Magnetorheological Elastomer (MRE) based torsional vibration isolator for application in a prototype drilling shaft

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Abstract

Magnetorheological Elastomer (MRE) is a type of smart composite material consisting of a polymer matrix embedded with ferromagnetic particles. In the presence of an external magnetic field, its mechanical properties, such as stiffness, changes make it attractive in vibration isolation applications. Unwanted vibration in machines can cause severe damage and machine breakdown. In Qatar, the extraction of the natural gas from the ground requires sophisticated drilling machines. In this work, a semi-active vibration isolator using MRE is proposed for a potential application in a drilling system to isolate the torsional vibration. MRE was fabricated with a 35% mass fraction (MF) consisted of silicon rubber and iron particles. It was fitted with aluminium couplers and attached to the shaft (drill string) to study its efficiency in vibration isolation under a magnetic field. Two tests were conducted on the drilling prototype setup used in this work; the first test was a hammer impact test. The torsional transfer function TTF analysis showed that the system's natural frequency has shifted from 13.9 Hz to 17.5 Hz by the influence of increasing magnetic field around the MRE. The results showed that the continuous rotational vibration amplitude of the prototype is attenuated by more than 40%.

Significance and contribution

Enormous developments are happening in various sectors worldwide such as Oil & Gas, industrial, buildings, power, rail transport and infrastructure. These projects require sophisticated technologies. Oil & Gas is the main source of energy and economy in the GCC countries. The extraction of natural gas from underground requires very advanced drilling machines and operations onshore and offshore. Therefore, there is a massive need to perform research in vibration isolation for such a process. This work contributes to utilizing MRE as a semi-active vibration isolator to reduce the drilling system's torsional vibration. By studying such material on a drilling test rig, this can lead to a significant enhancement in such technology such as a better lifetime of machines that can improve the energy sector's economy by improving the efficiency of machines.

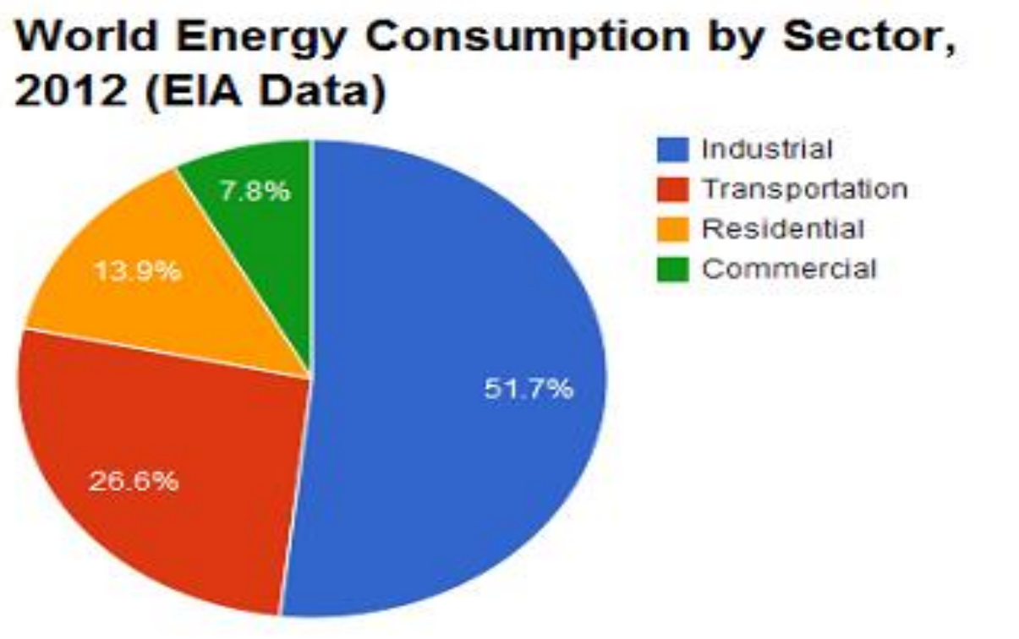

Fig. 1. The world energy consumption by economic sectors in 2012 [1].

