Apparent stress-strain relationships in experimental equipment where magnetorheological fluids operate under compression mode

S A Mazlan, N B Ekreem and A G Olabi
School of Mechanical and Manufacturing Engineering, Dublin City University,
Glasnevin, Dublin 9, Ireland

E-mail: saiful.mazlan2@mail.dcu.ie, nasser.ekreem2@mail.dcu.ie and
abdul.olabi@dcu.ie

Abstract. This paper presents an experimental investigation of two different magnetorheological (MR) fluids, namely water-based and hydrocarbon-based MR fluids in compression mode under various applied currents. Finite Element Method Magnetics was used to predict the magnetic field distribution inside the MR fluids generated by a coil. A test rig was constructed where the MR fluid was sandwiched between two parallel cylinders. During the compression, the upper cylinder was moved towards the lower cylinder in a vertical direction. Stress-strain relationships were obtained for arrangements of equipment where each type of fluid was involved, using compression test equipment. The apparent compressive stress was found to be increased with the increase in magnetic field strength. In addition, the apparent compressive stress of the water-based MR fluid showed a response to the compressive strain of greater magnitude. However, during the compression process, the hydrocarbon-based MR fluid appeared to show a unique behaviour where an abrupt pressure drop was discovered in a region where the apparent compressive stress would be expected to increase steadily. The conclusion is drawn that the apparent compressive stress of MR fluids is influenced strongly by the nature of the carrier fluid and by the magnitude of the applied current.

1. Introduction

Controllable fluids are materials that respond to an external field. When exposed to an electric or magnetic field, their rheological behaviours exhibit remarkable changes. These materials are commonly referred to magnetorheological (MR) fluids, electrorheological (ER) fluids and ferrofluids. Amongst these smart fluids, MR fluids receive more attention since they can cause higher yield stresses and can be applied into many applications (Sims *et al* 1999, Jolly *et al* 1999). These materials consist of magnetically permeable particles dispersed throughout the carrier medium either a polar or non-polar fluid, which then influence the viscosity of the MR fluids. Iron powder is the most popular material to be used as the particles due to its high saturation magnetization. Under the presence of the magnetic field, a magnetic dipole moment of the micron-sized particles is induced, so that dipole interactions are created between the particles. The particles form chains which are coordinated according to the flux paths (Hagenbuchle and Liu 1997). This formation is restricts fluid movement.

Although shear mode has been studied thoroughly by many researches, compression mode is becoming one of the most interesting modes to be investigated. The advantage of this mode is the attainment of high stresses as compared to shear mode under the same external field strength (Tian *et al* 2003). Under compression mode, many factors contribute to the variable stresses, such as ratio of solid suspension to carrier liquid (Monkman 1995), initial gap distances (Tian *et al* 2003) and external field strength (Hagenbuchle and Liu 1997, Nilsson and Ohlson 2000, Kulkarni *et al* 2003). Monkman (1995) has considered the compressive effect for different types of ER fluids and observed that the hardness modulus of the fluids increases as the gap closes. Furthermore, the sizes of the particles also cause a significant effect on the shear stress. Higher stresses can be obtained with coarser particle sizes (Genc and Phule 2002).

From another point of view, the studies of compressive stress of MR fluids in squeeze mode conducted by many researches were mainly on squeeze film dampers for rotor applications (Forte *et al* 2004, Ahn *et al* 2004, Carmignani *et al* 2006). They worked on the performance of the squeeze film damper in dynamic behaviour according to the magnetic field strength. Forte *et al* (2004) have been carrying out a preliminary test to obtain the optimum conditions for each steady rotational speed of MR squeeze film damper. Latter, Carmignani *et al* (2006), continued to work on the effectiveness in dampening the rotor vibrations and controlling its dynamic characteristics. In any event, however, not many people have done experiments in quasi-static tests to characterize MR fluid under compression stress. In consequence of the potential commercial impact of MR fluids, it is essential to understand the fluid behaviour at ranges of values which are valid during the compression mode operation. In previous work, we reported on a unique behaviour of MR fluids under compression on the basis of a water-based MR fluid with respect to different applied currents and starting with different gap sizes (Mazlan *et al* 2007). Therefore a further study of MR fluids in squeeze mode with other factors was needed. In this paper, experimental investigations of two types of MR fluids under various applied currents have been carried out.

