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TECHNOLOGICAL APPLICATIONS OF FERROFLUIDS

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Ferrofluids have novel properties and their behaviour in magnetic fields leads to many interesting applications. Although magnetic fluids are already used in some devices they have not yet been exploited to any extent. It is hoped this article may stimulate the reader to think of new uses for this fascinating material

The elements iron, nickel and cobalt are ferromagnetic in the solid state at room temperature. However, the ferromagnetic properties disappear above the Curie temperature (1042 K for iron, 631 K for nickel and 1130 K for cobalt) which is well below the melting point. Magnetite and other ferromagnetic materials show a similar behaviour with strong magnetic properties only in the solid state. A ferromagnetic liquid cannot, therefore, be produced by simply melting a ferromagnetic solid.

Dr John Popplewell is a senior lecturer in physics at the University College of North Wales, Bangor and is also currently involved in a project to provide academic and technical assistance to Yarmouk University, Jordan. His research interests have always been concerned with magnetic materials and in the last ten years he has been successful in developing and promoting magnetic fluids as a new technological material.

The production of a magnetic fluid, commonly called a ferrofluid, presented a challenge which initially began with Gowan Knight's attempts in 1779 to produce a magnetic fluid by suspending iron filings in water. His attempts failed because particle sedimentation occurred in a short time. Current methods of producing ferrofluids are more refined but use a similar principle. The magnetic particles are dispersed in a carrier fluid (water, oil or diester) in such a way that the particles remain dispersed indefinitely in spite of the long range magnetic forces and short range van der Waals forces of attraction. To prevent particle aggregation due to the short range forces the particles are covered with a surfactant, usually a long chain polar molecule, which adheres to the surface of the particle thereby preventing aggregation by entropic repulsion. In the case of the long range magnetic forces the magnetic energy is a minimum for two particles in contact. This energy is given by the expression

$$E_m = -\mu_0 \pi D^3 M_s^2/72 \qquad (1)$$

where M_s is the magnetisation per unit volume and D the particle diameter. When the energy E_m is less than the thermal energy kT the magnetic forces alone cannot cause aggregation. The size of the particles must, therefore, be made small ($D = 4$–20 nm) to satisfy this condition.

The potential energy curve for different particle separations is shown in figure 1 for a particle with $D = 10$ nm, $M_s = 1000$ kA m^{-1} and the surfactant chain length $\delta = 2$ nm. The energy barrier ~25 kT, which prevents aggregation due to the short range forces, reduces for particles of higher magnetisation. Should the total energy become negative or

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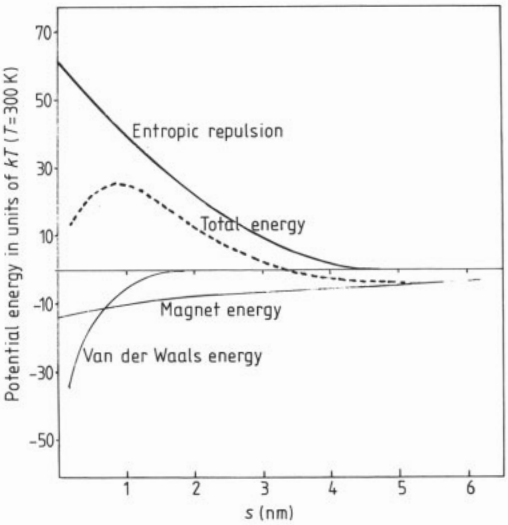


Figure 1 Variation of potential energy for two spherical particles 10 nm diameter, surfactant chain length 2 nm and saturation magnetisation M_s. The dotted line represents the combined potential energy and shows the energy barrier ~25kT which prevents particle aggregation

less than kT stability cannot be achieved.

It is important for the production of ferrofluids for commercial applications that the ferrofluids are stable under gravity and in strong magnetic fields. Any instability is enhanced by aggregation which produces particle clusters of large mass and large magnetic moment.

The effect of magnetic fields on ferrofluids is clearly seen. A stream of magnetic fluid can be deflected by a magnetic field and the surface can be distorted by a uniform field normal to the surface (figure 2).