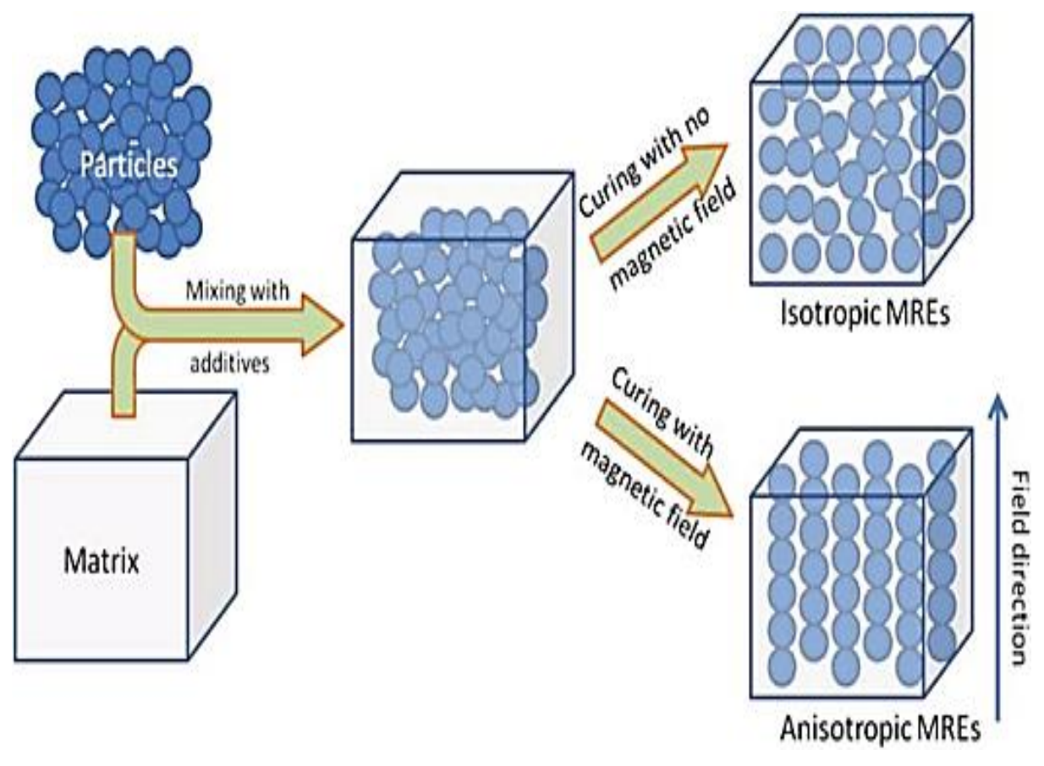

Fig. 2. Preparation of MRE [3].

