DEVELOPMENT OF ADVANCED ELECI'RO-THEOLOGICAL FLUIDS AND COMPLEMENTARY DEVICES

SYNTHESIS REPORT

Compiled by

Dr D A Brooks
Technical Coordinator
Advanced Fluid Systems Limited

Date 6 December 1996

Partners: Advanced Fluid Systems Limited (AFS)
Technische Hochschule Darmstadt (Darmstadt)
Metzeler Gimetall AG (Metzeler)
University of Hull (Hull)
Thompson Marconi Sonar S.A.S (TMS-SAS)

Reference Period: 01 June 1993 to 31 May 1996

Starting Date: 01 June 1993 Duration: 36 months

Reference No: BRE2.CT92.0137
Project No. BE 5072

CONTENTS

1 SUMMARY

1.1 Key words

electro-theological fluids, linear dampers, anti-vibration devices, theological measurements, mathematical models.

1.2 Abstract

The purpose of the thirty-six months project was to conduct research into electro-rheological (ER) fluids, both existing and improved, and to build advanced prototype devices based on these fluids. The program included the evaluation of the prototypes with the intention of subsequent commercial development.

ER fluids possess the unique property of changing from liquid to solid and back again in a fraction of a second when a voltage is applied and removed. The program examined organic and polymeric materials, including conducting. polymers, which could be used in ER based devices. Typical ER applications are electrically controlled clutches, dampers, shock absorbers, vibration mounts, actuators, and acoustic reflectors. The fluids' unique behaviour allows a designer to combine several functions within a single device or to offer performance characteristics which are unavailable with conventional techniques.

The overall <u>industrial</u> objective was to produce ER based prototype devices with wide application which are simple, controllable, and give better performance than conventional equivalents. Work was directed towards applications in robotics, machine tools, and automotive. The major effort, to meet the industrial objective, covered the following areas:

a. Design requirements - this covered fluid specifications and design techniques to be used in creating ER devices, including electrode shape and geometry, shear rates, seals, access, filling, and fluid performance.

b. High Voltage Power Supplies and Control Circuits - all ER devices require controlled high voltages and work was conducted on the development of small, efficient power supplies and their associated control circuits.

c. Development of Devices - hardware developed and evaluated covered anti-vibration devices, both automotive engine mounts and linear dampers, clutches, actuators, and tactile arrays.

d. Acoustic Devices - the acoustic properties of ER fluids was extensively studied and a range of unusual and attractive potential applications, such as smart acoustic reflectors, were developed.

The overall <u>technical</u> objective was to be able to predict and measure the behaviour of ER fluids.' This involved development of mathematical models of fluid behaviour under different conditions and the testing of fluids under these conditions. This included wide frequency and amplitude ranges. Specific tasks covered were:

a. Mathematical models - models were developed covering the behaviour of ER fluid under steady and oscillatory shear.

b. Fluid dynamic models - models were developed covering the flow behaviour of ER fluids in a range of potential devices.

c. Electric field models - this covered both elementary electrode configurations and complex electrode designs suitable for complaint manipulators.

d. Basic fluid properties - measurements were made of rheological 'and physical properties of a wide range of ER fluids.

e. Fluid Development - fluids based on inorganic, polymeric, and liquid crystal materials were developed along with associated production technology and quality control requirements.

2 CONSORTIUM

The project has five Partners, three industrial and two academic, and commenced on 1 June 1993 with a planned duration of 36 months. The Partners represent an attractive integration of companies and universities with complementary skills, -All of the industrial concerns have a substantial background in the technology, both from an engineering and chemical standpoint. Collectively the consortium provides the capabilities to successfully design, manufacture, and evaluate improved ER fluids and devices.

PARTNER	PROFILE	INTEREST	ACTIVITIES
Advanced Fluid Systems Limited 10/14 Pensbury Industrial Estate Pensbury Street London SW84TJ ENGLAND	Advanced Fluid Systems Limited" (AFS) was incorporated in 1990 to exploit market opportunities for "smart" materials and devices. AFS Ltd offers consultancy, research and design services, and research quantities of these fluids.	This project is integrated with the existing products, expertise, research strategy and long term product development plans of smart materials and devices. These plans are focused on the human environment situation including, medical, office, warehouse, and automation markets.	AFS coordinated the project and had particular responsibility for organic fluid development and the development and evaluation of linear dampers for general industrial applications.
Metzeler Gimetall AG Erbacher Strasse 50 D-64747 Breuberg GERMANY	The core business activity of Metzeler is anti-vibration elements made from rubber, rubber bonded to metal and plastics. The company supplies several major automobile manufacturers as well as numerous general engineering concerns.	ER fluid controlled anti-vibration elements are a logical successor to the conventional hydraulically damped elastomeric mounts. The work has demonstrated their superior performance, particularly at frequencies difficult to control by any current means. ER technology is located directly at the core of Metzeler's anti-vibration business..	Responsible for the development of inorganic ER fluids and anti-vibration mounts. These were targeted at the automotive industry. .

