On the magnetic field and temperature monitoring of a solenoid coil for a novel magnetorheological elastomer base isolator

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Abstract. Following a successful experimental validation of a magnetorheological elastomer (MRE) base isolator, this study presents one of the major concerns, the heating of the magnetic coil, in the design and development of the adaptive MRE based isolator. In this research, the MRE materials, with a total thickness of nearly 150 mm, are placed as the magnetic core of the device to best utilize the magnetic energy provided by the coil. A series of tests are undertaken to investigate the magnetic fields inside the coil with or without the MRE materials. Thermocouples are used to monitoring the surface temperature of the coil when it is applied with various currents for 10 min. It is shown that the measurement of field inside the solenoid when no MRE is placed inside agrees with the theoretical analysis. It is also shown that the temperature of the coil increase dramatically when a current is applied. Cooling of the coil may takes even longer, about 4 h, till down to the room temperature. Dropping of the magnetic field is observed when the temperature goes high.

1. Introduction

Finding engineering applications for a new class of smart material, magnetorheological elastomer (MRE), has been a major task for researchers in this field. Novel MRE devices, such as vibration absorbers [1-2] and vibration isolators [3-4], have been proposed and fabricated to pioneer its engineering applications. In civil engineering, Li [5] has proposed a novel MRE based isolator to be used in the base isolation system for mitigating the devastating effects of earthquakes on civil structures.

For any MRE-based device, electromagnetic coil is evitable involved to provide magnetic field for the MRE materials. Comparing with magnetic circuit design in MRF device, i.e. MR damper, MRE devices normally need a larger coil to energise the MRE materials, particularly for a large-scale MRE device. Therefore, investigation of the solenoid on the magnetic field distribution is of great importance. In particular, provision of sufficient and uniform magnetic field is essential towards the success in designing MRF/MRE devices. To understand the mechanism of magnetic field generation in a solenoid is the key for device design and optimisation.

Large electromagnetic coil has high electric resistance. Thus, heating becomes a great concern for the engineering design. Breese and Gordaninejad [6] presented theoretical and experimental studies on heat generation and dissipation of controllable MR fluid shock absorbers. Dogruoz *et al.* [7] performed

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theoretical and experimental analysis for enhancing heat transfer from MR fluid dampers using fins. Kavlicoglu *et al.* [8] studied heating of a high-torque, multi-plate magnetorheological (MR) fluid limited slip differential (LSD) clutch. These researches focused on the influence of the temperature rising on the performance of the ER/MR devices. Little attention has been paid to the electromagnetic coil itself.

The objective of this research is to investigate the magnetic field distribution and heating performance of a solenoid. Finite element analysis is explored to find the magnetic field distribution in the solenoid. To validate the analytical analysis, an experimental research is conducted to compare with the numerical findings. Finally, temperature monitoring on the solenoid under various applied current inputs is presented.

2. Electromagnetic coil for the magnetorheological elastomer based isolator

The solenoid is designed to provide magnetic field for the MRE based isolator. The sketch map of the solenoid is shown in Figure 1. The solenoid is made of electromagnetic coil and thin non-magnetic support as illustrated in the Figure. The electromagnetic coil is a cylinder shape configuration and is winded by 1.2 mm copper wire. The cylinder shape non-magnetic support is made of epoxy material and was folded into I-shape to protect the coil. Detailed structural parameters of the solenoid are shown in Table 1. The coil is firmly attached with the epoxy support. The total winding number of the coil is 3100 turns. The diameter of the coil wire is 1.2 mm and the total length of the wire is 2.1 km. The wire is made of copper and the resistance of the coil is 32.3 Ω.

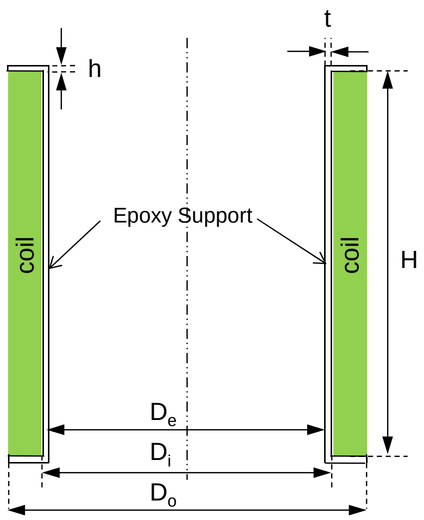

Figure 1. Cross-section of the solenoid.