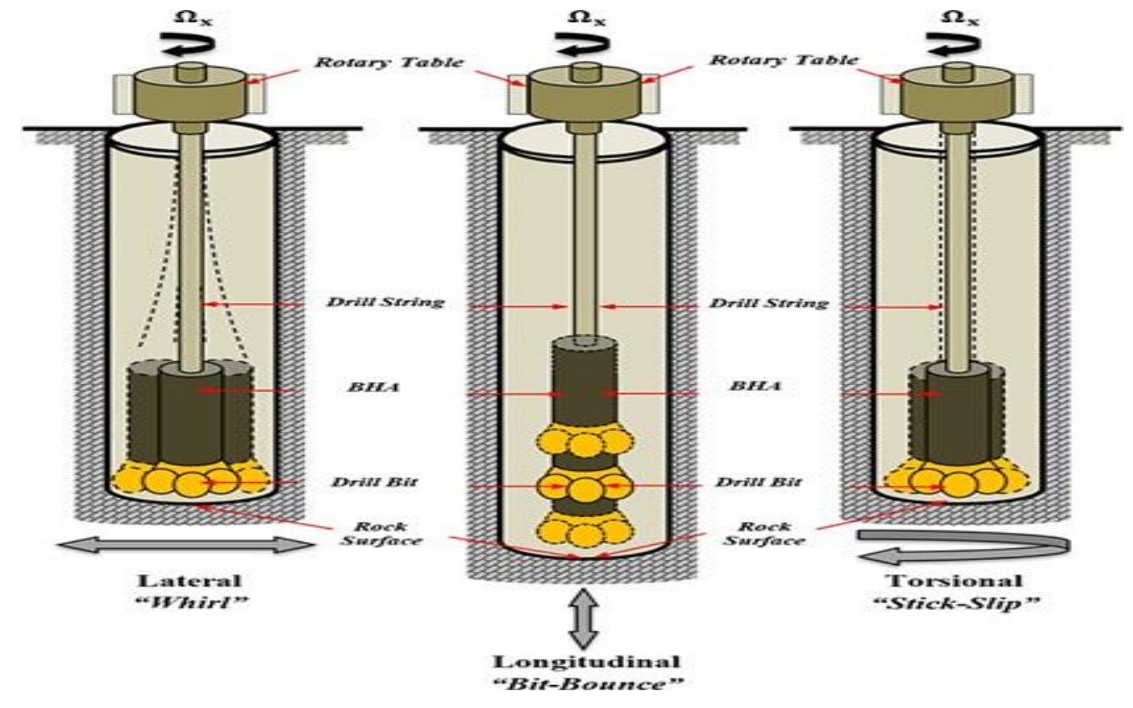

Fig. 3. Modes of vibration during the drilling process [2].