2. Experiment

The apparatus employed in this study is the same as that used in our previous report (Mazlan *et al* 2007), and is depicted in figure 1. MRF-241ES (a water-based MR fluid) and MRF-132DG (a hydrocarbon-based MR fluid) were used in these experiments. They are produced by the Lord Corporation. Typical magnetic properties of both materials are shown in figure 2. Magnetic density of the MRF-241ES exhibits greater values for a given magnetic field strength compared to the MRF-132DG. This is due to the higher particle density of the MRF-241ES (3.80 to 3.92 g/cc) compared to the MRF-132DG (2.98 to 3.18 g/cc). All experiments were carried out in a displacement control mode. An analysis of the magnetic field inside the MR fluids was performed using Finite Element Method Magnetics. The magnetic field distribution within the fluids is shown in figure 3. This figure shows the variation of the flux density when the applied current to the coil was set at 1.6 Amp while the gap size was set at 2 mm.

Two sets of experimental trials have been accomplished. In both sets, the initial gap size between the two cylinders was adjusted to 2 mm. In the first set, the compression of the MR-241ES was carried out by pressing down the upper cylinder at a constant speed of 0.5 mm min^{-1}. Different trials were conducted with different currents in the coil, but the current was constant for each trials. Current values of 0.8, 1.2 and 1.6 Amps were applied. In the second set of experimental trials, the same procedure was applied except that the sample was changed to the MRF-132DG. During compression, the applied current *I* was kept constant and the experiment was stopped when the final gap sizes reached about 30% of the initial gap size for the case of the 241ES fluid, and 70% of the initial gap size for the 132DG fluid.

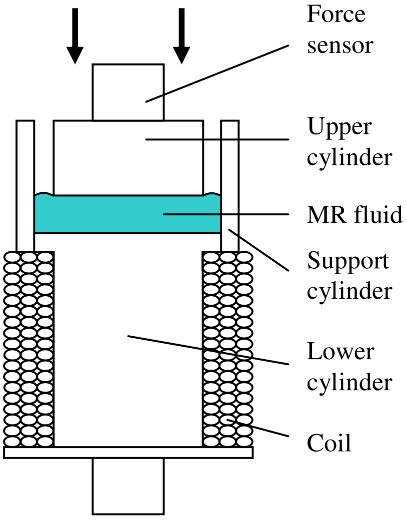


Figure 1. Sketch of the experiment apparatus.

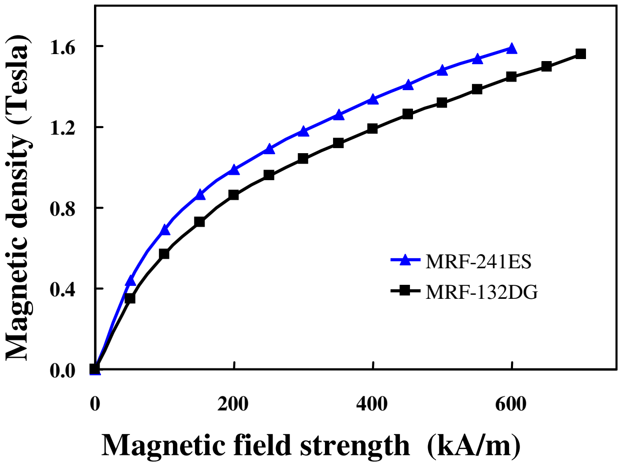


Figure 2. Magnetic induction curves for MRF-241ES and MRF-132DG.

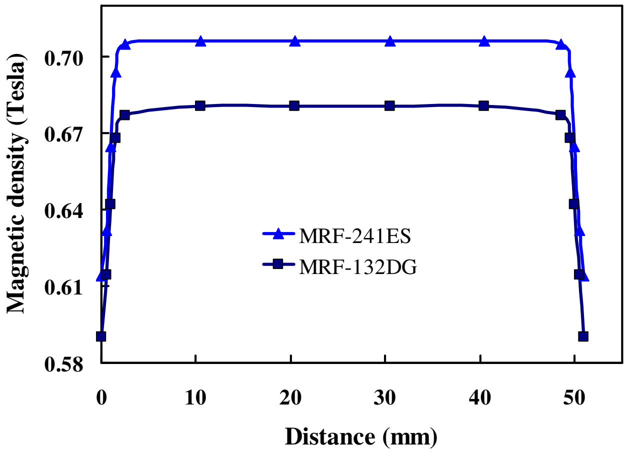


Figure 3. Magnetic field distribution inside the MR fluids in the middle of two cylinders through a straight line perpendicular with the plane of compression.