Table 1. Structural parameters of the solenoid.

Item	**Size** (mm)
Inner diameter of the epoxy support $\boldsymbol{D_e}$	192
Inner diameter of the coil $\boldsymbol{D_i}$	196
Outer diameter $\boldsymbol{D_o}$	232
Height of the epoxy wall $\boldsymbol{H}$	276
Thickness of the cylinder epoxy wall $\boldsymbol{t}$	2
Thickness of the top epoxy plate $\boldsymbol{h}$	2

3. Finite element analysis of the solenoid

To analyse the magnetic field inside the solenoid, a finite element model is developed in Ansoft Maxwell. The FE model is shown in Figure 2. The material properties of the coil and the coil and the epoxy support are properly selected according to the design. Figure 3 shows the magnetic field distribution inside the solenoid when the applied current is 5 A. Figure 4 and 5 are to quantify the magnitude of the magnetic field inside the solenoid, both axially and longitudinally. It can be seen that the magnetic field intensity in the longitudinal middle of the solenoid is higher than in the top and bottom of the solenoid. The magnetic field in the longitudinal-middle is also more uniform than other locations.

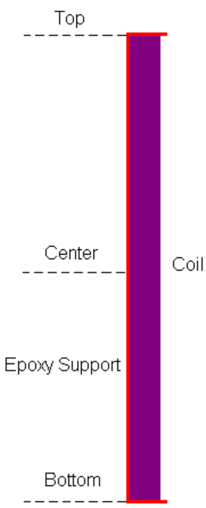

Figure 2. Finite element model in Ansoft Maxwell.

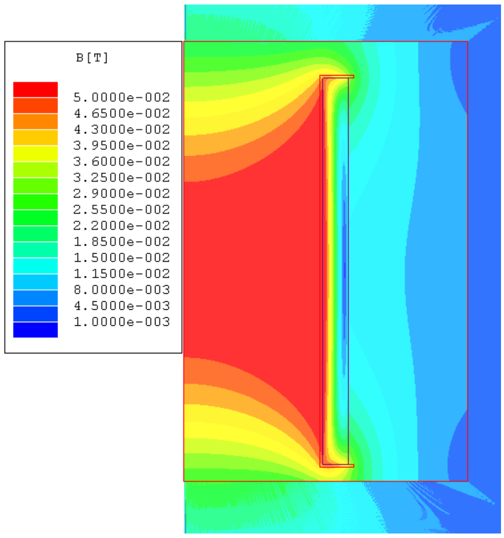

Figure 3. Magnetic field inside the solenoid (I=5A).

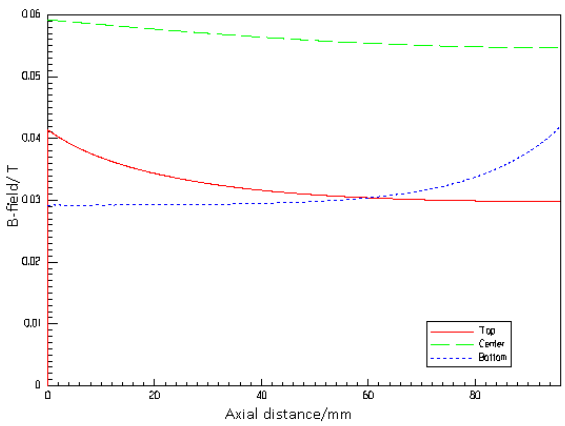

Figure 4. Magnetic field along axial direction (I=5A).