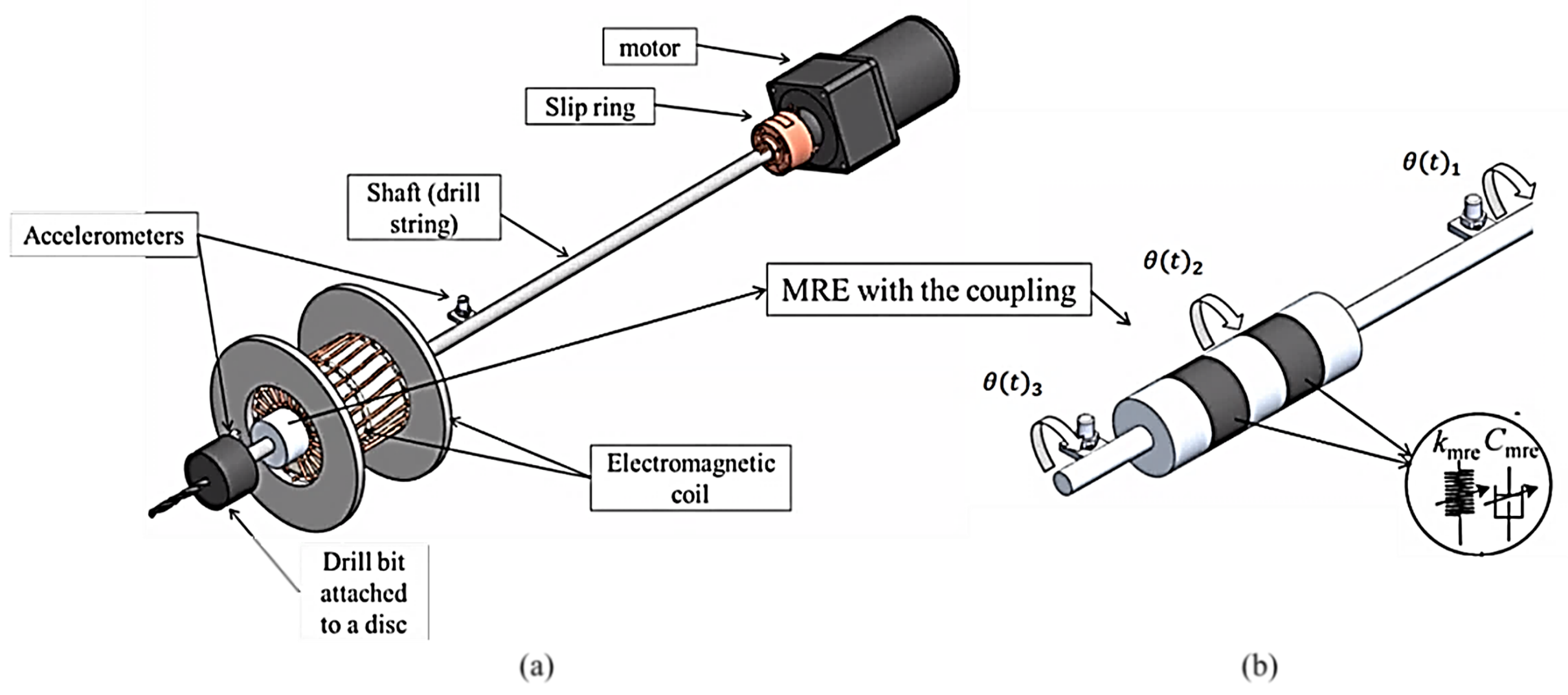

Fig. 4. (a) 3D CAD drawing of the proposed drilling system, (b) Schematic mathematical model derivation.

Methodology and experimental developments

- ☐ The methodology of this work starts with MRE fabrication, building a prototype and testing (Fig.5)
- ☐ The MRE was fabricated with a 35% mass fraction (MF) consisted of silicon rubber and iron particles.
- ☐ The fabrication procedure taken to achieve the desired coupling with MRE fitted in it started with modelling and printing the 3D mold as well as the dimensions are shown in Fig. 6.
- ☐ It was fitted with aluminium couplers and attached to the shaft (drill string) to study its efficiency in vibration isolation under a magnetic field (Fig. 6).
- ☐ A prototype test rig was developed to perform two different tests, the impact hammer test (static) and continuous rotation test (dynamic) (Fig. 7).
- ☐ Part 1- Impact hammer test to obtain the angular displacement transmissibility. In this test, excitation is given before MRE coupler, and the response is obtained after the coupler as a Frequency Response Function (FRF).
- ☐ Part 2- dynamic test will investigate the angular displacement transmissibility before and after MRE during continuous rotation of the shaft (drill string).