It is true that the only type of compressive stress experienced by a liquid is volumetric compressive stress which is pressure, and this was not measured at any stage in the work. Similarly the compressive strain exhibited normally by liquids is volumetric compressive strain which is related to the compressibility of the liquid.

Because of this, it would be better to refer to the compressive stress as an apparent compressive stress, to be understood in terms of an analogy with solids which deform easily. If the compression mode arrangement is examined in greater detail, this compressive stress can be shown to be related to the pressure experienced by the MR fluid, but a single value of the compressive stress measured by the experimental arrangement, indicates that various regions of the MR fluid are experiencing different values of pressure. Near the centre line of the equipment the pressure is very intense, but near the outside rim, the pressure is close to atmospheric pressure. This difference in pressure causes the fluid to accelerate, and some the forces opposing this movement are related to the viscosity of the fluid. The apparent compressive stress is also therefore related in a complex way with the viscosity of the fluid.

Similar complications exist in the relationships between the apparent compressive strain and the fundamental fluid properties. The compressibility of the liquid is almost certainly so small that its effect on the apparent compressive strain is negligible. The major effect is the displacement of the liquid from the region between the upper and lower cylinders to a region outside this. While the compressive strain is applied at a constant rate, the actual fluid velocity will change depending on the region of the fluid and the instantaneous value of the apparent compressive strain. Near the centre line of the equipment velocities will be low, but near the rim, the velocities will be high. When the apparent compressive strain is low fluid velocities will be comparatively low, but at high values of the compressive strain, the fluid velocities will be much greater. With each value of the fluid velocity, there will be values of the shear rate. Therefore, to some extent, the apparent compressive strain bears a complex relationship with the different shear rates experienced by the fluid. A further complication occurs because, in the presence of a magnetic field, there will be a tendency for the carrier fluid to move leaving the magnetic particles behind. The apparent compressive strain is also, therefore, an indication of the ratio of the amount of solid particles to the amount of liquid in the MR fluid.

It follows that when the relationship between apparent compressive stress and apparent compressive strain is being examined, it is difficult to draw any conclusions about the relationships between the fundamental characteristics of the MR fluid. Instead, the measurements are closely related to the characteristics of the experimental arrangements, and it is difficult to apply the results to other experimental arrangements. Probably the only safe conclusion that can be drawn from the results is that in the so-called constant region, the viscosity of the fluid remains almost constant even though the various shear rates and the solids to liquids ratios are increasing. From this point onwards in the paper, where expressions such as compressive stresses and strains occur in the paper, and they refer to the MR fluid, they are to be understood to be, strictly speaking, apparent compressive stresses and strains.

3. Results and discussion

Compressive stress versus compressive strain for both materials is depicted in figure 4. At the beginning of compression, both curves show a slow increase as the compressive strain increased. Then the compressive stress became almost constant before proceeding to increase tremendously.

Each experimental set of trials showed a similar behaviour for the compressive stress throughout the applied current range from 0.8 to 1.6 Amps. Figures 5*(a)* and 5*(b)* show the changes in the compressive stress versus compressive strain characteristic as the applied current increases. A higher value of the stress-strain line can be achieved at a higher value of current.

The magnetic field strength H can be determined by using the following equation (Kraus 1991):

$$NI = \oint H dl \qquad (1)$$

During an experimental trial, the number of turns N and the current I are fixed. The total length of the flux path l consists of the length of the solenoid which is fixed, the size of the gap, and the length of the return path for the magnetic flux, which does not change very much during an experimental trial. It is also true that, for a given size of the gap, since most of the geometrical features of the experimental arrangement do not change, the values of the magnetic field strength, H, in each component of the flux path remain approximately proportional to each other. Finally the sum of the reluctances in each part of the flux path, the right hand side of the above equation, is dominated by the very large component representing the return path of the flux, because this is mostly through non-magnetic materials. Therefore, it is approximately true that the magnetic field strength H in the gap is proportional to the value of the current set for the trial. It follows then that a higher value of the stress-strain line occurs when the magnetic field strength is higher. Similar experimental results to ER fluid have been reported for the case of ER fluids by Tian *et al* (2002). They found that at high compressive strains, compressive stresses increased significantly as the electrical field strength increased.

