

Introduction:

Electrorheological (ER) fluids are fluids which exhibit fast and reversible changes in their rheological properties under the influence of external electrical fields. Electro-rheological (ER) fluids are a class of smart materials exhibiting significant reversible changes in their rheological and hence mechanical properties under the influence of an applied electric field. Efforts are in progress to embed ER fluids in various structural elements to mitigate vibration problems. ER fluids commonly are composed of polarisable solid particles dispersed in non conducting oil. Upon the imposition of external electric field, the particles are polarized and form a chainlike structure along the direction of the field. The change in apparent viscosity is dependent on the applied electric field, i.e. the potential divided by the distance between the plates. The change is not a simple change in viscosity, hence these fluids are now known as ER fluids, rather than by the older term Electro Viscous fluids. The effect is better described as an electric field dependent shear yield stress. When activated an ER fluid behaves as a Bingham plastic (a type of viscoelastic material), with a yield point which is determined by the electric field strength. After the yield point is reached, the fluid shears as a fluid, i.e. the incremental shear stress is proportional to the rate of shear (in a Newtonian fluid there is no yield point and stress is directly proportional to shear). Hence, the resistance to motion of the fluid can be controlled by adjusting the applied electric field.

An ERF damper or electrorheological fluid damper, is a type of quick-response active non-linear damper used in high-sensitivity vibration control. Enhanced actuation and sensing capabilities of the smart materials have led to effective means of handling unwanted vibrations in automobile and aerospace industries. Varied physical phenomena such as the piezoelectric effect, magnetostriction, and electrostriction underpin the functioning of these materials. The complexity of these phenomena leads us to the question of characterizing their behaviour in terms of specific parameters of relevance in a given application. In vibration control applications, one is mostly concerned with the inertial and viscoelastic properties quantified in terms of the mass, stiffness and damping, respectively. A brief account of the physics of electro-rheological (ER) fluids will aid the understanding of their vibration properties.

An electro-active material is a suspension where a semi-conductive material (particulate or liquid) is dispersed in a dielectric liquid medium. The rheological properties change in reversible form by several orders of magnitude under external electric fields. Since, the rheological properties can be easily controlled within a wide range, many scientific and technological applications may be developed. The potential applications are as:

- Clutch, brake and damping systems, actuators, fuel injections systems
- Joints and hands of robotic arms
- photonic crystals.
- Microswitches.
- Mechanical-electronic interfaces