Thompson Marconi Sonar S.A.S 525 Routes des Dolines BP 138 06561 Valbonne FRANCE	TMS has 25 years experience in developing sonars of all kinds together with a significant capability in underwater acoustics and acoustic imaging. TMS designed and developed high performance multi-beam echo-sounders, for example "SAR" which detected 'the wreck of the Titanic at a depth of 3,000 m.	The development of acoustic arrays or acoustic sensors depends on the development of suitable materials. ER fluids represent a radical breakthrough in that the acoustic properties can be changed electronically. This opens up the expectation of new acoustic devices as well as significant improvements over existing devices. Consequently this project is of strategic importance to the company.	Responsible for the development of software techniques and basic measurements on the behaviour of ER fluid at acoustic frequencies. Developed novel measurement techniques and acoustic equipment suitable for sonar devices.
Technische Hochschule Darmstadt Fachgebiet Technische Stroemungslehre Petersenstr-30 D-64287 Darmstadt GERMANY	A leading technical University in Germany devoted to higher. learning, basic and applied research with a student population of about 16,000.	Interests include the formulation of constitutive equations for ER Fluids, the measurement of material behaviour and measurement of the necessary material properties. Theoretical description of the fluid dynamics of ER Fluids in flow geometries of typical devices, such as engine mounts, dampers, and shock absorbers,	Responsible mainly for the mathematical models predicting the behaviour of ER fluid in steady and oscillatory flow. Developed models covering the fluid dynamic behaviour of devices.
University of Hull Department of Electronic Engineering Hull HU6 7RX ENGLAND	A leading technical University of the UK, the University of Hull has considerable expertise in robotic systems and robotic control, particularly related to the textile industry. The University has had a considerable interest in ER fluids over the past eight years.	Attention being focused on the development of techniques applicable to robotics and automation applications with a particular interest in compliant manipulation and tactile sensing. The University has been actively co-operating with industry on ER fluids and in particular with AFS Ltd.	Contributed knowledge and expertise in electronics, control systems and control dynamics as well as experience in robotics and remote handling. Developed novel devices such as tactile arrays and compliant manipulators.

3 DESCRIPTION OF THE ACHIEVEMENTS

3.1 Development of Mathematical Models

The main goal was to develop an original comprehensive model that explained and described the major change of an electro-theological (ER) fluid, the property of changing from liquid to solid and back again in a fraction of a second when a voltage is applied and removed: Supplementary goals were models that enabled predictions of secondary fluid properties such as 'conductivity and the behaviour of ER fluids in specified geometries. These models being particular to the behaviour of the materials in practical devices.

The observation that particles in ER fluids form network structures in an applied electric field - in dilute systems these are often chains -, serves as starting point for a considerations of the electrostatics of the system. This leads to the calculation of the stored electrostatic energy and the attracting forces between the particles, whose strength is determined by the structure. This principle was used to develop the formula below for a fluid with bricklike particles in shear flow. It is a pplicable to all flows of ER suspensions, where the structure of particle chains perpendicular to the flow prevails. It predicts the generated shear stress dependent on particle size, shape, dielectric constants, field strength and volume fraction. The dependent e on field frequency is given implicit in the dielectric constant. *Experiments* confirm the dependence on field strength, from 0 to 3 kV/mm and field frequency from 20 to 500 Hz.

$$\Sigma_{ale} = \frac{1}{2} k \frac{h_k}{a} \varepsilon_f \Phi \left[1 - \frac{\varepsilon_f}{\varepsilon_k}\right]\left[\left(\frac{\varepsilon_k}{\varepsilon_f}\right)^2 - 1\right] E^2 \tag{1}$$

with

Σ_{ele}	electroviscous shear stress
kh_k / a	geometrical factor (particle size and shape)
ε_f, ε_k	dielectric constant of the carrier fluid and of the suspended particles
Φ, E	volume fraction of suspended particles, electric field strength

The deviation of the real particle size from the rectangular shape is modeled with a geometrical factor, from theoretical studies and experiments its value was found to be about 0.3. The initial bricklike structure model was developed analytically whereas the extension to real particles was carried out numerically using a proprietary electromagnetic field software package, distributed in Germany by CST and known as MAFIA. This package was run on an IBM RS 6000 workstation. Subsequent refinement of the model to account for the hydrodynamic forces was also computed numerically using a C++ programme written by Darmstadt running on a PC.

In the case of oscillatory shear, which is found in many applications, the use of this formula is limited to the quasisteady case which is when the friction forces, viscosity, dominant the inertia forces.

It is assumed that in simple shear flows ER fluids behave globally like Bingham materials and that two material properties, viscosity and yield stress, are sufficient to describe the behaviour of the ER fluid. Simulations were carried out on the RS 6000 using the package FIDAP from Fluid Dynamics International Inc.

Basic Electric Field Models

The field between two electrodes, for example in the simple geometry defined by a Couette cell, varies across the gap according to the equation:

$$E_0 - \frac{V_0}{R_c \ln\left(\frac{R_c}{R_B}\right)}$$

where V. is the applied voltage
R_c is the cup radius
and R_b is the rotor radius.

This model is also applicable to Poiseuille flow devices, which are usually simple annular channels.

A further element in the modelling of the macroscopic electric fields concerns the practical consideration of, the required shape of the electrodes to minimise electrical breakdown due to field concentrations at the electrode edge. The ideal profile is derived from a two dimensional analysis of the electric field between a finite electrode as discussed by Rogowski. Analysis has shown that for ease of manufacture a radius is a good approximation. Two distinct conditions were identified:

* If the two electrodes are of equal length, the radius on both electrodes should be equal to that of the electrode gap.

* If one electrode is longer than the other by two to three gap lengths, the radius of the shorter electrode should be twice the gap.

For more complex electrode configurations the modelling of electric field and design of electrode systems was examined, both micro and microscopically. It was found that the macroscopic model was very useful within the context of the design of complex electrode systems such as those formed by conformable electrode systems, such as the tactile array. Simulation software has been written to predict the electrical characteristics of a cell with an arbitrary 2½D surface.

Electro-Chemical Approach to Conductivity

A systematic study of a lithium polymethacrylate based ER fluid was undertaken in a purpose built conductivity cell. The static dc conductivity was measured as a function of electric field, temperature, volume fraction, polymer water content, and continuous phase. The observations clearly supported the view that the current density is a strong function of both the temperature and field strength.