The strength of a ferrofluid depends on the volume concentration ϕ of magnetic particles which varies between 2 and 10% by volume. However, the maximum particle content is limited because the viscosity increases with particle concentration and this eventually becomes so large that the ferrofluid loses its liquid characteristics. An expression for the viscosity in terms of particle concentration is given by the relationship

$$\eta/\eta_0 = 1/(1-2.5\phi + b\phi^2) \quad (2)$$

where

$$b = (2.5\phi_c - 1)/\phi_c^2 \quad (3)$$

ϕ_c is the critical concentration of solid particles above which the 'fluid' becomes solid; $\phi_c = 0.74$ for hexagonal close packed spheres. η_0 is the carrier viscosity.

The concentration gradient ∇n for particles in a gravitational field is given by

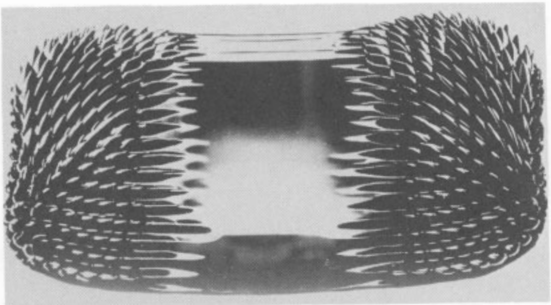
$$\nabla n = \pi D^3(\rho_s - \rho_0)gn/6kT \quad (4)$$

where ρ_0 is the density of the carrier liquid and ρ_s that of the particles, n the number of particles per unit volume and T the temperature. Similar concentration changes takes place in a magnetic field gradient ∇H. The equivalent expression to equation (4) is given in this case by

$$\nabla n = nD^3\pi\mu_0 M_s \nabla H/6\,kT \quad (5)$$

The factor $\nabla n/n$ is important in determining stability. If ∇n is appreciable the viscosity of the ferrofluid increases in the field gradient leading to solidification when $\phi > \phi_c$. A criterion for stability can be derived in terms of a value of ∇n. This is established as a limiting value for a particular ferrofluid application and it depends on what change in particle density can be accepted. Thus D, M_s and ∇H are parameters which may be adjusted to meet the stability criterion. It can readily be appreciated that a ferrofluid may be regarded as stable in conditions of small ∇H but unstable according to the criterion in a larger ∇H. A

Figure 2 Surface instability around the pole pieces of a permanent magnet (*photograph courtesy of Ferrofluidics Corp.*)



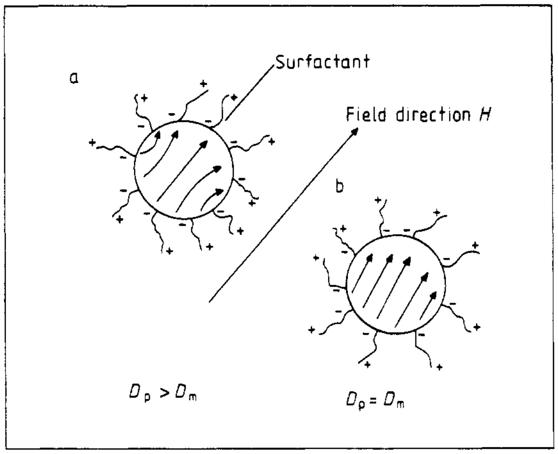


Figure 3 Two different modes of particle magnetisation. **a**, Magnetisation is less than the saturation value and a calculation of size assuming all dipoles aligned will lead to an underestimate of the physical size. i.e. $D_m < D_p$. **b**, With complete alignment the physical size and that determined from magnetic measurements are the same, i.e. $D_m = D_p$

ferrofluid chosen for a particular commercial application is selected with reference, therefore, to the field gradients within the device, and ferrofluids suitable for one application may not be suitable for others where the field gradients are larger. Thus it would be necessary in the latter case to reduce the particle size to meet the stability criterion.