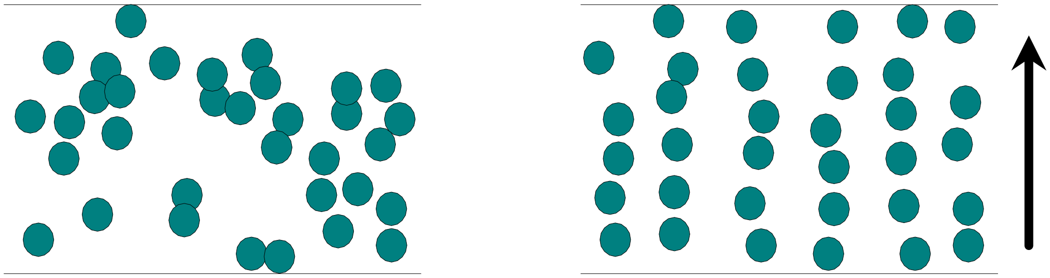
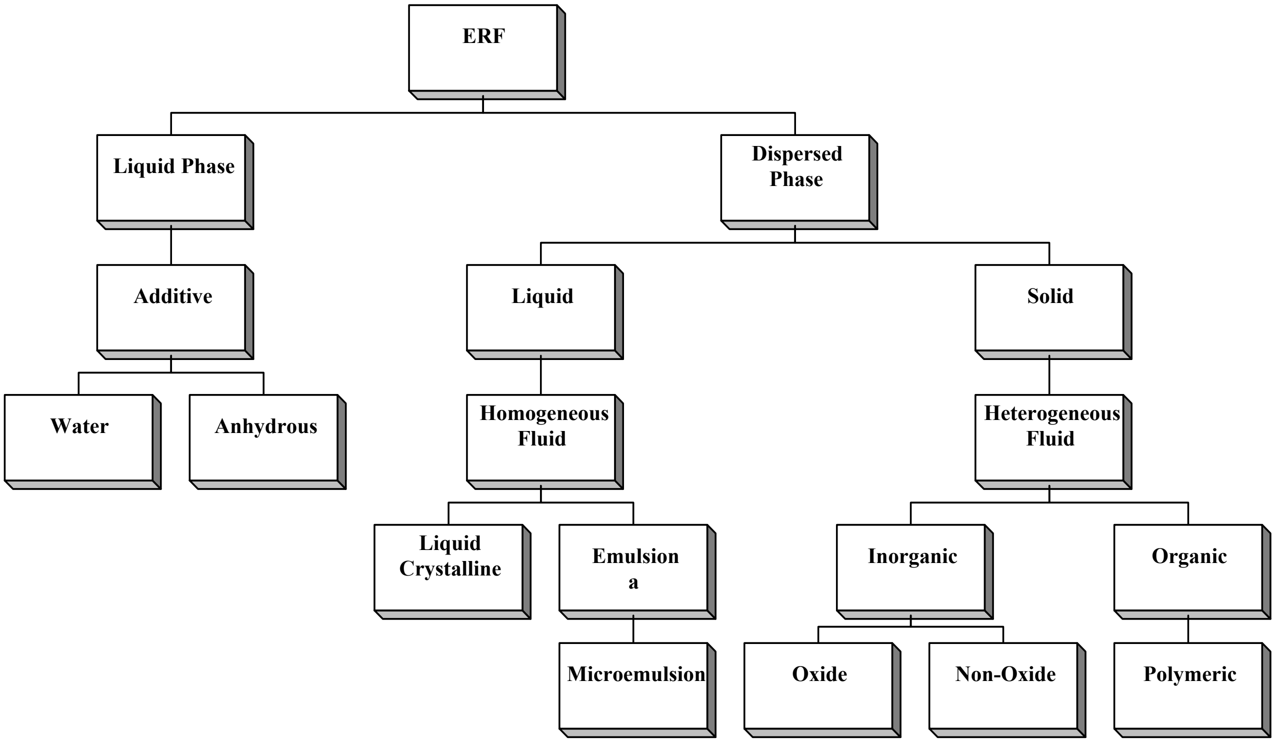


Fig. 8.22 (a) Before an external electric field (b) Structure of an ER materials after electric field

The interaction between nanoparticles and electric field is explored from the electrorheological (ER) point of view, using variational formulations for both the static and dynamic characteristics. Electro-rheological (ER) fluids are suspensions of extremely fine non-conducting particles (up to 50 micrometres diameter) in an electrically insulating fluid. Yield strengths of a typical ER fluid are of the order of 10 and 5 kPa under static and dynamic loading conditions, respectively, for electric fields (both a.c. and d.c.) of the order of a few kVs. Moreover, the change in apparent viscosity is reversible subject to the presence or absence of electric field. Consider a dispersion of particles in a fluid medium in which the particles are nano-sized or otherwise.