The behaviour was modelled on the assumption that the current was the product of the total transported charge and the drift velocity of these charges. Neither the charge nor the charge carrier were specified and they were combined and referred to as a "particle-charge". The particle-charge is subject to a number of influences, it is field dependent exhibiting a preferential drift in an external field and as part of a chemical system it has chemical energy and, in particular, an activation energy. Finally, the particle-charge is subject to thermal energy. Provided that the sum of the thermal and electrical energy exceed the activation energy, the particle-charge will move with a net drift velocity in the direction of the applied field and a current will flow. If additional fields are applied to the system, for example the hydrodynamic field of Couette or Poiseuille flow, the net current flow will be modified.

This analysis yields an equation of the form:

$$J = A_o \exp^{\alpha/kT} \sinh(\delta q E_0/kT)$$

where
- A_o is a constant of proportionality.
- α is an activation energy
- k is Boltzmanns constant
- T is the temperature in "K
- δ is a jump distance
- q is the electron charge
- E_o is the applied electric field

3.2 Development of Measurement Techniques for ER Fluids "

Reliable and reproducible data are the key elements to developing both the understanding of, and mathematical model for, the behaviour of ER fluids. The objective of this aspect of the project was the measurement of basic fluid properties and the development of techniques to assess the behaviour of ER fluids in typical devices, this included electrical measurements.

Particle Size Distribution

The particle size and the size distribution of the polymeric and inorganic fluids were measured along with the effects of size distribution on the steady shear properties of the fluids. The particle size distribution of the standard polymeric fluid was a monomodal distribution centred around 2-3 μm skewed to larger particles with most particles having sizes between 1-5 μm. This distribution is characteristic of the type of "comminution production process used in the fluid preparation. The distribution of the inorganic fluid is also dependent on the process used. Using a rotating disc mixer about 20% of the particles were in excess of 10 μm, the upper limit being 40 μm with a mean of 5 μm. After treatment by a high shear mixer for 5 minutes the distribution consisted of particles less than 8 μm with the mean value of 3 μm. Continued grinding had little effect. Particles less than 1 μm were not generated. All fractions of the fluid showed good ER properties from which two conclusions are drawn:

* The particles size distribution will reduce during service with the mean reducing to an asymptotic value.

* ER fluids are able to tolerate high mechanical stress without degradation.

Viscosity Measurements

A series of viscosity measurements were undertaken using polymeric ER fluids in two continuous phases, chlorinated paraffin and silicone oi . ER fluids are intrinsically non-Newtonian materials, however, within the normal range of usage, less than 40% volume fraction, the fluid behaves approximately as a Newti mian fluid. The shear stress being proportional to the shear rate although a small degree of shear thinning is often observed, typically a 5-1 O% reduction from 100 to $1000s^{-1}$.' The viscosity is a function of the temperature of the fluid, the viscosity of the continuous phase, η_f, and the nature and volume fraction of the dispersed phase. The effect of tern perature on the suspension viscosity is dictated by the temperature dependence of the continuous phase and consequently the conventional relationship between viscosity and temperature, the viscosity index, is observed with ER fluids. The low viscosity index of silicone oil is reproduced in, ER fluid manufactured using these oils. This relationship is independent of volume fraction although the magnitude of the viscosity will vary.

Numerous attempts at defining the relationship between volume fraction and viscosity using semi-empirical relationships related to the maximum packing factor of the system have been proposed. One of the simpler relationship ps is of the form:

$$\eta_r = (1-\tfrac{1}{2}k\phi)^{-2}$$

where η_r is the' relative viscosity which is defined as the suspension viscosity divided by the oil viscosity and $k = 2/\phi_m$. ϕ_m is the maximum packing h-action for mono-dispersed spherical particles varies from 0.74 for face centred cubic or close packed to 0.525 for simple cubic packing, ϕ is the volume fraction. Fitting the experimental data to the above equation gives a value for ϕ_m as 0.55. This compares favourably with the experimental value for the maximum packing fraction of 0.58 collected via centrifugation. It is therefore appropriate to use the simple expression:

$$\eta_s = (1-1.83\phi)^{-2} * \eta_f$$

to derive, as a first approximation, the suspension viscosity for any oil at any volume -- fraction of dispersed phase.

Compatibility Issues

Testing of different ER fluids, organic, inorganic and liquid crystal based, indicated these fluids as suitable for use with elastomers. The tests showed that the silicone fluids were most suitable for use with the tested materials, including rubber and perspex. This is important as the selection of suitable fluid for use with different materials is essential for cost effective devices.

Measurement of ER Properties Under Shear

Measurement of ER properties under steady shear were made either using proprietary Couette flow apparatus or Poiseuille flow apparatus developed during the course of the project. Measurements under oscillatory shear were done with a rheometer, also developed and enhanced during the project. A system was also developed and implemented' on this rheometer to measure the electrical properties of ER fluids under oscillatory shear. It was tested by comparison with theoretical results, experimental data of RC-devices and fluids with known permittivity. The, setup is adaptable to other ER devices like commercial rheometers or prototype devices to measure the electrical behaviour of the ER fluid or power consumption of the device respectively.

3.3 Development of Advanced Electro-Theological Fluids

This task, which relates to the development and supply of improved ER fluids, was expanded slightly to encompass ER fluids available from other sources. Within the consortium Metzeler and AFS supply ER fluids, although recently the Chemistry department of the University of Hull have developed an alterı iative ER fluid. Outside the consortium a number of companies have developed, and a:e prepared to supply, ER fluids. AFS have contacted most of these companies and, tc date, three have provided samples for evaluation.

The companies prepared to supply samples are Brid:gestone, Nippon Shokubai, and Bayer. Samples received have been evaluated by AFS and comparisons made with both Metzeler and AFS materials. Within the broad thrust o! device development there are now available a range of ER fluids all with somewhat cliff erent characteristics. These are summarised below in table 1.

Table 2 can be used to assess the fluids available aga inst a range of five primary criteria and table 3 highlights test methods, circumstances under which data is measured for these criteria, and objectives in the fluid studies. To achieve these goals inorganic and polymeric materials were studied along with the effect of the continuous phase.