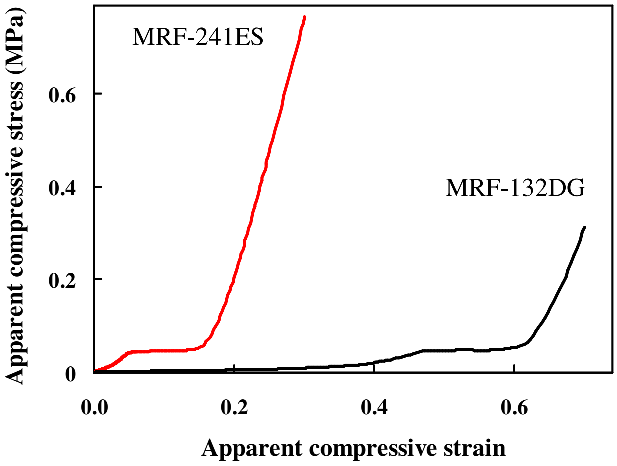
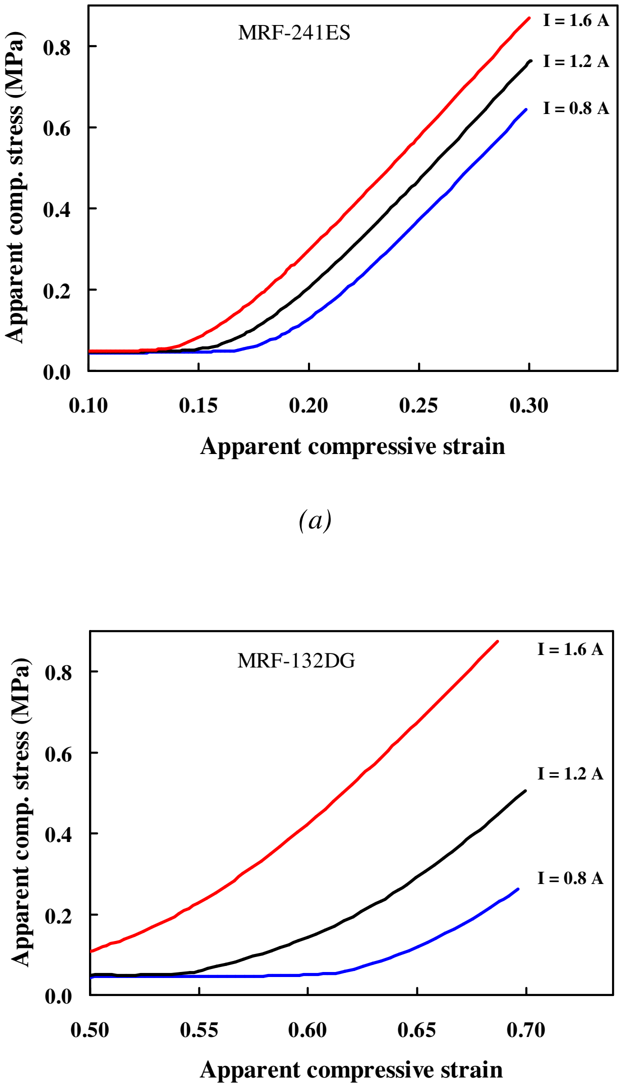


Figure 4. Curves for both MR fluids when the applied current was set to 1.2 Amps.



(a)

(b)

Figure 5. Apparent compressive stress of compressions of *(a)* MRF-241ES and *(b)* MRF-132DG.

