(c) by direct payment into the Institute's National Giro account no. 554 8152. Please quote the name of the applicant and the meeting.
(d) by Access/Master or Barclay/Visa Credit Card (please complete the relevant section on the registration form).

Applications received without payment or details of how payment will be made (a,b,c or d above) may not be accepted.

6 **CANCELLATIONS** - No payment can be refunded to those cancelling if such cancellations are notified after .

7 **MEMBERSHIP OF THE INSTITUTE OF PHYSICS** - Details of membership and application forms may be obtained by completing the tear-off slip at the bottom of the registration form.

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Programme and Registration Details

Electrorheological and Ferro Magnetic Fluids

Wednesday 28 October 1992

The Institute of Physics
47 Belgrave Square
London SW1X 8QX

Organised by
The Static Electrification Group
of The Institute of Physics

in collaboration with
Solid Mechanics & Machine Systems Group
Institution of Mechanical Engineers
Tribology Group, Institution of Mechanical Engineers
Tribology Group, Institute of Physics

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ELECTRORHEOLOGY AND FERRO MAGNETIC FLUIDS

Organised by IOP Static Electrification Group

IOP
28 October 1992

LIST OF PARTICIPANTS AS AT 27 OCTOBER 1992

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Electrorheological & Ferro Magnetic Fluids

Wednesday 28 October 1992

The Institute of Physics

Programme:

10.15 Registration and Coffee

10.45 1 **SEMI-CONDUCTING POLYMERS AS ER FLUIDS SUBSTRATES**
H Block (Cranfield Institute of Technology)

11.15 2 **SIMULATIONS OF ER FLUIDS**
J R Melrose (University of Surrey)

11.45 3 **ELECTRORHEOLOGICAL FLUIDS IN THE SQUEEZE-FLOW MODE**
R Stanway and J L Sproston (University of Liverpool)

12.15 4 **ER INTERFACED HIGH SPEED FLEXIBLE MACHINES**
W A Bullough (University of Sheffield)

12.45 Lunch

14.00 5 **FERROFLUIDS - PROPERTIES AND APPLICATIONS**
B Boulton (Ferrofluidics Limited)

14.30 6 **FERROFLUIDS AND MAGNETORHEOLOGICAL FLUIDS**
S W Charles (University of Wales, Bangor)

15.00 Tea

15.30 7 **LUBRICATION OF NON-CONFORMAL LINEAR CONTACTS WITH FERROMAGNETIC FLUIDS**
P N de Souza (Cranfield Institute of Technology)

16.00 8 **PROPERTIES OF MAGNETIC FLUID COMPOSITES**
J Popplewell (University of Wales, Bangor)

THE INSTITUTE OF PHYSICS
LONDON

ELECTRORHEOLOGICAL AND FERRO MAGNETIC FLUIDS

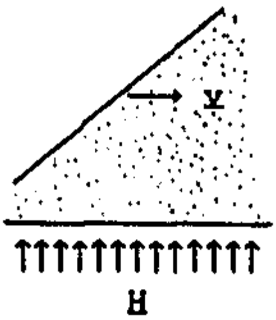
LUBRICATION OF NONCONFORMAL LINEAR CONTACTS WITH FERRO MAGNETIC FLUIDS

P N DE SOUZA
CRANFIELD INSTITUTE OF TECHNOLOGY

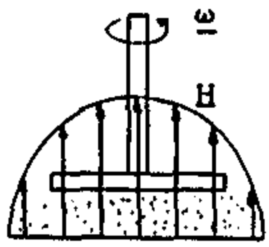
OCTOBER - 1992

MAGNETIC FLUIDS IN HYDRODYNAMIC BEARINGS

TYPE	AUTHOR (YEAR)	REMARKS
SLIDER BEARING	SHUKLA, J.B.(1987)	$\mathbf{M} \times \mathbf{H} \neq \mathbf{0}$; $\mathbf{M}.\nabla\mathbf{H} = \mathbf{0}$

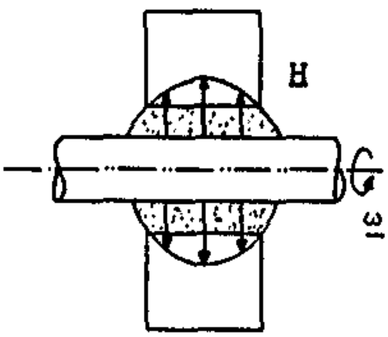


TYPE	AUTHOR (YEAR)	REMARKS
THRUST BEARING	WALKER, J.S.(1979) MIYAKE, S.(1985)	$\mathbf{M} \times \mathbf{H} = \mathbf{0}$; $\mathbf{M}.\nabla\mathbf{H} \neq \mathbf{0}$