For automotive applications, such as an engine nıount, many of the target properties have to be maximized over a particular temperat ure range. It is necessary to develop a fluid which is able to withstand a temperature range of -50^{0}C to 150^{0}C and is operable over a range -30^{0}C to 130^{0}C. These requirements are fulfilled by many Metzeler fluids, with fluid coded ER fluid 100/10 being the best.

For general industrial use a lower temperature range is required and polymeric based ER fluids are acceptable. The generic class of material tested was that of ionic “polymers as non-ionic polymers tend to produce little or no ER response. Lithium salts of poly(acrylate)s (LPA) as a function of molecular weight (MW), styrene-maleic anhydride copolymers (SMA) and a lithium salt of poly(styre ne sulphonate) (LPSS) were systematically studied. Several of the materials tested were found to have improved properties over the control lithium polymethacylate (LPMA) polymer. For the LPAs, a MW range of 30,000 to 150,000 was found to improve both t he ER response and current density characteristics, however, this was at the expense of a sedimentation problem. The SMAS were found to support high electric fields with low current densities. In common with the LPAs, the ER strength was found to increase with temperature. Also the SMA resins were found to increase their ER response with increas ing proportion of the styrene unit. This is possibly due to an increase in the size of the interstices in the polymer network facilitating ion transport.

Table 1 Available ER Fluids

Supplier	Description
AFS Ltd	Supplies a range of ER fluids based on lithium po ymethacrylate. Generally limited in temperature range (10-70^{0}C) but of high strength (5-10 kPa). Characteristics vary with temperature and shear ra :e.
Bayer	Fluids based on polyurethane. Reasonable perforn anee over a defined temperature range. Two types commercially available low temperature and high temperature. Maximum temperature approximately 120^{0}C. Very good lubrication properties. Characteristics vary with temperature and shear rate.
Bridgestone	Fluids based on carbonaceous materials. Unique c aaracteristic in that there is almost no temperature dependence of the ER effect. Wide operating temperature (-20^{0}C to 120^{0}C). Slightly abrasive, se aling problems experienced. Shear strength approximately 1-1.5 kPa at usable electric fields
Metzeler	Treated silica based ER fluids. Generally operate at low temperatures owing to high conductivity. Also show no dependence on sl ear rate.
Nippon Shokubai	Fluids appear to be based on an inorganic coating with a spherical silica bead substrate. Brown in colour. Fluid settles very quit kly but re-disperses with great ease. Performance increases significantly at temperature greater than 40^{0}C.

In addition to these polymers, LPSS was also stud ied. The water content was found to be too high producing high current den sities making quantitative characterisation of this material impossible.

For the LPMA an alternative polymer was studied in both Couette and Poiseuille flow. In addition, the effect of particle size on- the ER strength of the fluid was also assessed. The reduced particle size fluids were prepared by ball milling the fluids for extended periods of time. Several properties were altered in the milling process:

* the sedimentation rates were dramatically reduced f rom approximately 1 hour to 1 month as the particle size was reduced,
* the response was observed to be much smoother as the particle size was reduced,
* the viscosity increased slightly as the particle size w as reduced,
* the current density increased slightly as the particle size was reduced,
* peak excess shear stress was not observed to vary, however, the excess shear stress at lower temperatures was improved as the particle size was reduced,

This polymer was also tested in Couette flow as a 40% volume fraction fluid in Cereclor 50LV. The low shear rate performance of the fluids was very encouraging reaching a maximum of 7.9 kPa at 2.6 kV/mm and 100 s^{-1}. There was a significant fall in the excess shear stress at high shear rate. The fluid did however produce 2-3 kPa at 1,000 s^{-1} over a temperature range 30-70^{0}C which was an improvement of 100% over the control sample.

Table 2 Primary and Secondary ER Fluid Requirements

	PRIMARY		STATUS	SECONDARY
Electrical	P1a. Power density - is effectively a measure of the current density at operating conditions.	Original Revised Current	10 W/cm 2-3 W/cm³ 3-5 W/cm³	S1. Maximum sustainable field strength E_{0max}
	P1b. Maximum current density at operating conditions (120°C)	Original Revised Current	Undefined 100 μA/cm² "100 μA/cm²"	S2. Maximum suspension dielectric constant ϵ_{rmax}
Mechanical/ Fluid	P2. Suspension viscosity	Original Revised Current	50-3000 m ?as 50-250 ml 'as 50-100 ml 'as	S3. Operational temperature range
	P3a. Excess shear stress at 0.5 kV/mm	Original Revised Current	1 kPa at 0.5 kV/mm 1 kPa at 0.5 kV/mm 0.5 kPa at 0.5 kV/mm	S4. Non hazardous
	P3b. Excess shear stress at 3.0 kV/mm	Original Revised Current	Undefined 10 kPa at 3.0 kV/mm 3 kPa at 4.0 kV/mm	S5. Non flammable
	P4. Response times (time to reach 63% full scale)	Original Revised Current	Undefined 20 ms < 5 ms	
Physical/ Chemical	P5. Stability	Original Revised Current	Stable for 2 years Stable for 2 years Tested 6 months	S6. Recyclability S7. Lubricating
Economic	P6. Cost per litre (including any disposal costs)	Original Revised Current	100 ecu/litre 100 ecu/litre 200-400 ecu/litre	

Stabilisation

One of the major problems with the current generation of polymeric ER fluids, and ER fluids in general, is that they sediment. The sedimentation process often produces hard cakes which do not re-disperse easily. To overcome this, the surface of the dispersed phase require modification. There are two approaches, to produce a dispersion 'that is stabilised or to accept that sedimentation will occur and therefore re-dispersion must be facilitated.