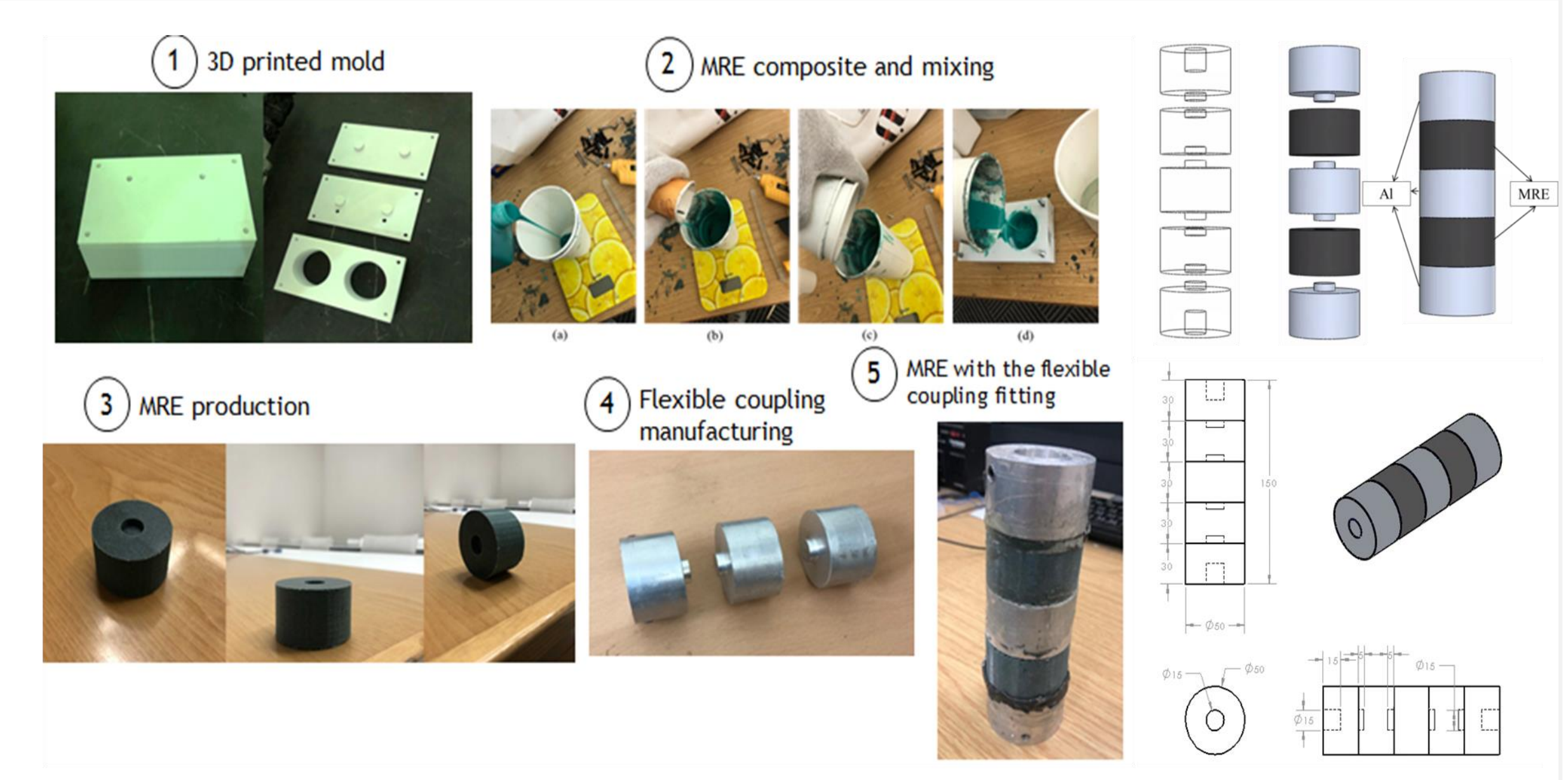

Fig. 6. MRE fabrication process and dimensions of the coupling.