The particles in a ferrofluid do not have a simple magnetic structure. They are single domain in that there are no domain walls but the magnetisation is not uniform throughout the particle. It would be more correct to consider the particles as consisting of a ferromagnetic core with magnetic dipoles aligned, surrounded by an outer layer which contains dipoles 'pinned' by a surface anisotropy. These surface dipoles only contribute to the particle magnetisation when a very strong magnetic field is applied (~20 T).

Thus the particle volume if determined by comparing the apparent saturation magnetisation per unit volume of the particles with that of the bulk material, will be less than that obtained from measurements of electron micrographs. The two measurements of particle diameter are called the 'magnetic diameter' D_m and 'physical diameter' D_p respectively (figure 3). Further, the surfactant layer hinders rotation of the particle in the carrier fluid, and particle size determined from measurements such as the viscosity (which depends on particle dynamics) are larger and different yet again. The diameter determined in this case is called the 'hydrodynamic diameter' D_H. Table 1 compares the different sizes obtained for cobalt and Fe_3O_4 particles.

It is necessary to include the appropriate size parameter in equations involving particle sizes and equation (5) should thus be written in terms of D_m. Equations relating to particle diffusion would include the diameter in the form of D_H.

Table 1 The different particle sizes found in a cobalt and Fe_3O_4 ferrofluid

		Diameter	
Particle	*Physical* D_p (nm)	*Magnetic* D_m (nm)	*Hydrodynamic* D_H (nm)
Co	6.8 ± 0.3	5.8 ± 0.2	11.5 ± 0.3
Fe_3O_4	14 ± 1.5	11.0 ± 0.5	—

Effects of magnetic fields

The surface instability shown in figure 2 depends critically on the value of the ferrofluid magnetisation and hence the applied magnetic field. The distance between the fluid 'spikes' and their number is related to such factors as ferrofluid surface tension and density. The dependence of the critical effect on the ferrofluid magnetisation can be nicely demonstrated using a ferrofluid based on a volatile carrier such as toluene. In this instance, if a fixed magnetic field is applied normal to the surface of a ferrofluid which has a magnetisation less than the critical value no surface 'spikes' are observed. However, the surface instability appears as the carrier evaporates and the ferrofluid strength reaches the critical value. It will disappear again if the ferrofluid is diluted with toluene.

Though the surface instability is a striking and dramatic phenomenon it is of little practical significance. The instability has an interesting appeal as a dynamic display which varies with the field value and field direction and a 'toy' based on this idea was developed and marketed with limited success in the early 1970s.

Applications of ferrofluids have developed because of their magnetic properties and the effect of magnetic fields. For ferrofluids the usual form of Bernoulli's equation

$$P + \tfrac{1}{2}\rho v^2 + \rho g h = \text{constant} \qquad (7)$$

which relates the pressure in an incompressible liquid to its kinetic and potential energy must be modified to include the magnetic pressure induced by the external magnetic field. The augmented form of equation (7) for a ferrofluid in a magnetic field H would be

$$P + \tfrac{1}{2}\rho v^2 + \rho g h - \mu_0 \int_0^H M\,dH = \text{constant} \qquad (8)$$

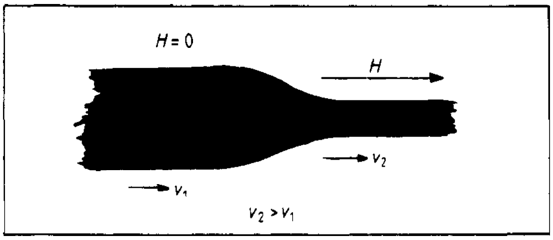


Figure 4 Ferrofluid jet formed by passing ferrofluid into a magnetic field H. The velocity changes from v_1 to v_2

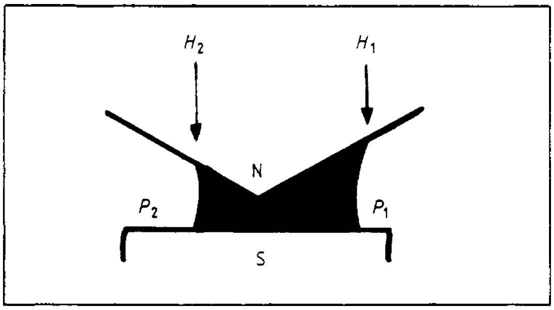


Figure 5 Effect of pressure on the position of a ferrofluid plug tapped between pole pieces. This is the principle underlying the ferrofluid seal

v is the streamline velocity and ρgh the gravitational potential energy. This equation describes the behaviour of magnetic fluids in devices. For example, for cases where the pressure and gravitational potential energy are constant a ferrofluid will experience an increase in velocity as it flows through a horizontal magnetic field. This would thus produce a horizontal ferrofluid jet of reduced cross section (figure 4).

