

2012-9

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Dave Gorman

Technological University Dublin, david.gorman@tudublin.ie

Stephen Jerrams

Technological University Dublin, stephen.jerrams@tudublin.ie

Ray Ekins

Technological University Dublin

Niall Murphy

Technological University Dublin

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Recommended Citation

D. Gorman S. Jerrmas R. Ekins and N. Murphy (2012). "Magnetic field design Reliable data for magnetic field design in magnetorheological elastomer damping applications is essential for accurate and cost-efficient operation " tire technology international 2012: 20-22.

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Magnetic field design

Reliable data for magnetic field design in magnetorheological elastomer damping applications is essential for accurate and cost-efficient operation

by Dave Gorman, Steve Jerrams, Ray Ekins & Niall Murphy, Center for Elastomer Research DIT Ireland

The importance that the applied magnetic field has on the changes in mechanical properties of any magnetorheological (MR) based device has been the subject of much research. As both the flux density and the direction of magnetic flux contribute to the overall MR effect, detailed and accurate data on the properties of the magnetic field need to be measured and specified for both effective physical testing of magnetorheological elastomers (MREs) and for the successful operation of MRE-based dampers and vibration isolators. Consequently, critical insights are provided into the design of an electromagnetic array for use in the biaxial testing of MREs under a suitable magnetic field. Data obtained from equi-biaxial dynamic testing of MREs is essential because it represents conditions experienced in real-world applications.

MREs are smart composite materials comprising both an elastomer matrix and ferromagnetic particles, which undergo a change in mechanical properties in the presence of an applied magnetic field.¹ Interaction of the ferromagnetic particles with each other (dipole-dipole interactions) and the applied magnetic field cause an instantaneous and reversible change in mechanical properties of the MRE and this is known as the MR effect.²

MREs can be subdivided into two categories: isotropic, which contain a homogeneous distribution of particles; and anisotropic, which

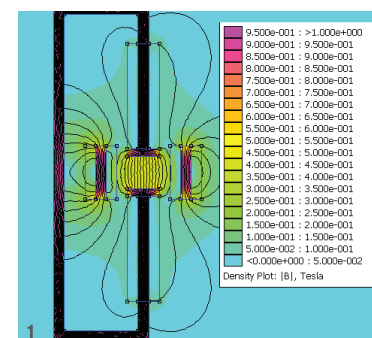


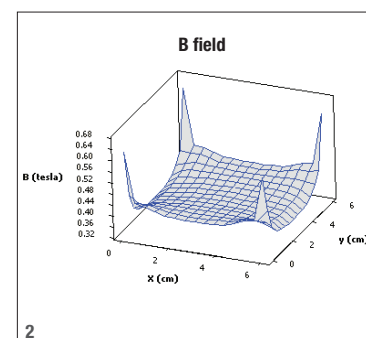
Figure 1: Electromagnetic array⁶

Figure 2: Plot of flux density

Figure 3: Modified array

contain aligned particle chains. The formation of the particle chains in anisotropic MREs is due to a magnetic field being applied during the curing process. The particles align in the direction of the applied field and are locked in position once the elastomer matrix is cured.³ The greatest overall increase in the elastic modulus is found for anisotropic MREs when the direction of the applied field is parallel to the aligned particle chains.^{1,3} The larger the variation in the elastic modulus, the greater the range over which an MRE damper can operate, therefore anisotropic MREs with magnetic fields applied parallel to the particle chains offer the greatest potential for MRE-based damping applications. MREs have a number of properties that make them suitable for use in variable dampening applications such as the immediate increase in the elastic modulus once the magnetic field is applied. As stated, this stiffening is completely reversed when the field is switched off.⁴

As well as this change in mechanical properties, MREs offer some advantages over their magnetorheological fluid (MRF) counterparts. Due to their solid state, the particles are not subject to sedimentation as with MRFs, and they eliminate the need to be contained within a vessel. Dynamic testing by Chen *et al*⁴ showed that damping ratio is influenced by the elastomer matrix. Tests on MRE-based, tuned vibration absorbers showed that using natural rubber as the matrix material in



MRE fabrication provided lower damping ratios and hence greater vibration reductions, making it ideal for an MRE-based damper.

Up to now, physical testing of MREs has been primarily confined to the uniaxial load case, although biaxial loading provides a more representative measure of the behavior of MREs in real-world applications and therefore allows more reliable predictions of fatigue life and other dynamic properties.⁵

Data from physical tests on MREs to date are of questionable value due to the paucity of information about the magnetic field applied during testing. Irrespective of the magnetic field applied, a magnetic flux density has a specific maximum value at a point and this value will fall away with movement away from that point in any direction. Hence if it is stated that a test on a sample of MRE is performed in a magnetic field of, for example, 400mT, this provides no information about the depth of that field or the change in flux density in mutually perpendicular planes.