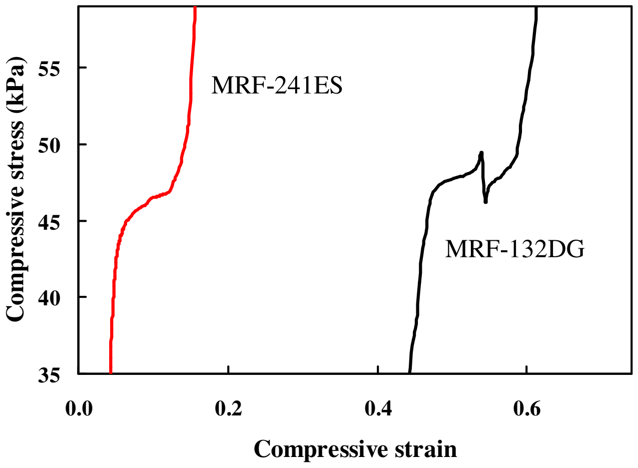
The basic phenomenon of the MR effect is understood to consist of the following. Under the influence of a magnetic field, the particles, which are initially in random positions, form chains along the field direction, and later these chains, tend to form into thicker structures. These formations in the MR fluids are reversible, but as the magnetic field increases, there is growth in the structures from single chains to columns and then thicker columns.

In general, the responses of the MR fluids to compressive strains can be divided into three regions. The first and second regions of the compression can be interpreted as the interaction of the fluid movement with the particles arranged in single chains, and in the third region the particles are arranged in thicker structures. It is assumed also that the behaviour occurs because of the relative movement between the particles and the carrier liquid in the MR fluid as described by Mazlan *et al* (2007), in which there is an increase in the ratio of solids to liquid.

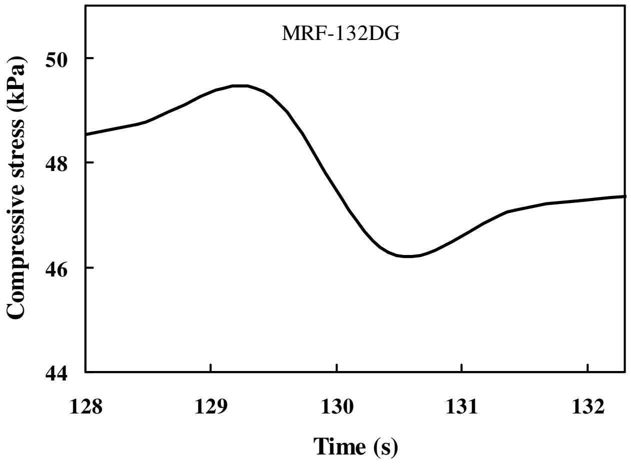
However, different values of compressive stress can be achieved by different sets of conditions. For instance, figure 4 shows that the MRF-241ES and the MRF-132DG started to experience large compressive stresses at very different values of compressive strain. In one case it was at a strain value of approximately 0.15, and in the other case it was at a strain value of about 0.62. It seems clear that the increases in the compressive stress at these particular points are due mainly to the values of the ratio of solids to liquid in the fluids. The two liquids started off with very different ratios of solids to liquid, and this factor, amongst others, gave them their different magnetic properties. By the process described in the preceding sentences, the ratio of solids to liquid in each fluid was steadily increasing. It is probable that at a certain critical value of the solids to liquid ratio, the point is reached when the compressive stress suddenly increases, while the compressive strains continued to increase at a steady rate. (These points occur at the beginning of the third region.) Since one of the MR fluids started off with a comparatively high solids-to-liquid ratio, it reached this critical value at quite a low value of the compressive strain. Consequently the 241ES fluid shows this characteristic response at a much lower value of the compressive strain when compared with the 132DG fluid.

It follows that one could make an MR fluid with magnetic particles composed of a material with a saturation of magnetisation which is lower than iron. If one then made a second MR fluid with iron particles, its magnetic properties would be superior. However if the second MR fluid had a lower ratio of solids to liquid, this would compensate for the difference in magnetic properties, and the two fluids could be tuned to have identical magnetic properties. However when working with the two materials in compression mode, the fluid with the particles with poorer saturation properties and starting with a higher solids to liquid ratio would reach the critical value of this ratio after only a small compressive strain value had been reached. The other fluid would reach this critical ratio after a much larger amount of compressive strain.