Classifications:

The ER fluid can be classified based on the existing phases as;



The particles and the fluid are electrically non-conducting or slightly conducting. The latter criterion will be better defined later. When an electric field $\vec{E}$ is applied to such a colloidal dispersion, the particles will be polarized electrically. Let ε_s denote the complex dielectric constant of the solid particles and ε_ℓ that of the liquid; then for spherically shaped particles, the induced dipole moment may be expressed as

$$\vec{p} = \frac{\varepsilon_s - \varepsilon_\ell}{\varepsilon_s + 2\varepsilon_\ell} a^3 \vec{E} = \beta a^3 \vec{E} \qquad (8.8)$$

where a is the radius of the particles. Here $\vec{E}$ should be understood as the field at the location of the particle. The resulting (induced) dipole-dipole interaction between the particles means that the random dispersion is not the lowest energy state of the system, and particles would tend to aggregate and form chains/columns along the applied field direction. The formation of chains/columns is the reason why such colloids exhibit an increased viscosity or even solid-like behavior when sheared in a direction perpendicular to the electric field. Such rheological variation is denoted the *electrorheological effect*, or ER effect. And the colloids which exhibit significant ER effect are denoted electrorheological fluids, or ER fluids. The formation of chains/columns is governed by the competition between electrical energy and entropy of the particles, manifest in the value of the dimensionless parameter $\gamma = \vec{p} \cdot \vec{E} / k_B T$, where k_B is the Boltzmann constant and T the temperature. For room temperature and $\vec{p}$ given by above Eq., $\gamma = 1$ defines the boundary between the entropy-dominated regime and the ER regime. The resulting relation between the electric field and the size of the particle, given by $(\beta a^3)^{1/3}$, is shown in Fig. 8.23.

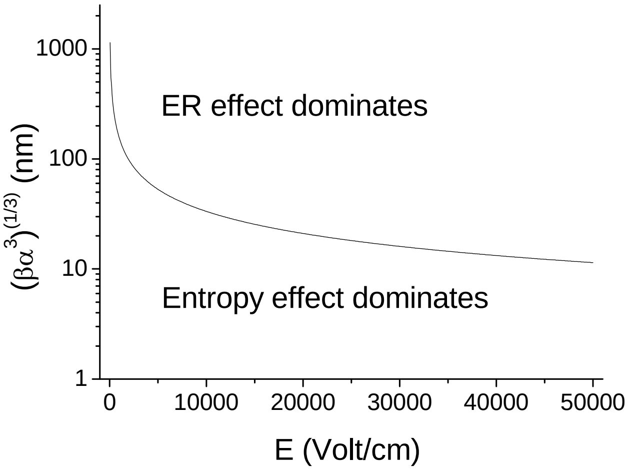


Figure 8.23: A plot of the curve $\gamma = \vec{p} \cdot \vec{E} / k_B T = 1$, above which the ER effect dominates and below which the entropy effect dominates.

Typical response times of ER fluids are of the order of a few milliseconds. The apparent viscosity of these fluids changes reversibly by an order of up to 100,000 in response to an electric field. For example, a typical ER fluid can go from the consistency of a liquid to that of a gel, and back, with response times on the order of milliseconds. ER fluids are fluids with controllable rheological properties. When an electric field is applied to these fluids, they respond by forming chain-like structures which results in enhancement of apparent viscosity by as high as five orders of magnitude. This results in a significant increase in the yield strength of the material.

ER fluid composition and theory

ER fluids are a type of smart fluid. A simple ER fluid can be made by mixing cornflour in a light vegetable oil or (better) Silicone oil. There are two main theories to explain the effect: the interfacial tension or 'water bridge' theory, and the electrostatic theory. The water bridge theory assumes a three phase system, the particles contain the third phase which is another liquid (e.g. water) immiscible with the main phase liquid (e.g. oil). With no applied electric field the third phase is strongly attracted to and held within the particles. This means the ER fluid is a suspension of particles, which behaves as a liquid. When an electric field is applied the third phase is driven to one side of the particles by electro osmosis and binds adjacent particles together to form chains. This chain structure means the ER fluid has become a solid. The electrostatic theory assumes just a two phase system, with dielectric particles forming chains aligned with an electric field in an analogous way to how magneto-rheological fluid (MR) fluids work. An ER fluid has been constructed with the solid phase made from a conductor coated in an insulator. This ER fluid clearly cannot work by the water bridge model. However, although demonstrating that some ER fluids work by the electrostatic effect, it does not prove that all ER fluids do so. The advantage of having an ER fluid which operates on the electrostatic effect is the elimination of leakage current, i.e. potentially there is no DC current. Of course, since ER devices behave electrically as capacitors, and the main advantage of the ER effect is the speed of response, an AC current is to be expected.