There are two main stabilisation techniques, electric double layer repulsion and steric stabilisation. Only steric stabilisation was attempted. A series of cationic and anionic surfactants were chosen. The anionic surfactants provided less stability than the cation surfactants. Both types, however, provided greater stability than the control sample. In the anionic case the increase in stability was only slight. In all cases, the ER response was maintained or slightly improved. Unfortunately, in all cases, the current density was also found to increase.

To facilitate re-dispersion a gelation process was employed. The additives form macro-structures within the oil in the form of a matrix which supports the particles in the suspension producing stabilisation. The matrix must, however, be easily broken down by a shear stress gradient. The matrix must also be able to reform easily once the applied stress has been removed. In the current study a series of hydrocarbons which contain polar groups were tested. In all cases stability was found to be excellent. This improved stability was however found to be gained at the cost of ER effect, but reduced current density.

Table 3 Test Conditions and Targets for Primary Requirements

No	REQUIREMENT	FULL DESCRIPTION REQUIRED
PI	Reduce power or current density	At a given field strength and temperature the current density should be low. At present, current density is approximately 400 $\mu A/cm^2$ at 70^0C and 3.0 kV/mm. Ideally this should be reduced to 100 $\mu A/cm^2$ at 120^0C. Corresponding power densities, at 3.0 kV/mm, are 12 W/cm^3 and 3 W/cm^3 respectively.
P2	Reduce no-field viscosity	At a given temperature and shear rate the viscosity should be low. This is possibly the ***easiest*** target, typical values being 20-50 mPas at 30^0C and 10QO s^{-1}.
P3	Increase ER effect	However defined, at a given set of conditions of field strength, shear rate, and temperature, the excess shear stress should be increased Current values of the ER effect, τ_e are 1-2 kPa at a shear rate of 3,000 S-l, field strength 3.0 kV/mm, and a temperature of 30^0C. Ideally values in the order of 5-10 kPa are required. The inclusion of the shear rate implies Couette flow, appropriate values for Poiseuille flow need to be defined. An additional requirement is for τ_e to exceed 0.5 kPa at a field strength of 1.0 kV/mm.
P4	Good dynamic performance	The response time is defined as the time taken for the excess shear stress to reach 63% of its final value following the imposition of the electric field. A suggested maximum value of 20 ms is proposed although for different applications this may well need to be reduced.
P5	Improved physical stability	The suspension should be stable against gravity for a period of two years or, as an alternative, be easily re-dispersed at any stage during this time.

Continuous Phase

A study has taken place into effect of the continuous phase on the ER properties of fluids based 'on lithium poly(methacrylate) (LPMA) as the dispersed phase. The continuous phases were a series of chloroparaffin and silicon oils. The continuous phase has a marked effect on both current density, J, and the excess shear stress, τ_e. The highest values of τ_e are from chlorinated paraffins. The trend in decreasing τ_e is as follows:

50LV > Cloparin 38> Fill/20 > M1O = Fill/50 > F111/100 = F175 > M5

The predominant trend is of reducing oil conductivity γ with reducing τ_e. It is also apparent that for the Ambersil series, τ_e reduces with increasing viscosity which i in contradistinction to the Bayer silicones. (NB F175 is a different class of silicon oil, poly(phenyl siloxane) rather than poly(dimethyl siloxane).) The relative oil conductivity is as follows:

50LV > Cloparin 38>> Silicon Oils

The conductivities of the fluids does not follow the oil conductivity series:

F175 > M5 > M1O > Fill/20 > 50LV > Fill/50 > F111/100 > Cloparin 38

Between the chloroparaffin based fluids, it is the conductivity of the oil that predominates (50LV > Clop 38). With the silicon oil fluids the trend is for reducing conductivity with increasing viscosity. ,

The data suggests that both dielectric polarisation and conductivity of the dispersed and continuous phase pay important roles in the ER effect, this is in agreement with the theories developed by Felici, extended by Conrad, and recently included in the dielectric models developed by Spurk.

Hull made a contribution in the form of liquid crystal based ER fluids. The Hull team, in collaboration with the Department of Chemistry, identified a liquid crystal continuous phase (E7) which appears to provide an ER fluid stronger than others tested. The results of these tests were published in a paper entitled 'Comparison of Electrorheological Fluids based on Silicone "Oil and Liquid Crystalline Materials" in the Journal of Material Chemistry. The liquid crystal fluid is potentially useful for applications in which strong shear stresses are a requirement. This conclusion has been made since the liquid crystal fluids have exhibited a shear stress an order of magnitude greater than any available ER fluid. However, the main draw back is that it demands a larger power compared with the majority of conventional ER fluids.

3.4 Development of Advanced Electro-Rheological Devices

Advanced ER devices are conceived either as existing conceptual ideas taken to an advanced stage, that is far beyond the feasibility stage to the point where the majority of the engineering difficulties are resolved. Novel devices are conceived as totally new hardware that are taken to the feasibility stage.

Advanced engineering devices were the dampers, the anti-vibration mount, and the clutches. Novel devices were the tactile array and the acoustic devices.

Data Required

Experience of damper design and evaluation by Advanced Fluid Systems Limited has led to the following minimum information to enable a working prediction of the performance of a damper. These should be expressed as equations:

Table 4 Fundamental Fluid Equations For Damper Desire

Item	Data Required	Reason
1	Variation of viscosity as a function of temperature. Typical expression of the form: $\zeta_f = 102.6 * T^{-0.0167}$ where T is in 'C.	Effectively defines the minimum operational forces.
2	Variation of ER effect as a function of temperature, applied field, and shear rate. Eight parameter fluid model as defined below.	Defines the maximum force, the range over which control can be exertised, and the maximum velocity of the damper.
3	Variation of current density as a function of applied field and temperature. Typical expression of the form: $J = E_0^{2.727} \{0.102 + 0.0358 * T\}$	Defines the maximum temperature at which the damper can operate given the input power.