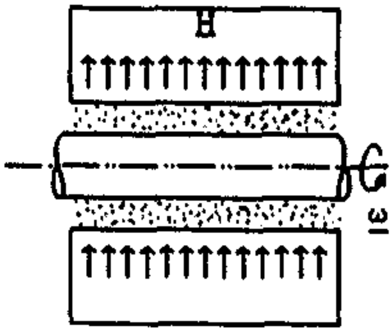


CONFORMAL CONTACTS - JOURNAL BEARINGS

TYPE	AUTHOR (YEAR)	REMARKS
SHORT BEARING	TIPEI, N.(1982/1983)	$\mathbf{M} \times \mathbf{H} = \mathbf{0}$ $\mathbf{M}.\nabla\mathbf{H} \neq \mathbf{0}$



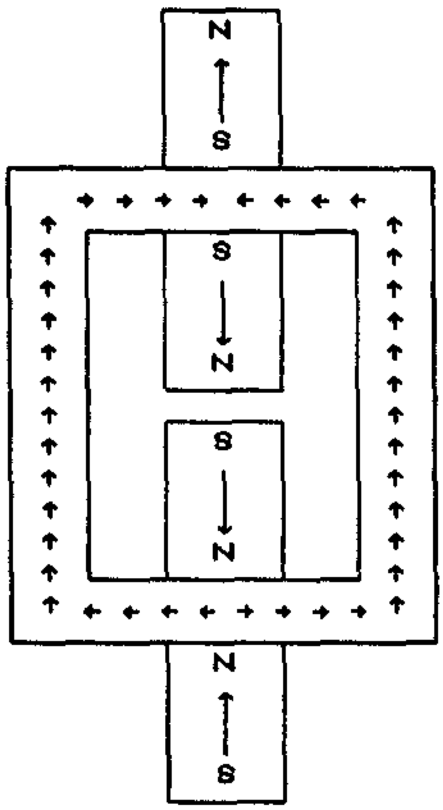
FINITE BEARING	SORGE, F.(1987)	$\underline{M} \times \underline{H} = \underline{0};\ \underline{M}\cdot\nabla\underline{H} \neq \underline{0}$
	CHANG, H.S.(1987)	$\underline{M} \times \underline{H} = \underline{0};\ \underline{M}\cdot\nabla\underline{H} \neq \underline{0}$
	CHI, C.H.(1990)	$\underline{M} \times \underline{H} = \underline{0};\ \underline{M}\cdot\nabla\underline{H} \neq \underline{0}$
	ZHANG, Y.(1991)	$\underline{M} \times \underline{H} = \underline{0};\ \underline{M}\cdot\nabla\underline{H} \neq \underline{0}$
LONG BEARING	HUANG, S.Y.(1986)	$\underline{M} \times \underline{H} = \underline{0};\ \underline{M}\cdot\nabla\underline{H} \neq \underline{0}$
	CHANDRA, P.(1992)	$\underline{M} \times \underline{H} \neq \underline{0};\ \underline{M}\cdot\nabla\underline{H} = \underline{0}$
	NAGAYA, K.(1992)	$\underline{M} \times \underline{H} \neq \underline{0};\ \underline{M}\cdot\nabla\dot{\underline{H}}' = \underline{0}$



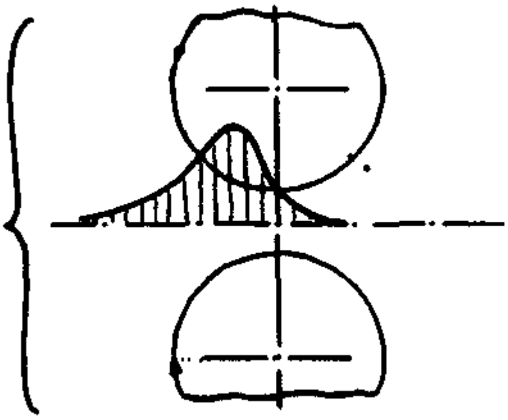
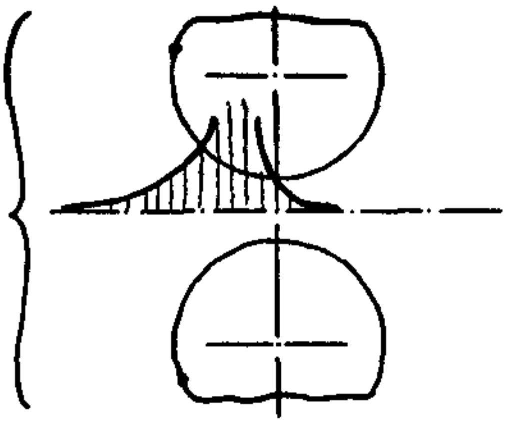
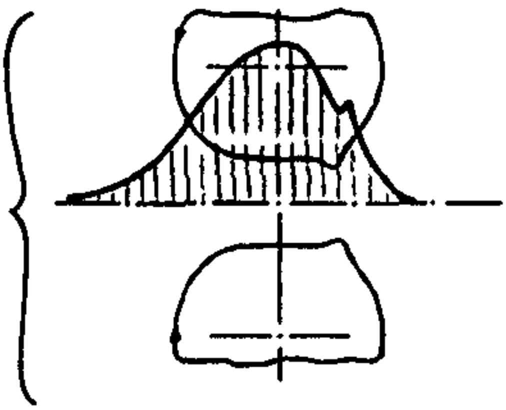
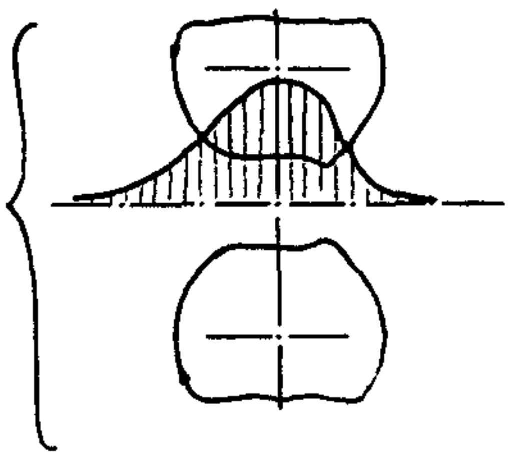
7