To test MREs under biaxial loading using the bubble inflation method, the magnetic field must exhibit a uniform flux density (within acceptable limits) over the entire sample volume and act in a single direction.⁶ The larger sample volumes of biaxial test pieces compared with their uniaxial counterparts require more complex magnetic arrays to generate a uniform field due to the flux being proportional to $1/r^2$ where r is the distance from the

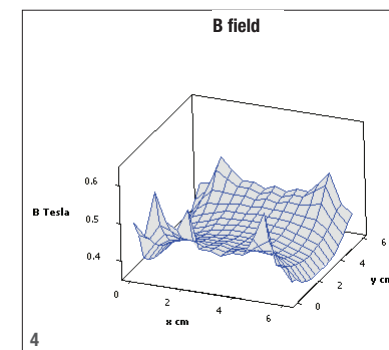
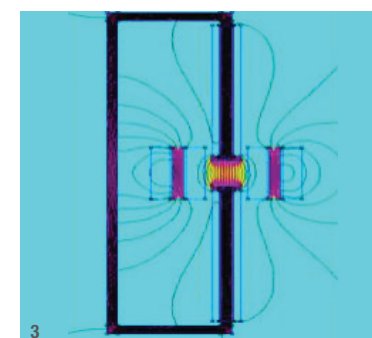
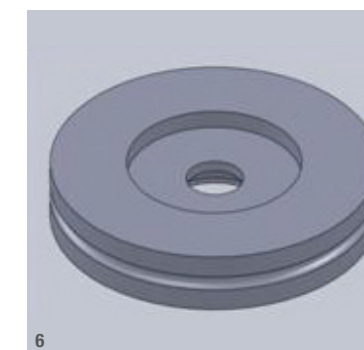
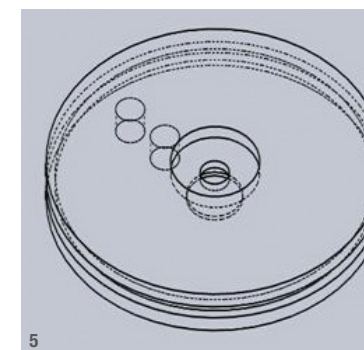


Figure 4: Plot of flux density

Figure 5: Side coil endplates

Figure 6: Pole pieces



magnetic source. The modulus of an MRE increases as the flux density of the applied field is increased with the majority of the increase occurring between 0 and 400mT, and thereafter less increase between 400mT and 600mT and none above this value.^{1-3,7} Therefore a suitable magnetic field for the testing of MREs using bubble inflation should be of uniform direction and variable between 0 and 400mT. A Halbach cylinder can provide a field of up to 400mT with the required uniformity within tolerance and direction, but as it is a permanent magnetic array the flux density is fixed, making it unsuitable for testing MREs over a wide range of magnetic fields.

Magnetic field design

An FEA simulation of a suitable electromagnetic array based on the geometry of a Halbach cylinder was presented in a previous paper⁶ and is depicted in Figure 1.

The array presented in Figure 1 consists of four electromagnets each of 1,500 turns of 1mm diameter copper wire. The uniformity of this array demonstrates that an electromagnetic array is capable of providing a similar field profile to that of a Halbach cylinder, but with a variable flux density between lower and upper limits of 0 and 400mT. The plot in Figure 2 shows the magnetic flux (in Tesla T) against the position in the array shown in Figure 1. For fields of approximately 400mT above the sample volume, a current of 15A is required. This saturates the iron

core at 2T. Increasing the current further provides no additional increase in the magnetic field.

The main disadvantage of using electromagnets over permanent magnets is that they require a constant energy input to maintain the magnetic field. This results in increased temperatures and requires continual cooling. The array presented in Figure 1 was designed for air cooling. Results presented by Gorman *et al*⁶ showed that the cooling system was sufficient for currents up to 6A, however for currents above this, runaway temperature increases were observed. To overcome these runaway temperatures, the cooling was redesigned as a water-based system. The direction of the cooling channels was changed to radial from the previous end-to-end configuration. The water enters the electromagnet between the core and the windings, a copper sleeve is placed around the iron cores and keeps the windings off the core and provides the space for the water to enter the electromagnet. Copper was chosen for the sleeve material as it does not interfere with the magnetic field. The standard tight-wound, close-packed format for standard electromagnetic coils is unsuited for water cooling and results in blockages and pressure build-ups. To prevent this, regular corrugations were introduced in the wire during the winding process, preventing the wire from fully close packing. This ensured that cooling channels were kept open. The coils are enclosed and

water tight. The design in Figure 1 was modified to accommodate the new cooling system. The redesigned array is shown in Figure 3.

The array in Figure 3 differs from that in Figure 1 in three ways. Firstly, the side coils have been increased in diameter. This results in the cores of the side coils being further away from the sample than in the former design. This lowers the overall flux density applied to the sample. To compensate for the reduction in flux density due to the increased diameter of the side coils, the central coils were narrowed and elongated. The narrowing of the coils was to reduce the area of the magnetic pole pieces, thus decreasing the volume over which the magnetic field is applied and thus increasing the flux density over the center of the sample. The coils were elongated to offset the reduction in space for the windings caused by narrowing the coils. A test on a prototype coil with this cooling system resulted in a constant temperature of 36°C being achieved with a current of 15A at a flow rate of 0.3 l/min. The plot in Figure 4 shows the flux density versus position for the modified array.