Another example would be to consider the case of zero flow and constant gravitational energy. This would be the situation for a 'plug' of ferrofluid held in place by a permanent magnet. Analysis of equation (8) enables the position of the 'plug' to be examined when there is a pressure differential across it. If $P_2 > P_1$ (figure 5) the ferrofluid 'plug' positions so as to maintain the sum of the magnet and pressure terms constant. Thus the magnetic energy term must be smaller at the low pressure surface at H_1. This occurs with the surface in a smaller magnetic field than that exposed to the pressure P_2 and $H_2 > H_1$. Such an analysis would be relevant for the construction and design of a ferrofluid pressure seal.

A magnet immersed in a ferrofluid will levitate and centralise between the vessel walls. For any displacement there is a restoring force due to the magnetic term in equation (8). Levitation of non-magnetic objects submersed in a ferrofluid is also possible by controlling the buoyancy force with a magnetic field. In this particular instance the magnetic term in Bernoulli's equation is increased by applying the magnetic field. The pressure in the liquid thus increases as does the buoyancy of any submerged object, and any non-magnetic object can be made to float. This system has been studied in some detail as a means of separating different solids by controlling the effective density with a magnetic field. The object will float when the vertical magnetic force is greater than the gravitational force. This occurs when

$$(\rho_s - \rho_L)g > \mu_0 M \nabla H \qquad (9)$$

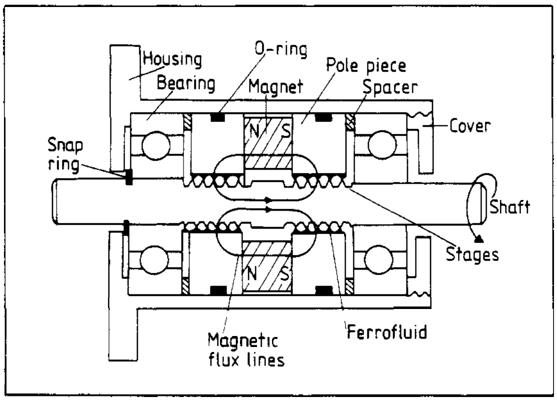
ρ_s is the density of the solid and ρ_L the effective density of the liquid. The magnetic field can be used to separate by flotation non-magnetic solids with densities differing by less than 10%. For large scale operations, however, the objects must be washed to remove the excess ferrofluid adhering to the surface. This can be a costly process, but necessary if the process is to be commercially viable. The flotation technique is attractive for certain applications such as gem separation. The usual method uses fluids of different densities to cause flotation. However, some of these fluids are toxic and objectionable and for this application the ferrofluid technique is a more convenient and agreeable alternative.

Let us now examine the use of ferrofluids in devices.

Rotating shaft seals

Ferrofluids are widely used in the construction of rotary shaft seals. The most simple would be the exclusion seal used for computer disc drives. In this

Figure 6 Ferrofluid rotating shaft seal manufactured by Ferrofluidics Corporation, USA



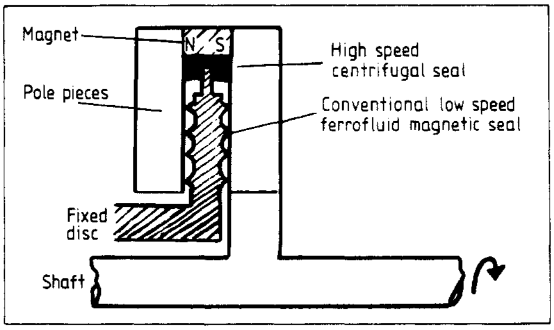


Figure 7 The centrifugal seal which uses the sealing effect of ferrofluid at low rotational speeds (<3000 RPM) and centrifugal forces at higher speeds