PHYSICAL CHARACTERISTICS OF THE PROBLEM

DEFINITION: THE LUBRICATION OF A NONCONFORMAL LINEAR CONTACT BETWEEN TWO ROTATING RINGS PERMANENTLY AND RADIALY MAGNETIZED OPERATING IN THE IVR ISOTHERMAL REGIME WITH A MAGNETIC OIL AS LUBRICANT AND CONSIDERING AN STATE OF ASYMMETRIC STRESS.



REGIMES OF LUBRICATION

NAME	VISCOSITY	SHAPE OF THE SURFACES	
ISOVISCOUS RIGID (IVR)	CONSTANT	CONSTANT	
PIEZOVISCOUS RIGID (PVR)	VARIABLE	CONSTANT	
PIEZOVISCOUS ELASTIC (PVE/EHD/EHL)	VARIABLE	VARIABLE	
ISOVISCOUS ELASTIC (IVE)	CONSTANT	VARIABLE	

THE CLASSICAL IVR SOLUTION FOR THE LINEAR ISOTHERMAL CONTACT

CAUCHY LINEAR-MOMENTUM EQUATION

$$\rho \frac{D\underline{v}}{Dt} = \rho\underline{F} + \nabla . T$$

$$i)\ T = -p\underline{I} + \eta[\nabla\underline{v} + (\nabla\underline{v})^T] + \lambda(\nabla.\underline{v})\underline{I}$$

$$ii)\ \lambda = -\frac{2}{3}\eta$$

$$iii)\ \frac{\partial^2\eta}{\partial x_i^2} = \frac{\partial^2\eta}{\partial x_i\,\partial x_i} = 0\ ;\ i=1,2,3$$

NAVIER-STOKES EQUATION

$$\rho\left(\frac{\partial\underline{v}}{\partial t} + \underline{v}.\nabla\underline{v}\right) = \rho\underline{F} - \nabla p + \nabla.\left[(2\eta)\nabla\underline{v}\right] - \frac{2}{3}\nabla\left[\eta(\nabla.\underline{v})\right] + \nabla\times\left(\eta\nabla\times\underline{v}\right)$$

$$iv)\ \rho\left(\frac{\partial\underline{v}}{\partial t} + \underline{v}.\nabla\underline{v}\right) = \underline{0}$$

$$v)\ h/l \le 10^{-2}$$

$$vi)\ \frac{\partial\eta}{\partial x_2} = 0$$

$$vii)\ \frac{\partial\rho}{\partial x_2} = 0$$

+

EQUATION OF CONTINUITY

$$\frac{\partial\rho}{\partial t} + \underline{v}.\nabla\rho + \rho(\nabla.\underline{v}) = 0$$

REYNOLDS EQUATION

$$\nabla . \left(\frac{\rho h^3}{\eta} \nabla p \right) = 6\nabla . \left(\rho h \underline{V}_1\right) + 6\nabla . \left(\rho h \underline{V}_2\right) + 12h \frac{\partial \rho}{\partial t} - 12\rho \underline{V}_2 . \nabla h + $$

$$+ 12\rho\left(V_{22} - V_{12}\right)$$

viii) $\frac{\partial p}{\partial x_3} = 0 \; ; \; v_3 = 0$

ix) $\frac{\partial \rho}{\partial t} = 0$

x) $\frac{\partial \rho}{\partial x_i} = 0 \; ; \; i=1,3$

REYNOLDS EQUATION FOR LONG BEARINGS

$$\frac{d}{dx_1} \left[\frac{h^3}{\eta} \frac{dp}{dx_1} \right] = 6 \frac{d}{dx_1} \left[h\left(V_{11} + V_{21}\right) \right] + 12\left(V_{22} - V_{12}\right) - 12V_{21} \frac{dh}{dx_1}$$