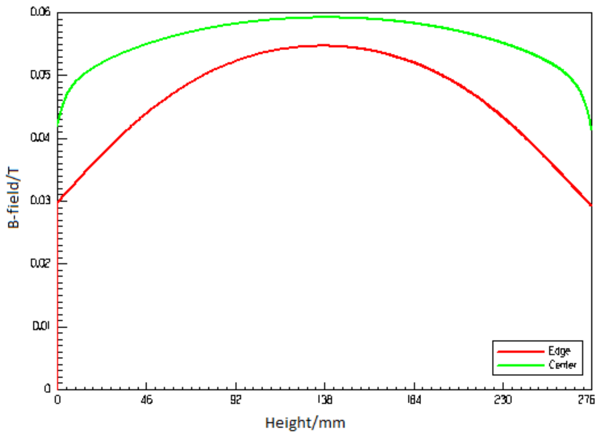

Figure 5. Magnetic field along longitudinal direction (I=5A).

4. Experimental testing

4.1. Experimental setup

To experimentally verify the findings from finite element analysis, an experimental testing is set up as shown in Figure 6. It consists of a solenoid, a DC power supply, a host computer, a magnetic field sensor and a temperature monitor. Details of the solenoid can be found at section 2. The DC power supply, with capacity of 250 V and 10 A, provides the solenoid with required currents from 0 A to 5 A. The magnetic field sensor, IDR-325 Gaussmeter, from Integrity Design and Research Corp, USA, is used to measure the magnetic field inside the MRE layer. The temperature monitor, model YC747UD-k type, is a four-channel thermometer with resolution of 0.1°C and capacity of -100°C to 1300°C. All the data from the magnetic field sensor and the thermometer is recorded by the host computer.

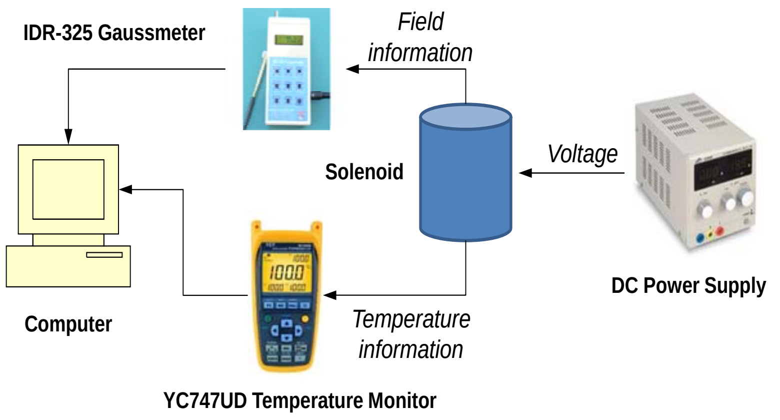

Figure 6. Experimental setup for the magnetic field and temperature measurement.

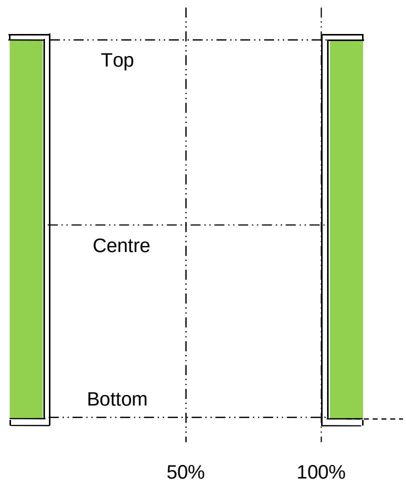

Figure 7. Baselines for the analysis.

4.2. Results and discussion

Figure 8 shows the magnetic field distribution inside the solenoid when the currents applied to the coil are 1 A, 2 A, 3 A and 4 A. The meanings of the terms used in the figures, i.e. "50%", "100%", "Top", "Centre" and "Bottom" are shown in Figure 7. For example, 50% top means the location in the top of vertical centre line inside the solenoid. Comparisons between the finite element analysis and measurements are also listed in Figure 8. It is quite clear to see that the measurements of the magnetic fields follow the simulation results very well. With the increasing of the applied currents, the magnetic field appears a linear increasing trend.

Figure 9 shows the magnetic field distribution along vertical directions inside the solenoid. It can be seen that the maximum magnetic field is in the centre of the solenoid. As indicated from the finite element analysis and the test results, the field intensity here is high and uniform.