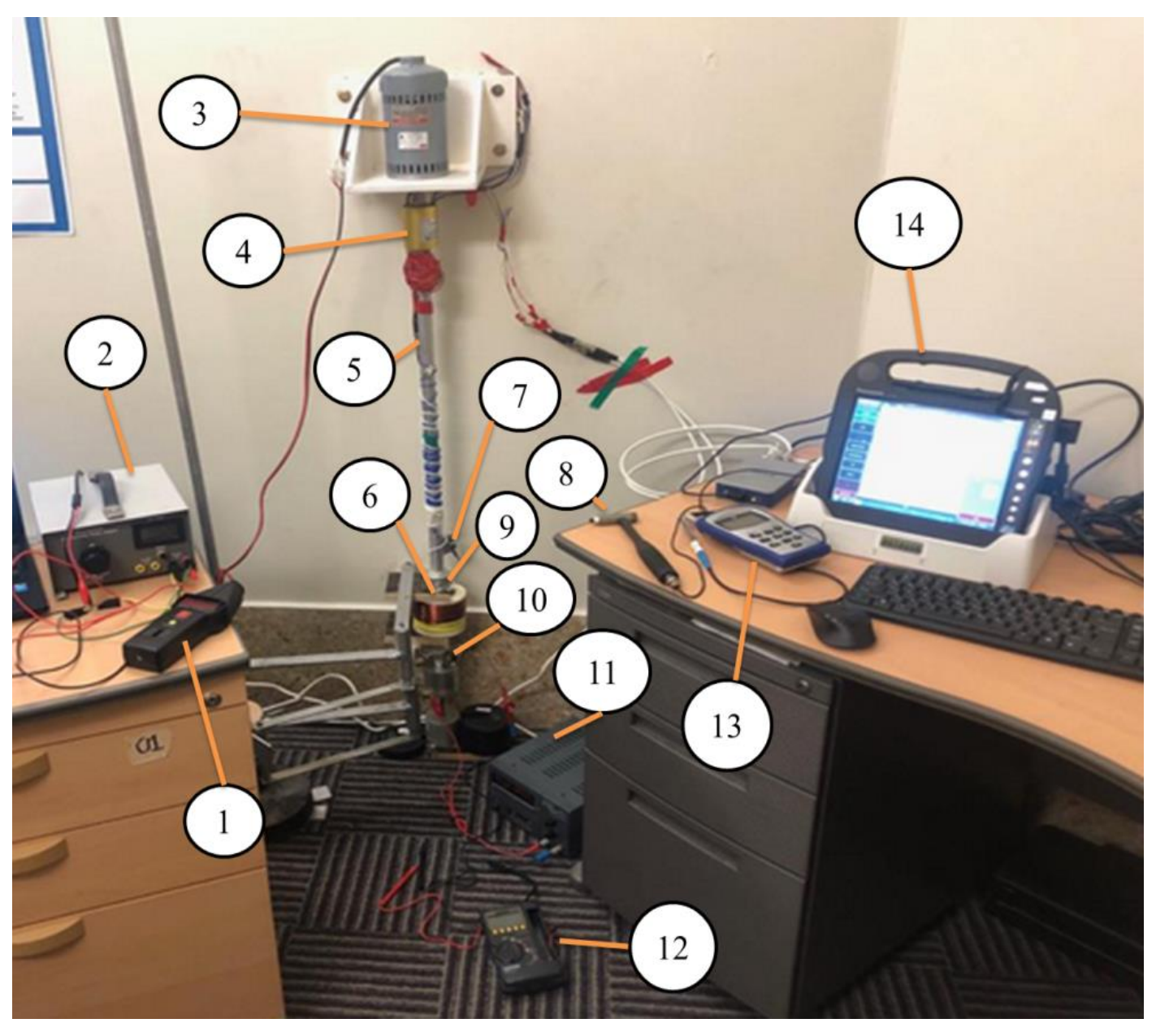

Fig. 7. Experimental setup.