INTEGRATED FORM OF THE REYNOLDS EQUATION FOR LONG BEARINGS

$$\frac{dp}{dx_1} = 6\left(V_{11} + V_{21}\right)\eta \frac{h - h_0}{h^3}$$

8

xi) $\left.\frac{dp}{dx_1}\right|_{x_b} = 0 \; ; \; p\Big|_{x_b} = 0$ REYNOLDS BOUNDARY CONDITION

xii) $\lim_{x_1 \to -\infty} p = 0$ FULLY FLOODED CONTACT

xiii) $h = h_o\left[1 + \frac{x_1^2}{2Rh_o} \right]$ PARABOLIC APPROXIMATION OF THE CURVATURE

MARTIN'S SOLUTION FOR THE PRESSURE AND FILM THICKNESS

$$p^* = \frac{12\sqrt{2Rh_o}}{h_o} \times \frac{1}{2}\left\{ \gamma + \frac{\pi}{2} + \frac{1}{2}\,\mathrm{sen}2\gamma - \frac{1}{\cos^2\bar{\gamma}}\left[\frac{3}{4}\left(\gamma + \frac{\pi}{2}\right) + \right.\right.$$

$$\left.\left. + \frac{1}{2}\,\mathrm{sen}2\gamma + \frac{1}{16}\,\mathrm{sen}4\gamma \right]\right\}$$

$h^* = 4.89$

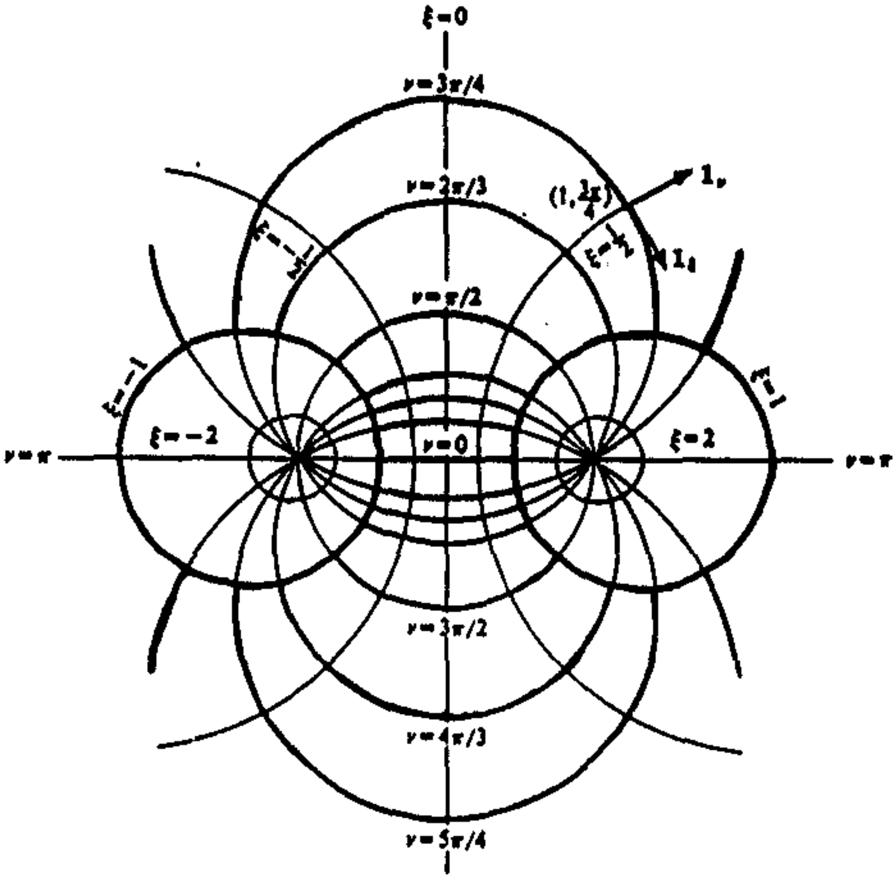
WHERE:

$$p^* = \frac{(2Rh_o)}{\eta RU}\, p \qquad h^* = 2\frac{W_e h_o}{\eta RU}$$

$$\gamma = \tan^{-1}\frac{x_1}{\sqrt{2Rh_o}} \qquad U = V_{11} + V_{21}$$

$$R = \left(R_1^{-1} + R_2^{-1} \right)$$

THE BIPOLAR CYLINDRICAL COORDINATE SYSTEM



THE FERROHYDRODYNAMICS LUBRICATION PROBLEM

$$\frac{\partial \rho}{\partial t} + \underline{v}\cdot\nabla\rho + \rho\nabla\cdot\underline{v} = 0$$

EQUATION OF CONTINUIT

$$\rho \frac{D\underline{v}}{Dt} = \rho\underline{F} + \nabla\cdot T$$

CAUCHY LINEAR-MOMENTUM EQUATI

WHERE: $T = \eta[\nabla\underline{v} + (\nabla\underline{v})^T] + \lambda(\nabla\cdot\underline{v})I + \frac{1}{2}\underline{\underline{\varepsilon}}\cdot\underline{A} - \left(p^* + \frac{\mu_o}{2} H^2\right)I +$

$$p^* = p(\rho,T) - \mu_o \int_o^H \rho^2 \left[\frac{\partial(M/\rho)}{\partial\rho} \right]_{H,T} dH$$

$$\rho \frac{D\underline{s}}{Dt} = \rho\underline{G} + \nabla\cdot C + \underline{A}$$