The particles are electrically active. They can be ferroelectric or, as mentioned above, made from a conducting material coated with an insulator, or electro-osmotically active particles. In the case of ferroelectric or conducting material, the particles would have a high dielectric constant. There may be some confusion here as to the dielectric constant of a conductor, but "if a material with a high dielectric constant is placed in an electric field, the magnitude of that field will be measurably reduced within the volume of the dielectric" (see main page: Dielectric constant), and since the electric field is zero in an ideal conductor, then in this context the dielectric constant of a conductor is infinite.

Another factor that influences the ER effect is the geometry of the electrodes. The introduction of parallel grooved electrodes showed slight increase in the ER effect but perpendicular grooved electrodes doubled the ER effect. A much larger increase in ER effect can be obtained by coating the electrodes with electrically polarisable materials. This turns the usual disadvantage of dielectrophoresis into a useful effect. It also has the effect of reducing leakage currents in the ER fluid.

The giant electrorheological (GER) fluid was discovered in 2003, and is able to sustain higher yield strengths than many other ER fluids. The GER fluid consists of Urea coated nanoparticles of Barium Titanium Oxalate suspended in silicone oil. The high yield strength is due to the high dielectric constant of the particles, the small size of the particles and the Urea coating. Another advantage of the GER is that the relationship between the electrical field strength and the yield strength is linear after the electric field reaches 1 kV/mm. The GER is a high yield strength, but low electrical field strength and low current density fluid compared to many other ER fluids. The procedure for preparation of the suspension is given in. The major concern is the use of oxalic acid for the preparation of the particles as it is a strong organic acid.

APPLICATIONS

The normal application of ER fluids is in fast acting hydraulic valves and clutches, with the separation between plates being in the order of 1 mm and the applied potential being in the order of 1 kV. In simple terms, when the electric field is applied, an ER hydraulic valve is shut or the plates of an ER clutch are locked together, when the electric field is removed the ER hydraulic valve is open or the clutch plates are disengaged.

Other common applications are in ER brakes (think of a brake as a clutch with one side fixed) and shock absorbers (which can be thought of as closed hydraulic systems where the shock is used to try and pump fluid through a valve).

There are many novel uses for these fluids, including use in the US army's planned future force warrior project. They plan to create bulletproof vests using an ER fluid because the ability to soak the fluid into cloth creates the potential for a very light vest that can change from a normal cloth into a hard covering almost instantaneously. Other potential uses are in accurate abrasive polishing and as haptic controllers and tactile displays.

ER fluid has also been proposed to have potential applications in flexible electronics, with the fluid incorporated in elements such as rollable screens and keypads, in which the viscosity-changing qualities of the fluid allowing the rollable elements to become rigid for use, and flexible to roll and retract for storing when not in use. Motorola filed a patent application for mobile device applications in 2006.

Static mode	**Release mechanisms**
Shear mode	Clutch devices, ER fluids mechanical couples two surfaces by increasing or decreasing its viscosity with the application or removal of an electric field
Damping device	Shock absorber, ER fluids usually operates in either the shear or extensional configuration. Shear configuration is used when the fluid undergoes strain and extensional configuration used for compression stress.
Variable flow controls	Adjusting the viscosity of a fluid as it flows through a porous electrode separating two chambers can control the volume of the flow.