Referring to figures 5*(a)* and 5*(b)*, the 241ES shows a small variation in the compression curves in response to changes in the current in the coils, while the 132DG fluid was affected by the changes in the applied current more dramatically. Probably, this is due to changes in the magnetic field strength, which in turn has an effect on the interaction of the particles with the movement of the fluid. For the case of a fluid with a lower ratio of solids to liquid (MRF-132DG), the compressive stress is mainly determined by the strength of magnetic field but the influence of this factor is less significant for the fluid with the higher ratio of solids to liquid (MRF-241ES). The factor of greater significance for this fluid is the steadily increasing solids-to-liquid ratio.



(a)



(b)

Figure 6. In (a) the data, already given in figure 4, is scaled to show details in the range of values of compressive stress between 40 and 60 kPa. in *(b)* the compressive stress versus time data is given for the 132DG fluid.

Values of the compressive stress of the 132DG fluid suddenly dropped during the second region, at about 50 kPa and then continued to increase again as shown in figure 6*(a)*. Since the particles are all approximately the same size, it is expected that the force required to break a chain composed of a single column of them would be of approximately the same magnitude throughout the volume occupied by the MR fluid. Also, as mentioned earlier, various regions of the fluid will move with very different velocities. Because of this, since the resistance to flow is mainly due to viscosity, the force tending to break apart the chains of particles will be much greater in a region of high velocity and much smaller in a region of low velocity. However the effect of a pressure drop phenomenon as large as that shown in figure 6*(b),* if it were caused by particle chains being broken*,* would have to be caused by a substantial number of chains being broken in a very short period of time. In view of these facts, it would seem statistically improbable that the pressure drop effect could be due to a large number of single column chains of particles being broken almost instantaneously by forces resisting the movement of the MR fluid. It is more likely that this is the explanation for the occurrence of the whole of the second region in the stress-strain relationship. The chains of particles are broken successively beginning in those regions where the velocity is greatest and moving to regions where the velocity was originally smaller but increases as the size of the gap decreases.

An effect similar to the pressure drop effect could be caused by air bubbles, originally in the MR fluid, being expelled from the region between the upper and lower cylinders. These air bubbles would introduce a small amount of compressibility as noted by Tang *et al* (2000), and this might explain the observed phenomenon. It also has been reported by them that MR fluids based on hydrocarbon carriers are very difficult to bleed satisfactorily, so that all air bubbles are removed. However, when the experimental trials were repeated, the same pressure drop was observed, and this would suggest that the same amount of air bubbles were present again and were expelled in the same way. In this work, no special attempts were made to expel air bubbles from the equipment before the experiments. In fact the equipment was not designed to allow for such a procedure to be carried out.

According to Lukkarinen and Kaski (1998), thicker structures may occur in a system with a small gap size between the two plates. Thus, at the beginning of compression, the gap is considered to have a large size and this occurs during the first and second regions. The stress-strain relationships for these regions are similar, but during the third region, as the gap size decreases further, the stress-strain relationship changes. Based on this consideration, the thick columns occurring in the third region are assumed to be the main structure, and are responsible for the changes in the stress-strain relationship. Hagenbuchle and Liu (1997) have reported that chain formation also depends on the applied field strength. As the applied current increases, there is also an increase in the magnetic field strength, and so the tendency of the particles to form thick columns also increases. This explains why the change from the second to the third region also depends on the size of the current.

4. Conclusion

The influences of the applied current on two types of MR fluids under compression mode have been experimentally investigated. Experimental results emphasize that the magnitude of the compressive stress of MR fluids is strongly affected by the nature of the carrier fluid and the magnitude of the applied current. Compressive stresses in the MR fluids are higher when the applied current is higher. The stress-strain lines for the 241ES fluid are almost parallel, while the stress-strain curves for the 132DG fluid have variations in their gradients. Furthermore, the compressive stress in the 241ES fluid, in response to a given value of the compressive strain, is of greater magnitude than the compressive stress in the 132DG fluid responding to the same compressive strain. This result, occurring at the same value of the magnetic field strength, is probably due to the higher ratio of solids to liquid in this water-based fluid (241ES) when compared to the hydrocarbon-based fluid. In all cases, during the compression, the 241ES fluid showed a more stable behaviour while the 132DG fluid experienced a very sudden drop in the compressive stress in a region where the compressive stress would be expected to rise steadily before proceeding to increase again abruptly.

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