INTERNAL ANGULAR MOMENTUM EQUATI

WHERE: $\rho\underline{G} = \mu_o \underline{M}\times\underline{H}$; $\nabla\cdot C = \underline{0}$; $\underline{A} = 2\zeta(\nabla\times\underline{v} - 2\underline{\omega})$

$$\underline{B} = \mu_o(\underline{H} + \underline{M})$$

$$\nabla\times\underline{H} = \underline{0}$$

$$\nabla\cdot\underline{B} = 0$$

MAGNETOSTATIC LIMIT OF MAXWELL´S EQUATI

$$\frac{D\underline{M}}{Dt} = \underline{\omega}\times\underline{M} - \frac{1}{\tau_B}\left[\underline{M} - \underline{M}_o \right]$$

MAGNETIZATION RELAXATION EQUAT

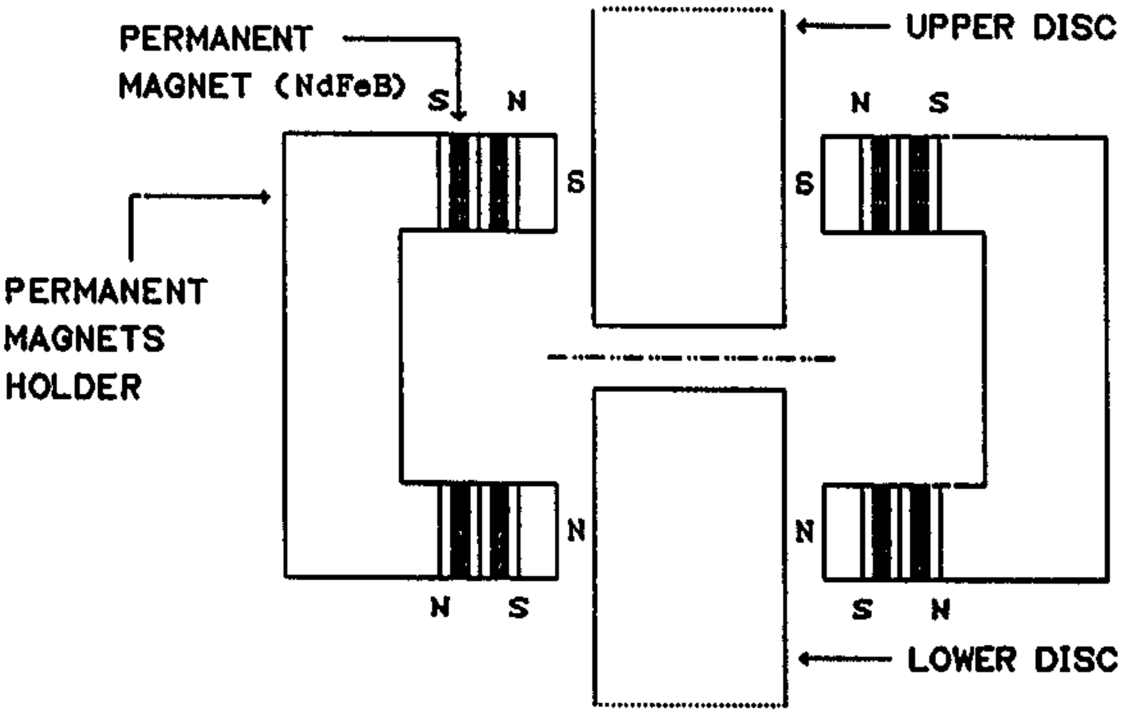
THE PERTURBED SOLUTION FOR THE MARTIN CASE, WHEN N´ IS CONSIDERED TOO SMALL, CAN BE PRESENTED IN AN INTERPOLATED FORM BASED IN A NEW DIMENSIONLESS NUMBER GIVEN BY THE PRODUCT τNA. THE EQUATION PRESENTED BELOW IS VALID ONLY FOR SMALL VALUES OF τNA:

$$h_o = \left[4.88 \frac{\eta R U}{2 W_s} \right] \left[e^{.162(\tau N A)} \right]$$