Linear Dampers developed by Advanced Fluid Systems Limited

The Poiseuille flow data is derived from the inclusion of a specific damper configuration, on a servo-motor driven ball screw device which can be down-loaded with a number of motion profiles. The apparatus is powerful and provides a maximum thrust of 5,000N at 300 mm/s with a maximum acceleration of 8.0 m/s^2. Displacement, velocity, and force are measured with appropriate signal sources and logged using a PC with two analogue to digital converters operating at 1.2 kHz to log simultaneous pairs of force and position readings.

Dampers were evaluated in both compression and extension at velocities of 10, 25, 50, 75, 100, 150, 200, 250, and 300 mm/s. Temperature is automatically incremented. from 20*C to 70^0C in 10*C increments. Sinusoidal motion profiles are also available and can be used when the equipment is modified for low frequency oscillation work.

Using a fast high voltage power supply transient measurements of force against voltage are possible. This is not earned out to provide modelling data but mainly to indicate that the ER fluid under test attains the minimum response time of 20 ms.

Data on the steady flow behaviour of ER fluid in Poiseuille flow was characterised by a multi-parameter parametric model. The model has eight parameters. The first four deal with the zero shear rate excess shear stress and model this behaviour against field strength and temperature. It is assumed that:

$$\tau_o = C * E_0^n \text{ where } C = C_s * T + C_i \text{ and } n = n_s * T + n_i.$$

The last four parameters deal with the variations caused by shear rate which result in an increment of excess shear stress, usually negative, which is 'summed to the value at zero shear rate. The four parameters are:

TEγ which is multiplied by the temperature, field, and shear rate

Eγ which is multiplied by the field and shear rate.

Tγ which is multiplied by the temperature and shear rate

γ which is multiplied by the shear rate only.

The' resulting four values are summated and added to the value given at zero shear rate, τ_0, to give the value at the chosen shear rate, τ_e.

A number of annular flow piston dampers were designed and manufactured as detailed in the table below:

Table 5 Damper Designs

No	Description	Used For	Comments
1	H=O.75 mm L=70 mm D_m=29 mm	Standard test vehicle for the evaluation of ER fluids and the generation of data for the parametric fluid model described in AFS's appendix. Model describes the variation of the steady state excess shear stress with applied field, temperature, and shear rate.	Piston speed 300 m/s γ_{max}= 15,000 s^{-1} E_{max}= 2.7 kV/mm
2	H=0.5 mm L=50 mm D_m=27.6 mm	High shear rate version of standard damper but with electrode built into piston and integral reservoir for piston rod volume. Requires a minimum piston length of 50 mm.	Piston speed 300 In/s γ_{max}= 45,000 s^{-1} E_{max}= 4.0 kV/mm Most suitable for longer stroke dampers.
3	H=O.5 mm L=70 mm D_m=27.6 mm	Longer stroke version of damper 2 with floating electrode and separated reservoir for piston rod volume.	Floating electrode leads to dead bands at ends of stroke. Floating piston arrangement very difficult to seal.
4	H=O.2 mm L=50 mm D_m=27.6 mm	Multi channel arrangement designed to overcome ***apparent*** Coulomb friction effect at low shear rates. The nature of the devices leads to low shear rates in ER section.	Piston speed 300 m/s γ_{max}= 4,000 S^{-1} E_{max}= 4.0 kV/mm
5-9	N/A	Simple piston type damper to evaluate sealing requirements and effect of sliding surfaces on ER fluid performance. Used in endurance testing of ER fluids.	Fluids tested: Bayer (1. 1M cycles) Bridgestone (1.3M cycles then to destruction)' Bayer repeat to 4.5M cycles

Anti-Vibration Devices developed by Metzeler Gimetal

From an anti-vibration standpoint ER fluid mounts will be much easier to adapt to the requirements of new cars than conventional passive mounts. This kind of flexibility allows substantial savings within the development process with respect to development time and effort. Not having to tune the mounts to the different driving. conditions by modification of hardware, ending up with a more or less acceptable compromise in terms of drivability and acoustic isolation, but tuning the mounting system by electronic means will be a significant "advantage in the development process. , A greater advantage would be the implementation of an electronic control device in the car for permanent optimisation of drivability and acoustic isolation (permanent adaptive control).

The energy consumption of electro-theological systems is quite small in comparison to competing technological solutions for adaptive mounts. Typical values for the *energy* consumption of three state of the art systems competing with each other are the mechanically adaptive hydraulic mount, 500 Watts, the electro-magnetic tuned absorber, 50 Watts, and the electro-theological mount with approximately 0.5 Watt. This low power consumption suits ER fluid systems particularly well to computer controlled hardware of modem cars.

Three design approaches were identified, each using the ER effect in a different *way*. Prototypes for the validation of these approaches were made using a specially constructed mount.

Table 6 Design Principles and Embodiments for Anti-Vibration Mounts

Design Principle	Prototype Mount
ER fluid is used as a dissipative control element working within an active shear or damping device. The electric field, controls the energy dissipation by changing the behaviour of the fluid. Adaptivity is by minimizing or maximizing damping effects by the shifting ***dynamic stiffness*** and phase angle in the low frequency range.	This design covers the early mounts using ER fluids of high viscosity. This principle has been proven by experiments not to be suitable for automotive applications due to its poor acoustic performance. However, it may well be suited for adaptive ***or*** active stationary machine mounts using the recent low viscosity ER fluids.
*3 fluid is a dynamic switch used to control physical changes in the mount. An off or constant field results in a passive mount and damping is by inertia effects and energy dissipation. ER fluid allows the tuning of the mount by changes related to its fluid dynamics. This leads to a passive decoupling and plunger module to control acoustic transmissibility.	This may prove to be an interesting design for adaptive hydromounts capable of a lower mechanical frequency than current mechanical solutions which are currently under production for the automotive industry. Its validity could well be shown by experimental results.
The ER fluid is a fluid dynamic control device using both effects of A and B acting in the low frequency range as an active phase shifting device to maximize damping and in the acoustic range to reduce acoustic transmissibility.	The most advanced design which controls the low frequency and the acoustic range. The verification of this demanding concept has been partly achieved by the 'fully controlled prototypes. The advantages of changing the dynamic behaviour of a mount with the ER effect is significant.

