Single cell magnetorheological fluid based tactile display

Yanju Liu*, R.I. Davidson, P.M. Taylor, J.D. Ngu, J.M.C. Zarraga

School of Mechanical and Systems Engineering, University of Newcastle upon Tyne, Stephenson Building, NE1 7RU Newcastle upon Tyne, UK

Received 6 February 2004; accepted 20 October 2004
Available online 11 November 2004

Abstract

A tactile display is a programmable device whose controlled surface is intended to be investigated by human touch, as a finger is dragged over it. It has a great number of potential applications in the field of virtual reality and elsewhere. In this research, a prototype tactile display incorporating magnetorheological (MR) fluid has been constructed and investigated. Surface force responses of the tactile display under various magnetic fields have been measured while a probe was moved across the upper (controlled) surface. The purpose of this experiment was to simulate the action of a human finger’s touch. As the applied magnetic field was varied, the sensed surface profiles changed in synchronisation with the magnet field strength. This preliminary research provides a new practical and effective way of achieving a tactile display without any moving components.

Keywords: Tactile display; Magnetorheological fluid; Force response; Magnetic flux density

1. Introduction

Recent research in virtual reality has recognized the need for more realistic tactile displays [1]. A tactile display is a programmable device whose controlled surface is intended to be investigated by human touch. Such devices have the potential applications such as virtual training for surgeons [2], telemanipulation [3] and internet access [4] for the visually impaired where a simulated tactile image maybe required for the user to actually feel. Tactile display devices stimulate the skin to generate sensations of contact such as high frequency vibrations, shape, pressure distribution or temperature: they can provide force feedback and surface information to the user via the skin and the muscles. Researchers have proposed a wide variety of pin or vibrator arrays to present the sensation of three dimensional local shapes, fine textures, and slippage of grasped objects. These tactile displays use many actuating techniques, ranging from shape memory alloy [5], piezoelectric ceramic [6], electrorheological (ER) fluid [7], ionic conductive polymer gel film [8] or a simple mechanical approach using miniature electric motors [9].

The previous research work on ER fluid based tactile displays highlights the possibility of constructing a tactile display in a very simple way—there are no moving components and few accessories for its operation. Though the ER fluid tactile display has excellent performance, there are still some disadvantages to limit its application such as high driving voltage, lower yield stress and the requirement for the fluid and components to be strictly free from impurities. To overcome these problems, using MR fluid as an alternative actuating method was proposed.

Magnetorheological (MR) fluids are suspensions of micron sized ferromagnetic particles dispersed in varying proportions of a variety of non-ferromagnetic fluids. MR fluids exhibit rapid, reversible and significant changes in their rheological (mechanical) properties while subjected to an external magnetic field. As with ER fluids, the MR fluids are also in liquid state without external stimuli. While MR fluids are subject to an magnetic field, they behave as solid gels, typically becoming the consistency of dried-up toothpaste. Recent MR fluids are becoming increasingly important in applications concerning active control of vibrations or switching/control of torque/force. Devices such as dampers, shock absorbers, isolators,
clutches and brakes have all been designed [10,11]. Some of them are commercially available in the market now. However, the challenges of producing strong magnetic fields over large surface areas still remains: this limits the application of MR fluid based devices to those with particularly advantageous geometries, such as concentric (piston and tube) vibration control ‘dampers’, controlled concentric ‘clutches’, etc. In recent years, MR fluid based haptic displays and haptic interfaces have been investigated by some researchers. Carlson and his colleagues have designed a prototype of portable hand and wrist rehabilitation device based on MR fluid has been proposed [12,13]. Also, some researchers used MR fluid to construct a haptic display to replicate perceived biological tissue compliance [14,15].

In this research, a prototype of single cell MR fluid based tactile display has been designed, constructed and tested. The surface force response of the display has been measured. This work is the preliminary research for the future development of an MR fluid based tactile array.

2. MR materials

A typical MR fluid contains 20–40% by volume of relatively pure, soft iron particles, e.g., carbonyl iron; these particles are suspended in a mineral oil, a synthetic oil or in water. MR fluids undergo a change in rheological behavior if an external magnetic field is applied. The mechanism responsible for this significant effect is the induced magnetic polarization of particles within the fluids. Upon application of a magnetic field, the particles become magnetized and align themselves roughly parallel to the imposed magnetic field. The rheological properties of MR fluids are dependent on such factors as the mechanical and magnetic properties of magnetic particles, the viscosity of the continuous fluids, the proportions of each substance in the fluid, any additives, as well as the mixing process of the fluids. Typically, the properties of MR fluids vary from a viscosity of 0.2–0.3 Pa s at 25 °C without implied magnetic field to a dynamic shear yield strength of 50–100 kPa with an applied magnetic field of 150–250 kA/m (2–3 kOe). Higher magnetic saturation materials can lead to an increase in the maximum dynamic yield stress. As with an ER fluid, a simple Bingham visco-plastic model is effective at describing the essential field-dependent fluid characteristics [16]. In this model, the total shear stress is given by:

\[
\tau = \tau_0(H) \ \text{sgn} \ (\dot{\gamma}) + \eta \dot{\gamma}
\]  

(1)

where \(\tau_0\) is the yield stress caused by the applied field (N/m²), \(H\) is the magnitude of the applied magnetic field (A/m), \(\dot{\gamma}\) is the shear strain rate, \(\eta\) field-independent plastic viscosity, is defined as the slope of the measured post-yield shear stress versus shear strain rate.