ER fluids exhibit an enhancement in shear stress and the development of a static yield stress. It remains to explain how this effect can be exploited in engineering devices and, in particular, in controlling mechanical vibrations. The device described by Jordan and Shaw (1989) as the 'cornerstone of ER technology', namely the flow control valve. Here the ER fluid is contained between a pair of stationary electrodes and the resistance to flow is controlled by adjusting the applied electric field. The operation of the device can be likened to that of a modulator where the flow of energy between an input and an output is controlled by a further input. The ER valve is shown schematically in the form of a modulator in figure 1. Referring to figure 1, the hydraulic power input (i.e. the product of inlet pressure and flow rate) is applied to inlet port 1. The corresponding power output (i.e. the product of outlet pressure and flow rate) emanates from outlet port 2. Control is applied through port 3 in the form of the applied electric field which influences the fluid's resistance to flow through the physical mechanisms. This model of the ER flow control valve aligns conveniently with the pressure drop versus flow rate characteristics which are used to characterize the experimental behaviour of a typical ER valve [R. Stanway et al. 1996].

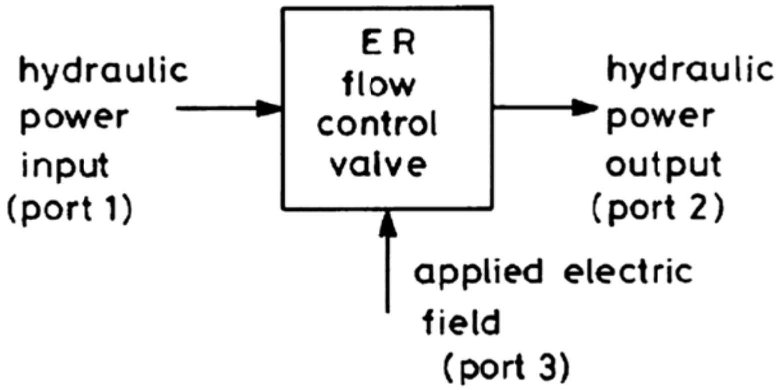


Fig. 8.24 Block diagram of an ER device represented as a modulator: the flow-control valve

The ER valve-controlled vibration damper [R. Stanway et al. 1996]**:**

A typical flow-controlled ER vibration damper is shown in figure 8.25. The ER valve is connected across the hydraulic piston by short connecting pipes whose influence on the performance is assumed to be negligible. The force/velocity characteristics of the piston, under steady flow conditions, The calculation is started by specifying the (steady) piston velocity and piston area. For a given size of valve this enables the volume flow rate, Q, to be computed and hence the mean velocity ($\bar{u}$ = Q/bh). A numerical value for the corresponding Reynolds number, π_2, follows from the definition, equation (2). For a given value of electric field strength the yield stress, τ_b, of the ER fluid is computed and hence equation (3) gives the Hedstrom number, π_3. The numerical values of π_2 and π_3 are then substituted into equation (4) and a root-solving routine is applied to find values of the friction coefficient, π_1. The physically meaningful value of π_1 is used to compute the pressure drop across the valve (and thus across the piston), i.e. $\Delta P_{e0} = \pi_1(2l\rho\bar{u}^2/h)$. The piston force follows by multiplying ΔP_{e0} by the piston area and this can then be plotted against the value of piston velocity which was used to start the calculation. The procedure is repeated for the desired range of values of piston velocity to generate the complete set of force versus velocity characteristics. Full details of the computational procedure, together with illustrative examples, are given by Peel *et al* (1995). The extension of the technique to include the effects of ER fluid compressibility and inertia is described by Peel *et al* (1996).