CORRECTION DUE TO THE ASYMMETRIC STRESS CAUSED BY THE PRESENCE OF THE MAGNETIC FLUID

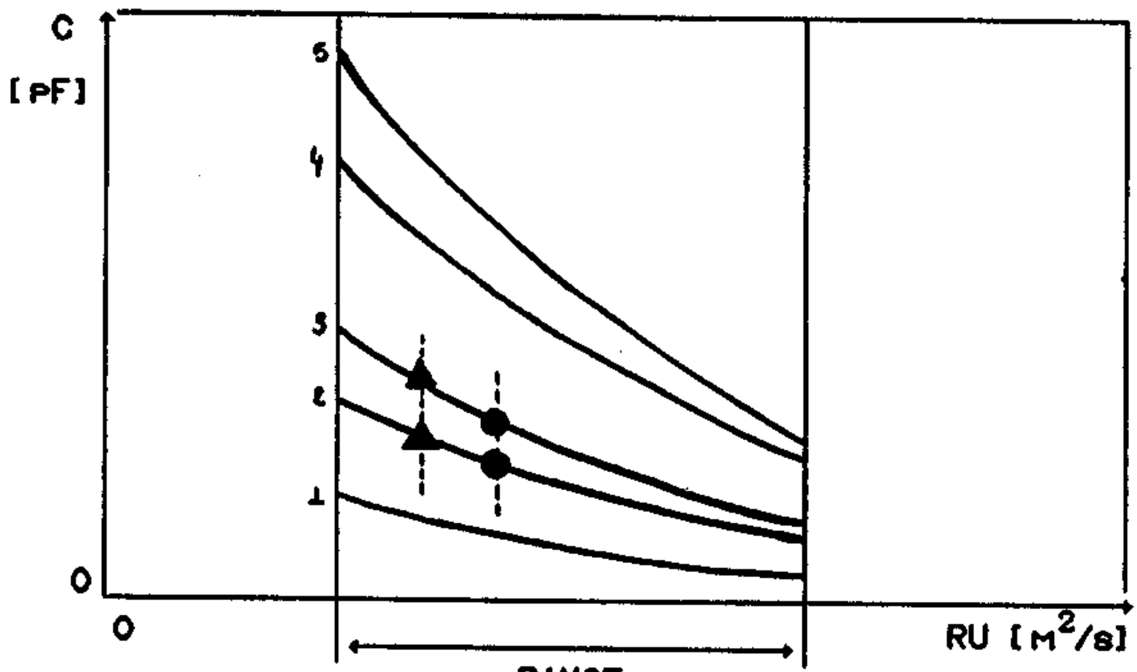
CLASSICAL SOLUTION

MECHANICAL ARRANGEMENT OF THE MAGNETS

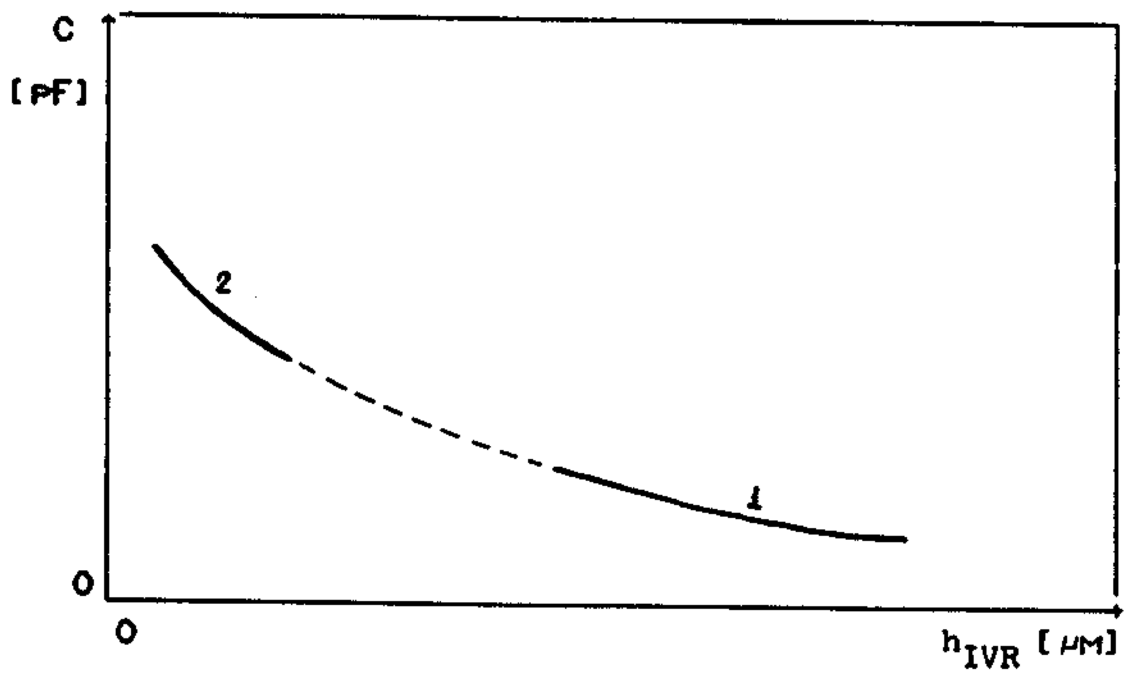


ANALYSIS OF THE DATA

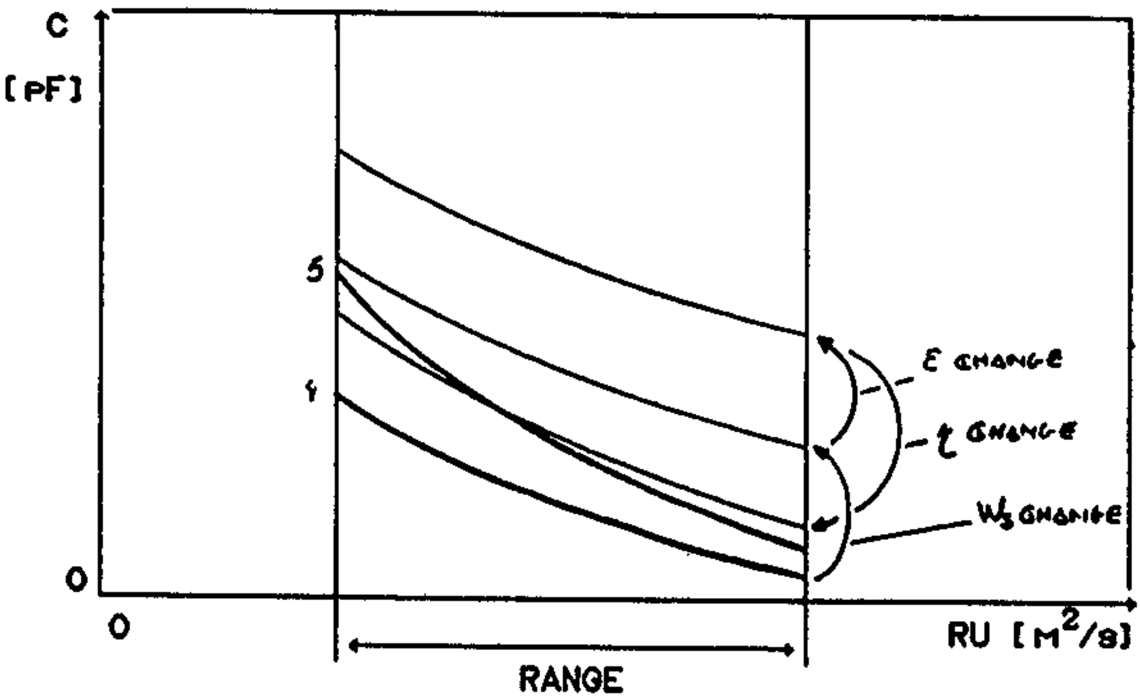
STEP 1



STEP 2



STEP 5



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Abstract Book

Electrorheological and Ferro Magnetic Fluids

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THE INSTITUTE OF PHYSICS

SEMI-CONDUCTING POLYMERS AS ER FLUID SUBSTRATES

Professor H Block
Centre for Molecular Electronics
School of Industrial and Manufacturing Science
Cranfield Institute of Technology

Selected semi-conducting polymers provide effective substrates for ER fluids for which role they are particularly useful in that promoting additives, such as water, are not needed. Their mode of action, and indeed that of water promoted fluids, is believed to be related to the polarization of such fluids under fields. For this reason, investigations of the mechanism of ER should involve the study of both their rheology and their polarization under electric fields. We have in the past undertaken studies of this sort[1] involving firstly, the response of ER fluids to applied stress under dc fields and secondly, the changes that occur in permittivity and dielectric loss in flow, but in the absence of ER causative fields. Recently we have been investigating the dielectric properties of ER fluids under high dc fields (< 1.0 kV mm^{-1}), doing so by using a small added ac sensing field in the frequency range 10 - 10^5 Hz and also applying stresses and thus inducing flow. Complementary rheological studies involving rectangularly pulsed electrical fields (< 2.5 kV mm^{-1}) with an adjustable on-to-off ratio and with a repetition frequency up to 10^4 Hz are also being undertaken.

The lecture will describe the techniques and equipments which have been developed, and some of the results obtained, in our investigation of ER fluids based on dispersed poly(acene quinone radicals), poly(aniline) and poly(lithium methacrylate). How these techniques help to probe the stages of polarization, aggregation and disruption will be discussed, including novel dielectric data showing the development, persistence and disruption of fibrillation under dc fields. The rheological response of ER fluids to electric fields of various forms is related to the dynamics of particle-particle interactions and as is described, these manifest themselves in the time scales of the mechanical response and hysteresis of the fluids.