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress @ 25 °C, 240 kA/m</td>
<td>70–90 kPa</td>
</tr>
<tr>
<td>Plastic viscosity</td>
<td>100–400 mPa/s</td>
</tr>
<tr>
<td>Magnetic induction, (B) @ 25 °C, 240 kA/m</td>
<td>1 T</td>
</tr>
<tr>
<td>Operable temperature range</td>
<td>−40–150 °C</td>
</tr>
<tr>
<td>Contaminants</td>
<td>Unaffected by most impurities</td>
</tr>
<tr>
<td>Response time</td>
<td>Less than several milliseconds</td>
</tr>
<tr>
<td>Density</td>
<td>3.42×10³ kg/m³</td>
</tr>
</tbody>
</table>

In this paper, the MR fluid used is VersaFlo™ MR-100 fluid (Lord Corporation, Cary, NC, USA). The typical properties of this kind of fluid are listed in Table 1.

3. Construction of the MR fluid based tactile display

To generate an MR effect, the design of the magnetic field generator is important. In this paper, two different designs of electromagnets are used to provide the magnetic field for MR fluid. One design is an open loop core type, the other design is based on modified commercial solenoid.

3.1. Open loop core type

Fig. 1 is the schematic diagram of the magnet designed. The open loop core is made of low carbon steel which has high magnetic permeability and saturation. To generate enough magnetic field to produce a satisfactory MR effect, the coil’s turns number is determined by theoretical modeling by considering such factors as the nonlinear magnetic properties of the MR fluid and core, fringing of magnetic flux and possible losses at junctions and boundaries. For this magnet, a coil of 2000 turns of 0.5 mm copper wire was used. The magnet was 70 mm in width, 10 mm in thickness with an open area of

![Fig. 1. Schematic of the open loop core type magnet.](image)
10×10 mm² (maximum). The magnetic flux density at the central point of the core gap is measured by a Gaussmeter. The Gaussmeter has a flat flexible probe whose sensing area is about 3×5 mm². While measuring the magnetic flux flow vertically into the sensing plane of the probe. Fig. 2 shows the distribution of magnetic field along the magnet’s width with input current of 0.4 A. In Fig. 2, the X axis datum (zero position) is the central point of the core gap. It can be seen that the maximum magnetic flux which passes through the MR fluid appeared at the edge of gap area.

3.2. Modified solenoid type

As shown in Fig. 3, this design used a modified 3W solenoid (RS Components Cat. No. 250-0669) with a variety of different pole pieces to obtain different magnetic pole geometries. For the majority of tests conducted, an outer poles piece with inner diameter of 4.6 was selected. Compared with the open loop core design, this magnet is small in size and this gives the possibility of constructing a compact MR fluid based tactile display array for future work.

The main frame of the tactile display was made of aluminium which has a relatively low magnetic permeability. MR fluid was poured into a machined aluminium tray with 0.5 mm thick base adjacent to the electromagnet. A flexible membrane enclosed the MR fluid within the tray and was clamped to the tray’s edge by a retaining ring. In this research, the flexible membrane was 0.24 mm thick neoprene rubber sheet with the underside protected by a 0.014 mm thick latex sheet in contact with the MR fluid. The thin layer of latex was used to reduce the swelling of main neoprene rubber sheet caused by the oil in MR fluid.

4. Experimental apparatus

Force measurement on the surface of the tactile display simulated the action of a human finger. Preliminary results and experience gained from the previous work indicated that it is sufficient and effective to examine the effect of the fluid as the probe moves along the surface, i.e. drag testing. For this purpose, the surface of the display was explored over a path in the middle of the surface. A force sensor (Interface SMT-50) is used to measure the forces in vertical direction. This sensor is based on temperature compensated strain gauges load cell with 50 N capacity. Meanwhile, in order to simulate the passage of a finger, a roller probe with adjustable vertical compliance was used. The probe’s roller was 20 mm in diameter and 8 mm wide.
Fig. 4 shows the arrangement of the test rig. The tactile display is fixed on a controllable X–Y table which was moved at a controlled speed whilst the force experienced by the force probe was monitored. The force sensor is positioned above the tactile display and could moved up and down by a stepper motor and threaded shaft. Force sensor’s output data were captured through a Microlink 4000 series waveform capture and analysis system. This system is a commercial, purpose designed modular data acquisition system specially for high speed waveform capture.

5. Results and conclusions

While performing the scanning test, the probe was moved along the central line of display’s surface from left side to right side and then moved back to its starting position. Please note that in all the graphs presented in this part, the distance ‘zero’ point is the reversing position located on the right side of the scanning path.