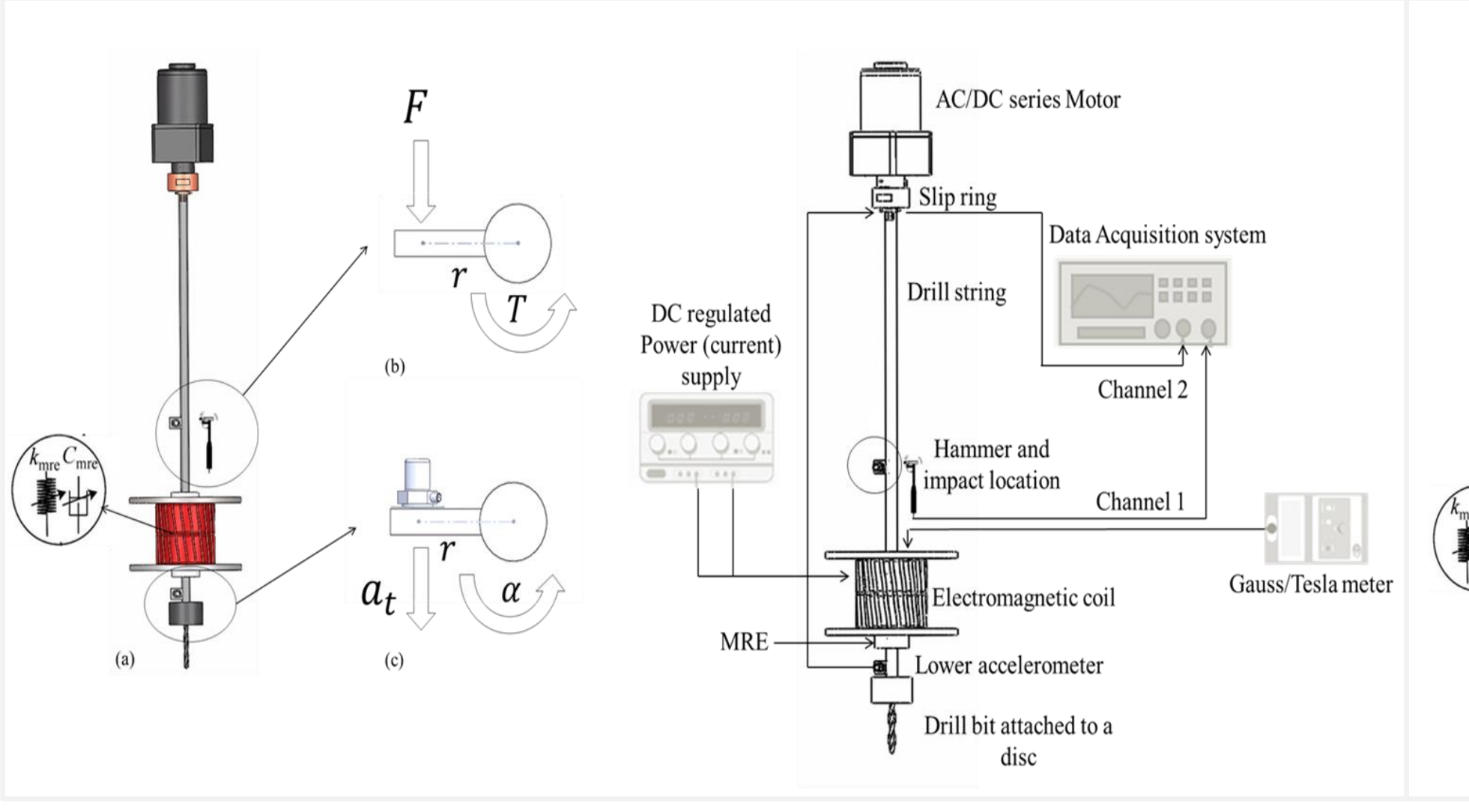

Fig. 8. Methodology and schematic representation of the impact test.