Power Supplies developed by Advanced Fluid Systems Limited and the University of Hull

The development of power supplies, electrodes and control electronics for ER devices identified an underlying principle. Power supplies are an intrinsic feature of ER hardware and are application specific, for example a simple step-up transformer would serve the tactile array, whilst dynamic applications need a fast slewrate power supply.

AFS developed a power supply suitable for linear dampers with a specification developed close to Metzeler's requirements for mounts. This was a 2 kV, 5 Watt supply with built in primary control functions. It can be configured to run either as a pulse width modulated (PWM) supply at fixed amplitude, or a proportional power supply at fixed pulse length. As both functions are independently controlled it is possible for it to be configured as a combined pulse and amplitude modulated supply giving a pseudo square output against the input voltage. Current size is 140 * 40 * 30 mm.

Robotics and Automation devices developed by the University of Hull

The inherent controllable stiffness properties of ER fluids make them candidates for implementation in producing artificial surfaces and exoskeletons which give tactile feedback information to the user of a virtual reality system. Work has been carried out in both of these fields but the majority of the effort has been put to use with the tactile feedback application.

A first prototype was developed having a solid square electrode used to create the illusion of the square shape when the fluid was energised. Following the success of this work, an array consisting of 5X5 tactels was constructed as a second prototype which was then tested for a range of geometric shapes and alphabetic characters. The presence of these shapes on the tactile array surface was verified in every test case by the use of sophisticated, dual axis force sensing equipment. A control system was developed to allow' total PC configuration of the surface pattern which also allows the array to display a moving image. For more complex surfaces flexible materials were required. A survey revealed that conductive rubber based on CIS-1-4-polyisoprene most reliably maintained the desired electrical potential whilst giving the array a smoother feel due to its high elasticity.

The work performed shows that great potential exists for these fluids to be successfully employed within virtual environment systems, not only for the purposes of complementing the visual systems already available, but also in the form of stand alone devices such as Braille displays. Such devices could also be used to enhance man/machine interface systems in general. The' application of ER fluids in this field is particularly favorable in that they require very little power to operate, especially with the addition of fabric layers which has the additional advantage of increasing the electrical safety of the device in general. Also, the active devices are of simple design comprising few moving mechanical components. These factors indicate that ER fluid based virtual environment systems would be considerably less expensive than the other available options.

Clutches developed by the University of Hull

A clutch has been constructed with associated instrumentation in order to fully characterise its behaviour in terms of (a) steady state, (b) step response, (c) frequency response. The clutch was carefully designed and modelled which allowed the natural frequency of the equipment to be neglected in experimental results up to around 800Hz.

Extensive steady state, step response and frequency response tests were carried out for a number of ER fluids. From the tests carried out with the Rheobay fluid at a temperature of 24°C and a motor speed of 1,000rpm, the fluid showed a time constant of about 1 ms hence the natural frequency of the fluid was approximately 200 Hz. The results from the frequency response tests showed that the fli id. appears to have a mixed first and second order characteristic with a corner frequency of around 200Hz and hence an agreement between the two methods of testing has been observed. The other fluids tested showed similar characteristics with some showing slightly lower time responses.

The prototype test. rig demonstrated the capability of a clutch and enabled dynamic testing of various ER fluids. The equipment has a high natural frequency, approximately 1,000 Hz, and therefore dynamic tests were possible at electrical excitation frequencies up" to 600Hz. This led to a deeper. understanding of the time and frequency response characteristics of ER fluids.

Acoustic Effects investigated by Thomson Marconi Sonar

TMS SAS developed various ER fluid character zation tools to determine theological parameters which are necessary to assess ER flu ds for acoustic applications. The use of these innovative measurement tools led to an extensive knowledge of the acoustic behaviour of ER fluids under either DC or AC electric fields. Moreover, modelling of ER fluid based structures under steady or oscil atory shear strains has been performed for both mechanical structures (such as valves) and acoustical panels. Modelling of the electric field shape in ER fluids was performed using a project developed finite element (FE) software package.

Combination of the ER fluid measurement results and of the developed models led to the design of two highly innovative acoustic smart structures. Constitutive parameters of these two structures were optimized and prototypes were manufactured and acoustically characterised. The influence of the driving method on the acoustical performances was studied in order to achieve power supplies development guidelines. These feasibility studies allowed the evaluation of the techr ical and market potential of ER fluids for underwater acoustics.

4 EXPLOITATION PLAN

It is anticipated that the devices developed will have wide industrial applicability. Subject to the terms of the exploitation agreement, appropriate companies will be approached "in other industrial sectors to maximise the benefits of this research for the EC as a whole. It is considered that the main applications will be found in intelligent automation systems, control technologies, and semi-active systems.

Applications include

Tactile Array for Medical Training - for example, training surgeons/doctors in the identification of cancerous tissues.

Virtual Reality Systems - in which the various properties of ER fluids allow the conveyance of haptic feedback to the user of such systems.

Non-Linear Control Systems - ER fluid technology is a prime candidate for use in such devices because of high activation speeds and low energy losses. If the remaining technical problems can be solved with a low cost device there are potentially very large numbers of applications in motor drive trains.

Power Supplies for ER devices - providing the necessary designs for electronic control and power supply requirements for many applications which are specifically related to the use of ER fluids.