Figure 10 is the temperature monitoring results when a certain current pass through for 10 min. When the applied current I = 4 A, the temperature of the coil rises from 25°C to 50°C within 10 min. For the cooling phase, after removal of the current, it will last a long period till back to the room temperature, as shown in Figure11. For the case when a 3 A current is applied to the coil for a certain period of time and the coil temperature is above 40°C, it will last nearly 5 h till fully cooling down. As we know, the MR elastomer will have a weaken MR effect at high temperature, therefore, optimal design of the coil should be considered to find the compromise between the achieved magnetic field and the heating caused by the input current.

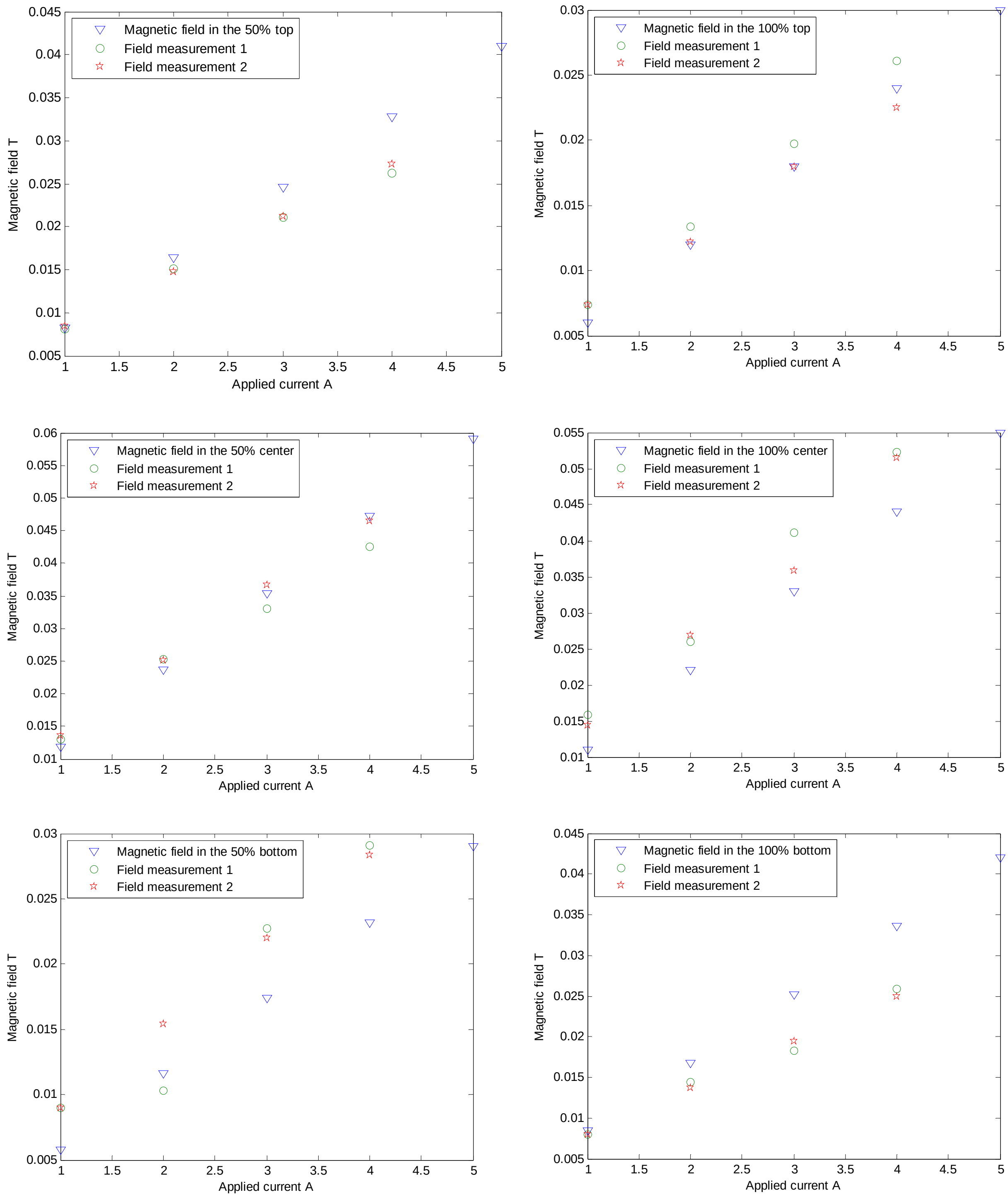

Figure 8. Magnetic field measurements vs. finite element analysis.