Figure 4 shows a flux density of over 400mT. In comparison with Figure 2, the plot in Figure 4 shows a larger drop-off in flux density at the edges ($x=0$ and $x=6$ positions on the graph). This is due to the narrowing of the central coils. The successful cooling of the prototype electromagnet and the results for the modified array depicted in Figures 3

and 4 show that an electromagnetic array can produce suitable magnetic fields of up to 400mT. This will provide testing of MREs using biaxial loading, and increased temperatures can be avoided by using an adequate cooling system.

Manufacturing of the electromagnets

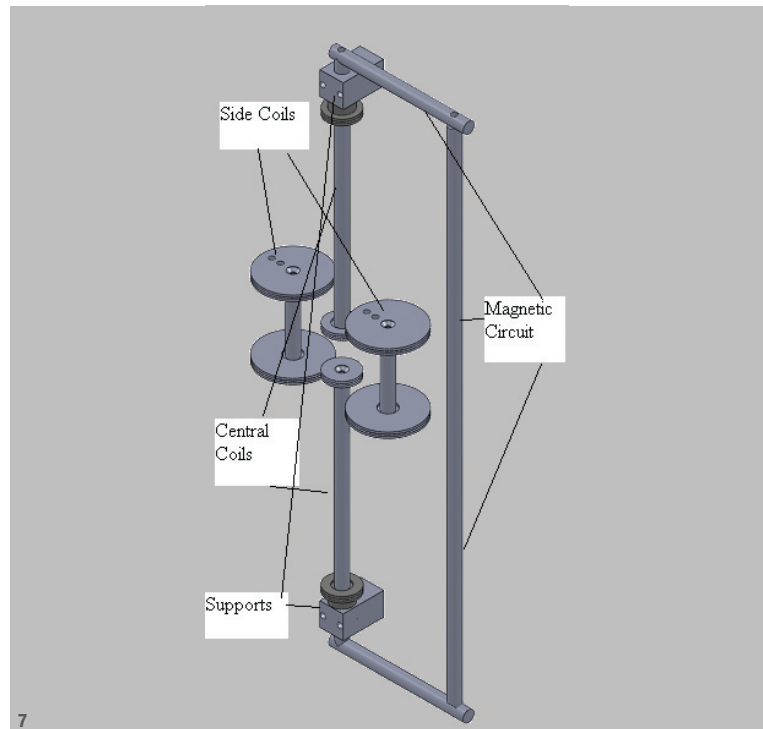
The electromagnetic array shown in Figure 4 consists of four main parts; the endplates, cores, windings, and the magnetic circuit. The cores and the magnetic circuit are made from 99.9% pure soft magnetic iron of 19.1mm diameter. The windings are 1mm diameter copper wire with an insulation coating. The end plates for the side coils are shown diagrammatically Figure 5.

The endplates are made from aluminum alloy as it has a relative permeability ($\mu_r = 1$) and so does not affect the magnetic field. There is an O-ring groove in the sidewall of the plate to ensure the entire coil is watertight. A recess is machined into the plate's inner face to hold the copper sleeve on which the windings are wound. This provides space for cold water to enter at the core. The water will flow through holes in the copper sleeve and through radial channels between the wires. Corrugations in the wire at regular intervals prevent the windings forming a perfect close packed arrangement as seen in some electromagnets and transformers, permitting evenly distributed water flow.

The pole piece in Figure 6 is similar in design to that in Figure 5 but is smaller. These pole pieces are made from magnetic steel. The effect of these on the magnetic field is to increase the area over which the field maintains its uniformity, with narrower pole pieces providing a higher flux density but less uniform field, which can be observed by comparing the graphs in Figures 2 and 4.

Figure 7 shows the cores and endplates and magnetic circuit assembled. The magnetic circuit is made from the same material as the cores and provides a path of least reluctance (magnetic resistance) for the magnetic flux to comprise closed loops. This results in the flux travelling through the circuit and through the sample gap between the pole pieces.

Figure 7:
Magnetic assembly



Conclusions

As both the direction and flux density of any applied magnetic field influence the MR effect of an MRE, it is clear that a detailed knowledge of the applied field is required. The same flux density applied in two different mutually perpendicular directions will cause a different increase in the modulus of an anisotropic MRE³ with the field applied parallel offering the greatest increase. This could allow for the same effect being achieved by a lower flux density, which will reduce the amount of energy required and lower the cost of operating any MRE-based device. Figures 1-4 show that an electromagnetic array is capable of providing a variable strength uniform magnetic field similar to that produced by a Halbach cylinder. This electromagnetic array will be suitable for dynamically testing MREs under biaxial loading using bubble inflation. The increased temperatures of electromagnets, having the potential to cause chemical aging of the rubbers, can be avoided by implementing an adequate cooling system. Testing of prototypes has shown that limiting this temperature rise to acceptable levels can be achieved. **tire**

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