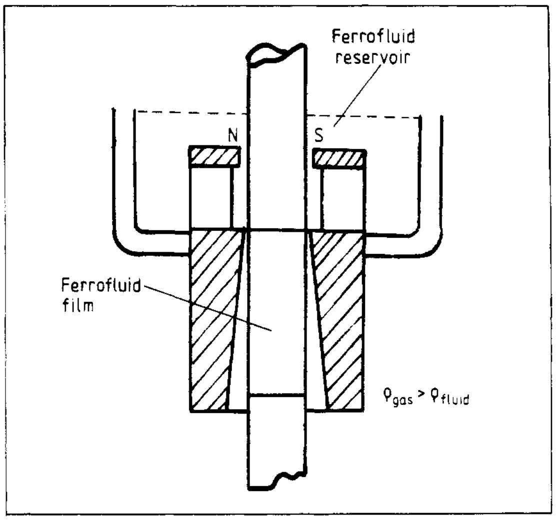


Figure 8 Linear seal with transverse amplitude determined by the length of the magnetic field gradient. (*courtesy N Goldowsky, Phillips Laboratory, USA*)

application the rotary shaft drives the storage disc from which information is transmitted via the read–write head. The disc is very close to the head (0.0002 cm) and it can be damaged if dust or smoke particles collect beneath the head. A ferrofluid seal ensures the disc can rotate in a clean environment. The principle of operation is the same as that of the high pressure seal shown in figure 6. This has an impressive specification and a typical shaft speed would be 4500 RPM for a differential pressure of 470 kPa (68 PSI) across the seal. For non-continuous operation shaft speeds of 50 000 RPM are possible. The seal is formed by a low vapour pressure ferrofluid held in position around the shaft by a magnetic field.

The magnetic flux is concentrated to increase the field and, therefore, the pressure capacity, by tapering the pole piece as shown in figure 5. In practice several tapers or 'teeth' are necessary to build up the pressure differential, each stage being capable of holding a pressure difference of 20.7–34.5 kPa (3–5 PSI). The final pressure capacity of the seal can be calculated from the relation

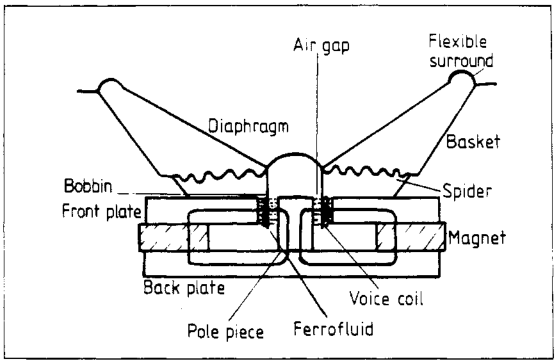
$$\Delta P = N\mu_0 Z \int_0^{H_0} M \, \mathrm{d}H \simeq \mu_0 Z M_s H_0 N \qquad (10)$$

where H_0 is the field between the tapered pole piece and the shaft, Z is an efficiency factor which depends on the shaft speed and the aspect ratio (the length of the stage divided by the radial gap), M_s is the saturation magnetisation and N the number of stages. The radial gap is approximately 0.02 cm and shaft diameters of several centimetres are common. The maximum rotational speed is limited by frictional losses in the sealing fluid. This increases with shaft speed and the heat generated in the seal eventually leads to degradation of the fluid. Ferrofluid temperatures of 100 °C at shaft speeds of 4500 RPM are usual but water cooling of the pole pieces can be used to reduce temperatures and, therefore, to increase maximum speeds. Seals have operated for many years without detrimental effects and, indeed, any sealing fluid lost can be readily replaced simply by the injection of new ferrofluid between the pole pieces.

A centrifugal seal which makes use of both centrifugal forces and magnetic forces has been developed and is shown in figure 7. The magnetic sealing is used for low rotational speeds (<3000 RPM) but at high speeds the centrifugal force drives the ferrofluid to an outer chamber where a seal is formed between the ferrofluid and an axial disc.