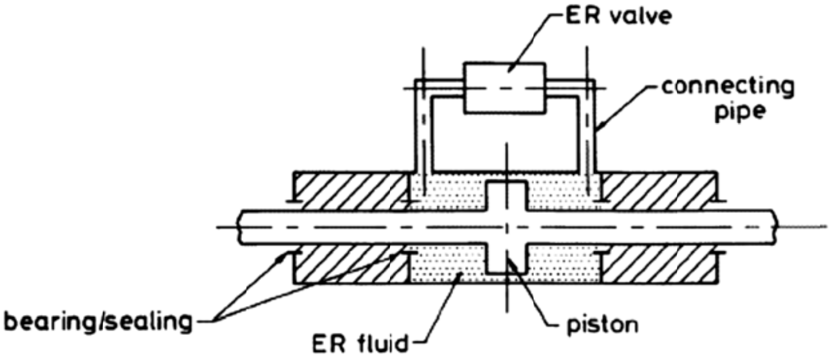
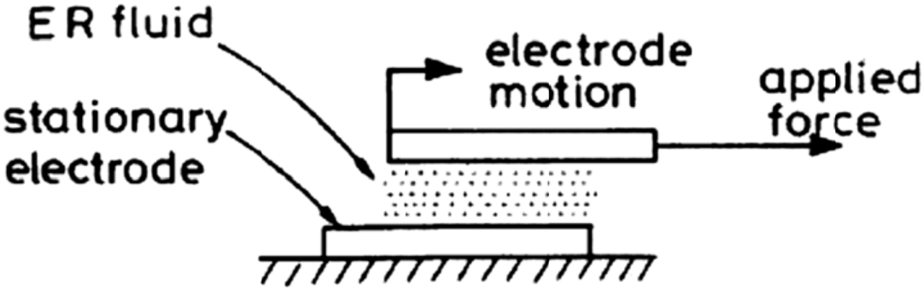


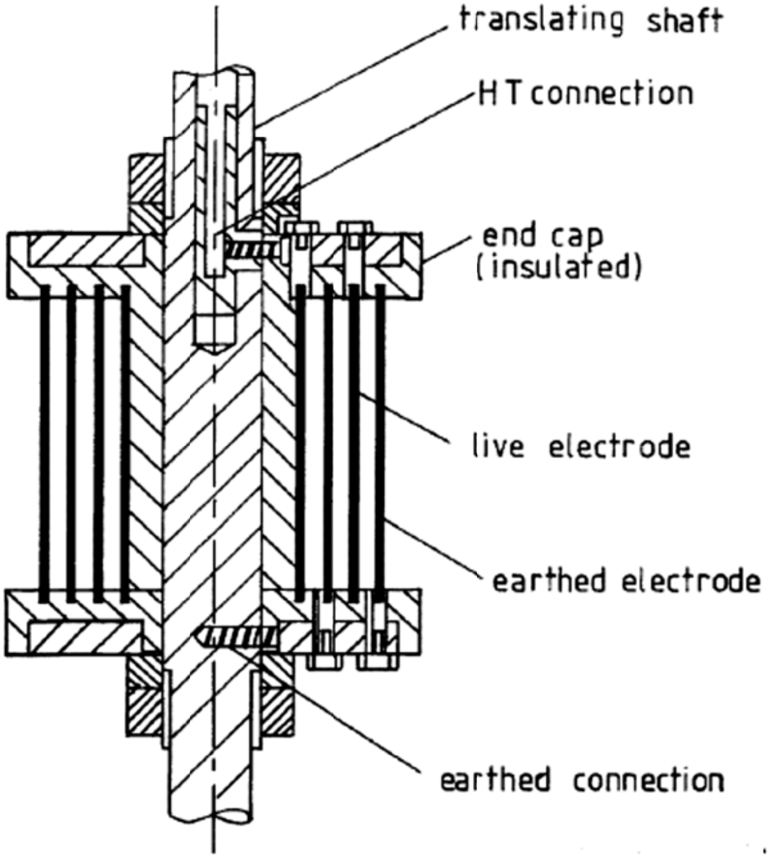
Fig. 8.25 ER valve-controlled vibration damper: simplified physical arrangement.