5.1. Open loop core magnet results

Fig. 5 shows the surface force response of the tactile display under various driving magnetic fields. The magnetic flux density ranges from 0 to 0.13 T. The results were obtained by exploring the surface with the roller probe in the stiff state with an initial contact force of 0.36 N. It is clear that the higher the magnetic field, the higher the response force level. Since two-way scanning was performed while monitoring the force response, it can be seen from the Figure that the responses of forward and reverse scanning have are little different. While the probe scanned across the surface, the fluid was pushed away from the path/location scanned, but because the MR fluid is viscous, it could not return to its original location immediately after the probe passed: this cause some changes in the sensed surface profile. Also, the upper flexible surface of the tactile display was not completely flat. For all these reasons, the forward and reverse responses were different. In addition, it can be found that the response have two peaks for each direction scanned. This is a reflection of the strength of the magnetic field around the pole edges. The magnetic flux density shown in this Figure is the value at the middle position of gap of the magnet.

The force response is also depended on how much initial vertical contact force is applied to the probe. Fig. 6 shows the effect of the contact force on the force response. For these tests, the magnetic flux density is 0.13 T and the probe in the stiff state was selected. The force response did not give a clear peak if the initial contact force was too low. If the initial contact force was too large, more and more noisy
peaks appeared. To determine whether the flexibility of the roller probe affects the measuring sensitivity, the surface force response was measured with the roller probe set to different flexibilities. As shown in Fig. 7, though the form of each trace is similar, the recorded responses still show some differences. For the response obtained with the most flexible probe, it can be seen that the two response peaks in the forward scanning cannot be separated well. Hence, it is important to select an appropriate flexibility to obtain the maximum sensitivity.

Several tests were also performed to investigate whether the response was be affected by different scanning histories, i.e. was there a ‘memory effect’. Fig. 8 shows the result of the tactile surface with a scanning history: scan with 0.13 T magnetic flux density, then power off (remove magnetic field) for 30 s, then apply 0.13 T magnetic flux density and scan again. This Figure shows that the responses during the reverse scan are nearly the same for both scans, while the responses during the forward scans are different. The difference is thought to be caused by the redistribution of the MR fluid during the first forward scan, causing a build up of MR fluid under the membrane near the clamped edge, so causing the membrane to bulge up and give a increased force reading. This effect was only apparent on the first pass of the probe, leading to the supposition that it was a excess of unaffected (i.e. un-solidified) MR fluid that was responsible for this effect. In Fig. 9, three full round scans are performed. For each round trip, during the forwards scan, 0.13 T magnetic flux density is applied to the MR fluid, but during the reverse scan, no power was applied. The most interesting result obtained from this test is that the change of responses during the reverse scan. In first round, there is only a very tiny double-peak response, while with the other two rounds’ proceeding, this double-peak response become larger and larger. This may indicate that for each power on state, a little amount of MR fluid is accumulated around the region subjected to magnetic field due to residual magnetism or hysteresis in the magnetic circuit or MR fluid. This may account for the force response of this area becoming larger with the number of applications of power (magnetic field) and scan passes. With a continuously applied magnetic field, a five-return trip repeated scan was performed: the results are shown in Fig. 10. The results
show stable and repeatable responses for each scanning path. Though the response forces are not identical during the first two or three scanning rounds, they are similar and tend to a constant level after more scans.

5.2. Modified solenoid type magnet

Figs. 11–13 show the test results for the MR fluid tactile display powered by the modified solenoid type of electromagnet. Since this kind of magnet is quite small in size, the area of MR fluid activated by magnetic field is smaller than that of previously described magnet. Also, as the outer pole size used in these tests was 4.6 mm diameter, it was difficult to measure the distribution of magnetic field around the whole area. The magnetic flux density indicated in the results is the maximum value in the activated area. These results are similar to the previous ones. From Fig. 11, it can be seen that the force response does not have a single peak. Unlike the results of the other kind of magnet, those lower peaks may be due to the flexible membrane material itself rather than forces coming from the MR effect. However, the geometry of the magnet poles means that there was possibility that, under certain assembly conditions, the position of the magnetic components was not exactly as intended and that these errors affected the results.

6. Conclusions

A single cell MR fluid based tactile display has been developed in this work. Two kinds of electromagnets were designed and used to activate the MR fluid. When a magnetic field was applied, a small bump could be easily felt by dragging a finger over the display’s surface. Surface force responses of the tactile display have been explored while a probe is moving across the upper surface.

The main conclusions of research are:

† MR fluid is suitable for use as an actuator in a tactile display;
† Both kinds of magnets can generate an MR effect for the tactile display sufficiently and effectively;
† The displayed surface information is stable and repeatable;
† The testing method is sufficiently effective and sensitive.

Though there are still problems to be solved in order to optimize the MR fluid based tactile display, all these results are encouraging and show the possibility of constructing a compact MR fluid based tactile array in future research.

Acknowledgements

The work reported in this paper was funded by the British Government under EPSRC Project ‘Interactive Smart Surfaces’.
References