An attractive development of the rotating shaft seal would be a shaft seal with liquid at high pressure on one side of the seal and gas at low pressure on the other side. Such an application might be the stern shaft seal for a ship. Earlier

Figure 9 Voice coil assembly of a loudspeaker showing the position of ferrofluid between the magnet pole pieces



experiments have shown that a combination of a differential pressure and high rotational speed leads to a rapid breakdown of the seal. It is still unclear what happens at the seal–liquid interface but a simple construction as used for sealing gas under pressure will not work. It is believed, however, that a seal can be designed to work with liquid under pressure and this is currently the subject of a patent application. Thus it may be possible in the future to produce ferrofluid seals for marine use which will find application not only in ships but also in oil drilling systems.

An oscillating shaft is more difficult to seal. The problem associated with a linear seal is that dynamic forces result in loss of fluid from the sealing area and there is a limited transverse amplitude. The seal shown in figure 8 uses a method of sealing which gives a linear displacement of ~5 mm. The shaft passes through a field gradient and the seal is formed in the usual way by trapping ferrofluid in the region of maximum field. Loss of ferrofluid is prevented by a strong field gradient which forces the ferrofluid back to the seal area. Provided that the length of the field gradient is greater than the amplitude of motion the seal operates without loss of ferrofluid or pressure. The seal described in figure 8 which uses the field gradient principle is capable of holding a differential pressure of 20 kPa (3 PSI) at a frequency of 10000 RPM, with a 15 kA m^{-1} ferrofluid and a stroke amplitude of 3 mm. The design was originally considered by Phillips Corporation USA for the use in an artificial heart. For this application a minimum seal life of ten years was specified.

Damping applications

A ferrofluid has a magnetisation in the range 4–40 kA m^{-1} and a viscosity ranging from 1 mPa s to 1 Pa s. The high viscosity fluids make excellent damping fluids which can be held in position by magnetic fields.

A more unusual application is that concerned with loudspeakers. In this case the voice coil oscillates between the pole pieces of a circular magnet. The limitations on the loudspeaker are usually the power handling capacity and the sound quality. The voice coil is damaged at high powers through overheating and the sound quality is affected by unwanted resonances in an undamped system. If ferrofluid is injected into the field region so that the voice coil is immersed the voice coil becomes damped thereby improving sound quality. In addition the ferrofluid transmits heat to the pole pieces thus increasing the power capacity of the speaker. The assembly of the speaker with ferrofluid is shown in figure 9.

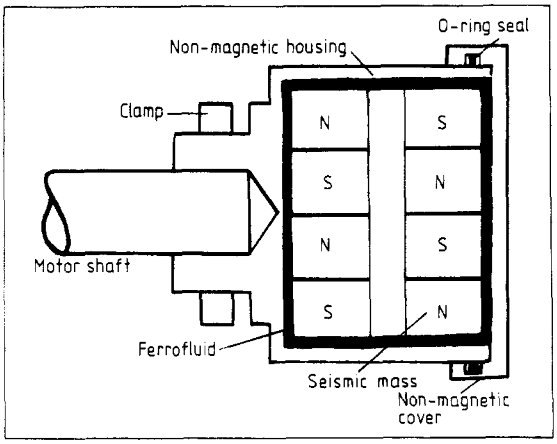


Figure 10 Inertia damper used for stepper motors. The seismic mass which consists of ring magnets levitates in ferrofluid and requires no bearings or further support

Ferrofluids can also be used in inertia dampers. In this application the settling time of a stepper motor can be reduced if a ferrofluid inertia damper is connected to the shaft of the stepper motor. The inertia damper is shown in figure 10. The seismic mass which consists of a series of permanent ring magnets levitates in the ferrofluid which is contained in an aluminium container. No support or bearings for the seismic mass are required. As the shaft rotates and is bought to rest the frictional forces between the seismic mass and the ferrofluid produce a torque which opposes the motion of the stepper motor assembly bringing it rapidly to rest without 'ringing'.