Reference

[1] H Block and J P Kelly, Proc *IEE Colloq.*, 14, 1-3, 1985. H Block "Polymers in Solution", Ed. W C Forsman, Plenum Press, New York and London, Chapter 2, 1986. H Block and J P Kelly, *J Phys D Appl Phys*, 21, 1661, 1988. H Block, J P Kelly, "First Internat. Symp. of ER Fluids", Ed. H Conrad, J D Carlson and A F Sprecher, North Carolina State Univ. Engineering Pub., Raleigh, NC, 1, 1989. H Block, J P Kelly, A Qin, and T Watson, *Langmuir*, 6, 6-14, 1990. H Block, J P Kelly and T Watson, "High Value Polymers", Ed. A H Fawcett, RSC Special Pub. No 87, 151, 1991

SIMULATIONS OF ELECTRORHELOGICAL FLUIDS

Dr J R Melrose
Department of Chemistry
University of Surrey

Understanding electrorhelogical fluids requires knowledge of the possible structures of the particulate components under both shear flow and applied electric field. Computer simulation offers a direct route to such structures, however computational limitations require simulations with N large in 3d to be carried out on simple models. The talk will describe a simple Brownian dynamics technique for simulating sheared suspensions. The technique is used on point dipole models for electrorheological fluids. The simulations adopt a variety of different layered, ordered and amorphous phases and reveals novel structures such as the aggregation of layers. The talk will describe these various structures. A *non-equilibrium phase diagrams* in the space of volume fraction, shear rate and interaction strength will be proposed. The different phases relate to the non-Newtonian rheology of the ER fluid.

ELECTRO-RHEOLOGICAL FLUIDS IN THE SQUEEZE-FLOW MODE

Dr R Stanway and Dr J L Sproston
Department of Mechanical Engineering
University of Liverpool

Traditionally, electro-rheological (ER) fluids have been used in the so-called "shear" and "flow" modes of operation. Recent research at Liverpool has been concerned with the investigation of an alternative mode of operation: the squeeze-flow mode.

In this presentation the authors will define the squeeze-flow mode for ER fluids and present results from static tests to show how the performance differs from that obtainable in typical shear mode operation. The development of mathematical models to describe squeeze-flow mode dynamics is discussed. The presentation is concluded with experimental results from a prototype vibration isolation and comparison with theoretical predictions.

ER INTERFACED HIGH SPEED FLEXIBLE MACHINES

Mr W A Bullough
Department of Mechanical & Process Engineering
University of Sheffield

The main sought after properties of ERF with respect to the development of the flexible high speed machine concept are set out and justified in a general comparison with the magnetic force transmission. Characteristic data is related to application requirements with likely fluid development trends being indicated. Future demands and auxiliary material and instrumentation etc are dealt with in brief.

FERROFLUIDS - PROPERTIES AND APPLICATIONS

Mr B Boulton
Ferrofluidics Limited

The principles underlying ferrofluids are outlined. Their properties are described, how some are utilised to meet specific requirements, thus providing a varied range of applications. Applications include use in different sealing, lubricating, heat transfer and damping problems.

Examples of both well accepted and lesser known applications will be detailed.

FERROFLUIDS AND MAGNETORHEOLOGICAL FLUIDS

Dr S W Charles
Department of Chemistry
University of Wales, Bangor

Ferrofluids (magnetic fluids) are colloidal suspensions of small (< 10 nm) single-domain magnetic particles, typically of ferrites, dispersed in various carrier liquids depending on the application. Such fluids have the usual properties of liquids but because of their magnetic content have in addition some unique properties. The application of a magnetic field has little effect on the viscosity of the fluids. These fluids are used in a number of commercial applications such as seals of various descriptions, bearings, inertial dampers etc, and have also been considered for medical applications.

In the case of magnetorheological fluids, the magnetic analogue of electrorheological fluids, the dispersions are of micron size particles of the transition metals. In contrast to the case of ferrofluids the application of quite modest magnetic field produces a liquid to solid transition. Such fluids have been used as magnetorheological throttles actuators, etc.

LUBRICATION OF NON-CONFORMAL LINEAR CONTACTS WITH FERROMAGNETIC FLUIDS

Mr P N de Souza
School of Industrial and Manufacturing Science
Cranfield Institute of Technology

The lubrication of the contact between two smooth cylinders with ferromagnetic fluids is analysed. The model adopted consists of a generalised Reynolds equation which takes into account the angular momentum of the particles and the influence of an external magnetic field in a direction normal to the lubricating film. The results are compared with those obtained by considering the same contact lubricated by a simple Newtonian fluid.

PROPERTIES OF MAGNETIC FLUID COMPOSITES

Dr J Popplewell
School of Electronic Engineering Science
University of Wales, Bangor

Magnetic fluid composites are mixtures of non-magnetic particles 1-100μm diameter dispersed in a magnetic fluid. In a magnetic field these non-magnetic particles which are 2 to 3 orders of magnitude greater in diameter that the colloidal particles of the magnetic fluid acquire a strong induced diamagnetic moment. As a consequence the particles interact to form chains aligned in the field direction. In a monolayer film where the particles are constrained, however, the interactions are repulsive when the field is normal to the plane of the film and the particles do not chain but form a hexagonal array.

It is possible using a magnetic field to align the composite particles to generate liquids with a structural anisotropy that can lead to unusual electrical, thermal and mechanical properties. Magneto-resistive devices have been constructed and a microwave modulator developed using a composite containing metal particles. Other uses of magnetic fluid composites can be envisaged where an alignment of particles or possibly large molecules can lead to novel solid state materials generated by either removing the aligned component of polymerising the magnetic fluid.