Vibration damping by direct shear

In the ER valve-controlled damper described previously, the oscillatory motion associated with the vibration was accommodated by a hydraulic piston/cylinder arrangement. The force/velocity profile of the damper was modulated through the ER valve which was constructed with fixed electrodes. An alternative arrangement for providing damping involves the direct shearing of fluids between translating or rotating electrodes. If the electrodes rotate then we have a torsional damper; if the electrodes translate then we have a linear damper. The arrangement of electrodes in a linear configuration is shown in figure 8.26. Figure 8.26 (*a*) shows the principle and figure 8.26 (*b*) shows a typical arrangement of electrodes in a prototype device. It was explained by Coulter *et al* (1993a) that the behaviour of ER fluids being sheared between sliding electrodes can be modeled on the basis of the idealized post-yield behaviour of a Bingham plastic.



(a)



(b)

Fig. 8.26 ER shear mode of operation: (a) principle of electrode arrangement; (b) typical electrode arrangement in a prototype device.

With reference to the Bingham characteristic shown in figure 8.27, the stress, τ_{ER}, developed in the ER fluid is given by

$$\tau_{ER} = \tau_b + \eta\dot{\gamma} \tag{8.9}$$

where τ_b is the Bingham yield stress, η is the plastic viscosity and γ is the shear rate induced by the relative motion of the electrodes.

PROBLEMS AND ADVANTAGES

A major problem is that ER fluids are suspensions, hence in time they tend to settle out, so advanced ER fluids tackle this problem by means such as matching the densities of the solid and liquid components, or by using nanoparticles, which brings

ER fluids into line with the development of magneto-rheological fluids. Another problem is that the breakdown voltage of air is ~ 3 kV/mm, which is near the electric field needed for ER devices to operate.

An advantage is that an ER device can control considerably more mechanical power than the electrical power used to control the effect, i.e. it can act as a power amplifier. But the main advantage is the speed of response, there are few other effects able to control such large amounts of mechanical or hydraulic power so rapidly.

Unfortunately, the increase in apparent viscosity experienced by most Electro-rheological fluids used in shear or flow modes is relatively limited. The ER fluid changes from a Newtonian liquid to a partially crystalline "semi-hard slush". However, an almost complete liquid to solid phase change can be obtained when the electro-rheological fluid additionally experiences compressive stress. This effect has been used to provide electro-rheological Braille displays and very effective clutches.

ER clutch:

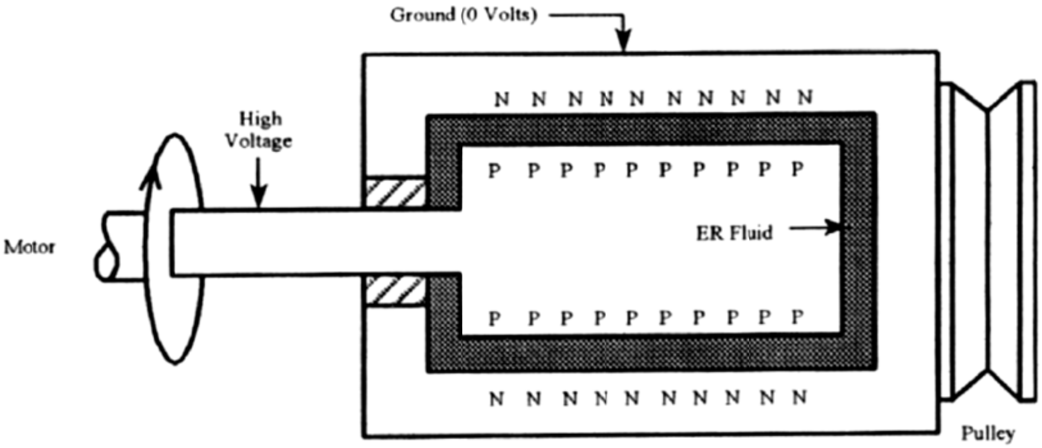


Fig. 8.27 ER clutch

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