Accelerometers

The ferrofluid accelerometer was first proposed by Dr R E Rosensweig and uses a magnet levitated in a ferrofluid as a detector. The magnet represents an inertial mass which is centred in a tube by magnetic levitation (figure 11). Accelerations are detected as the inertial mass is first displaced and then restored to its original position by centering coils around the tube. Sensors are used to track directions with respect to the three coordinate axes. Such a device is used in oil drilling to plot the direction of the drill head and is sensitive to 1 part in 10^4. It is rugged and can withstand g forces of $1000g$ and temperatures of 125 °C.

Optical applications

In dilute form ferrofluids possess a magnetic birefringence, dichroism and exhibit Faraday rotation. These are properties of magnetic fluids which raise the interesting possibility that they may be used in the construction of optical switches and shutters. The response time in magnetic fields would, however, appear too long to be competitive with that obtained with electric fields and liquid crystals. As development work proceeds shorter response times may be obtained.

Magnetic inks

A ferrofluid closely resembles an ink in appearance. The magnetic properties, however, enable magnetic fields to be used to produce jets of fluid which can be deflected by magnetic fields to form characters. The more familiar high speed printing techniques use electrostatic fields for a similar purpose. Both printing processes produce high quality print at high speeds but the magnetic system has an advantage in that only low voltages are required.

New printing techniques are being investigated in which ferrofluid ink is attracted to magnetised characters formed on magnetic tape prior to printing. The ink is then transferred on to paper by direct contact and the characters erased at the end of the printing process.

A magnetic ink has other advantages if the characters remaining after the carrier has evaporated retain magnetic properties. In this case the characters can be read with a magnetic reader provided the remanence of the ink residue is large. This will not always be the case if the particles in the ferrofluid are small since the remanence is then also very small and unsuitable for magnetic reading. In this situation it is necessary to optimise the size distribution to give maximum value for the remanence. The idea of using magnetic ink for magnetic reading has interesting possibilities in the field of security printing, bank note and cheque production.

Medical applications

Various suggestions have been made concerning the use of ferrofluids for medical applications. Ferrofluids injected into the blood stream can be directed to sensitive areas with magnetic fields. The blood supply can be blocked and the artery cut during surgery without using clamps. In this case there is no damage to the artery as is often the case when clamps are used.

Cranial aneurisms, which are ruptures of arteries in the region of the brain, may be treated without surgery using ferrofluid. In this instance ferrofluid is held by magnetic fields so as to isolate the rupture from the blood stream. Natural healing then takes place and scar tissue forms at the rupture which eventually disappears. Little research on medical applications takes place outside the USSR principally because of the sensitive question of undertaking biological experiments on animals. In the USSR at the Latvian Academy of Sciences, however, a substantial research programme is underway to study how magnetic fields can be used to control the distribution of ferrofluid after this has been injected into animals. A study of the effectiveness of ferrofluids as a vehicle for transporting drugs to specific areas of the body is an important part of this programme.

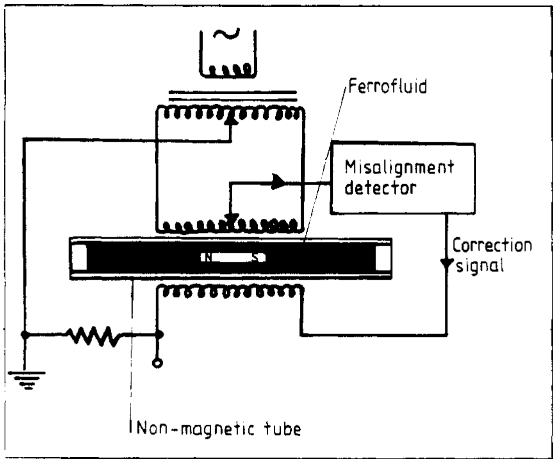


Figure 11 Diagrammatic representation of an accelerometer using the displacement of a levitated magnet to measure acceleration (*courtesy R L Bailey, Ferrox Ltd*)

Acknowledgments

Some of the diagrams in this article have resulted from suggestions made or published by Ferrofluidics Corporation, Nashua, New Hampshire, in their literature. Their contribution is gratefully acknowledged.

Further reading

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