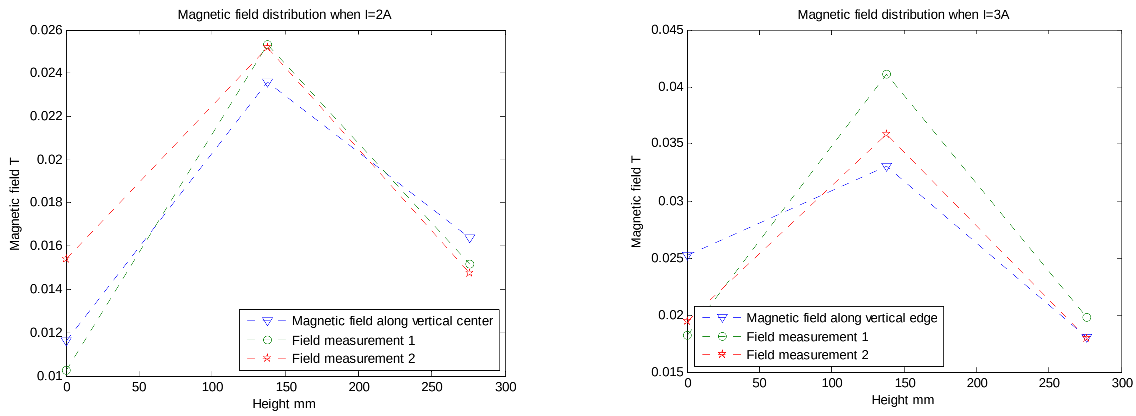

Figure 9. Magnetic field distribution along vertical directions.

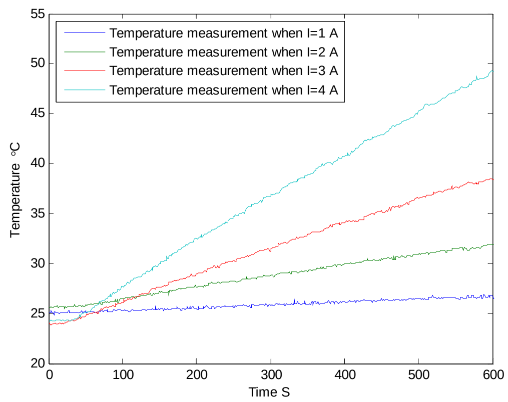

Figure 10. Temperature rising for various current inputs.

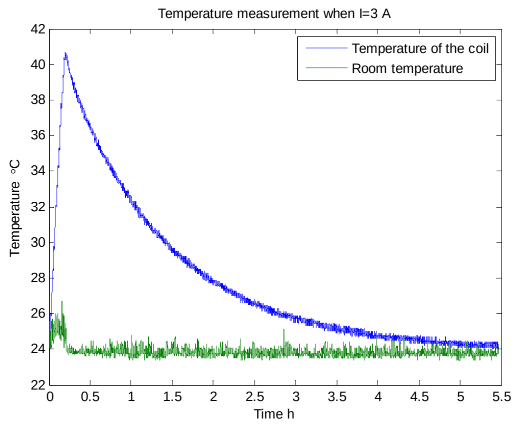

Figure 11. Temperature measurement for I=3A.

5. Conclusions

This study examined the magnetic field distribution and heating of a solenoid for a MR elastomer based isolator. Both finite element analysis and experimental testing were used for the magnetic field analysis in a solenoid. Experimental research on temperature monitoring was also conducted for the solenoid.

Acknowledgement

The authors gratefully acknowledge the financial support by the Early Career Researcher Grant (Grant No. 2032042) and the Chancellor's Postdoctoral Research Fellowship (Grant No. 2032032) from the University of Technology Sydney for this research.

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Frequency	Annual
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Refereed	Yes
Abstracted / Indexed	Yes
Open Access	Yes
Serial Type	Journal
Content Type	Academic / Scholarly
Format	Print
Website	http://iopscience.iop.org/1742-6596/
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