Linear Dampers - for the human environment, essentially ambient such as factories, offices, and warehouses. Typical guide specifications are masses up to 100kg, frequencies 1-20Hz, acceleration up to 2g, and velocities to 400 mm/see.

Anti-Vibration Devices -in the longer term remain an attractive possibility for ER fluids. however, there are still drawbacks to all Metzeler ER fluids which prevent their short term exploitation the automotive sector. These problems result from-the basic Metzeler fluid design, the use of dispersed solid particles such as Zeolites which cause wear and exhibit sedimentation after some weeks at rest.

Acoustic Systems -as it is now possible *to* modify the transverse shear waves propagation conditions of ER fluids. This unique property can be used in order to design smart acoustic windows or reflectors. The reflexion and transmission coefficients of those smart acoustic panels can be tuned electronically in order to give the structure particular behaviour versus incident acoustic waves.
Target markets are:

- underwater communication system (between vehicles, divers . ..).
- oceanography (multi-beam echo sounders),
- sonars for high-sea fishery.
- development of off-shore technologies for seabed exploration and exploitation

Contacts have been established in numerous areas, industrial and research, and it is hoped that these contacts will be ongoing. The results of the work will be communicated to interested partners via further publications, visits and general publicity. Some of the envisaged" applications may require further development of the existing technology.

Software

Software developed under this project tended *to be either* specific to equipment or of a refined technical nature and commercially confidential to individual partners. However, the University of Darmstadt are willing to provide the source code of the MAFIA and FIDAP programmed to interested parties.

ER Fluids

ER fluids developed by AFS are available to interested parties. on usual commercial terms. Development of the liquid crystal based ER fluid from the University of Hull is the subject of a UK government research submission. Metzeler have no plans to manufacture or distribute their ER fluids.

5 COLLABORATION SOUGHT

Areas in which more work needs to be undertaken and for which collaborators are sought are:

An investigation of the wide range of liquid crystal based ER fluids to see if other fluids can give even greater increases in yield strength (or lower voltages required from a certain yield).

An investigation of the use of fabric type structures within the ER fluid film and theoretical studies of the reasons behind the substantial improvement in the ER effect.

Development of the tactile array for medical applications such as training surgeons/doctors in the identification of cancerous tissues.

The use of ER fluid filled elements within flexible structures to give controllable compliance/vibration mode manipulation.

Development of the ER fluid based variable speed mechanism.

AFS have contacted a number of companies in specific industrial areas for the development of ER dampers. Generally the response has been favorable and in many cases project development work ensued. Further contacts are sought.

TMS SAS will try to have contacts with industrial companies, research centres and' universities performing research on ER fluid developments, especially' in the field of short response time ER fluids for AC-driven smart structures. Collaboration will be sought in order to keep on developing and improving ER fluids specifically for acoustic applications.

6 REFERENCES

Patents

ER fluid mount patent applied in Germany, 'Adaptives Hydrolager auf ERF-Basis", application no. 19617839.8,"03. May 1996

ER fluid decoupling module for ER fluid mounts and conventional hydromounts, patent applied in Germany, "Zweikammer-Motorlager mit Entkopplungseinrichtung", application no. 19617840.1, 03. May 1996

Journal papers

Hosseini-Sianaki A., Varley C.J., Taylor P.M., Lacey D., Malins C., "Comparison' of Electrorheological Fluids based on Silicone Oil and Liquid Crystalline Materials", Journal of Materials Chemistry, 1995, 5(11), 1853-1856.

Conference papers/presentations

Taylor P.M., Hosseini-Sianaki A., Varley, C. J., "An Experimental Investigation into the Application of Electrorheological Fluids in Tactile Display Systems", Proc. 5th International Conference on Adaptive Surfaces, Sendai, Japan, 5-7 December 1994.

Lacey D, Malins C, Taylor P.M., Hosseini-Sianaki A., Varley C.J., ."Investigation into the use of Liquid Crystalline Materials in Electrorheological Fluids", Proc. 5th International Conf. on ER Fluids, Magnetorheological Suspensions and Associated Technology, University of Sheffield, 10 - 14 July 1995.

Taylor, P.M., Hosseini-Sianaki, A., McKay K.R., Varley C.J., "A Variable Stiffness Element Utilising Electrorheological Fluid Enabling Tactile Feedback in Virtual Environments", Proc. 5th International Conference on Electro-theological Fluids, Magneto-theological Suspensions &Associated Technology, University of Sheffield, 10-14 July 1995.

Taylor P.M., Hosseini-Sianaki A., Varley C.J., "Surface Feedback for Virtual Environment Systems Using Electrorheological Fluids", Proc. 5th International Conference on Electro-theological Fluids, Magneto-theological Suspensions & Associated Technology, University of Sheffield, 10-14 July 1995.

Taylor P.M., Creed A., Hosseini Sianaki A., Varley C.J., "C-eating the illusion of shape for virtual environments", Colloquium on Innovative Actuators for Mechatronic Systems, IEE, London, 18 October 1995,-Digest no 1995/170, pp7/1 - 7/7.

Taylor P.M., Kaiser A.R., Hosseini-Sianaki A., Varley C.J., "Devices with Controllable Viscous Effects for Robotics and Virtual Reality", Automatic Robotics for Visco-Elastic Materials Workshop, 26-27 March, 1996, Málaga, Spain.

Lacey D., Malins C., Taylor P.M., Hosseini-Sianaki A., Vark y C.J., "A Study into the use of liquid crystalline materials in electro-rheological fluids", Materials Research Society 1996 Spring Meeting, April 8-121996, San Francisco (Presentation only based on earlier paper).'

Taylor P.M.; Hosseini Sianaki A., Varley C.J., "An Electrorheological Fluid-based Tactile Array for Virtual Environments", 1996 IEEE Conf. on Robotics and Automation, April 22-28, Minneapolis, Minnesota.