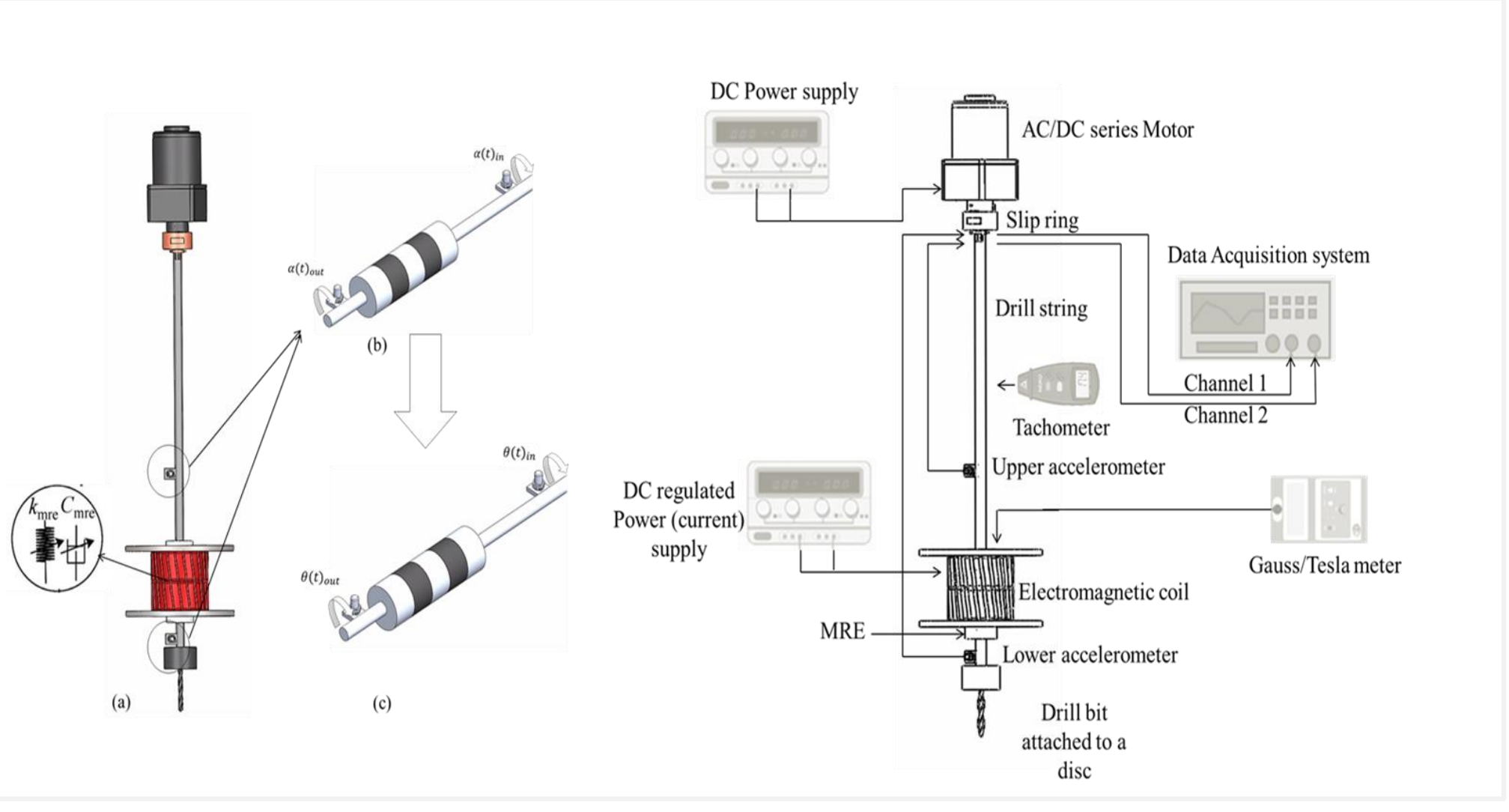

Fig. 9. Methodology and schematic representation of the continuous rotation test.

Results and discussion

- ☐ Results of the impact test give TTF for a range of frequencies. The 1st natural frequency occurs at 13.9 Hz with TTF magnitude of 0.15522 $rad/N.m.s^2$. At the same frequency, the magnitude drops to 0.1117 $rad/N.m.s^2$ under magnetic field produced by 1 A coil current. As the magnetic flux increases, the magnitude of TTF decreases. (Fig. 10 and Fig. 11)
- ☐ This means that a minimum magnitude of TTF can be achieved. When the current value is 1 A, the resonance frequency becomes 17.5 Hz. The natural frequency of the system reaches 21.45 under magnetic field produced by 3A current (Fig. 12).
- ☐ It can be clearly seen that as the current increases, the torsional stiffness increases. This illustrates the shifting in the natural frequency of the system. When the 1st value of the magnetic field is applied to the system, a rise of 36.8% in the stiffness is found (Fig. 13).
- ☐ Results show small changes in damping characteristics of MRE under magnetic field; changed from 0.079 $kg.m^2/rad.s$ to 0.12 $kg.m^2/rad.s$ when the current reached 3 A. This finding agrees with the literature that the damping characteristics of MRE are not influenced much by magnetic fields (Fig. 14).
- ☐ In the rotational test, the amplitude of the upper accelerometer is higher than the amplitude of the lower accelerometer, which shows that the rotation is more convenient and calm (Fig. 15). More than 40% of vibration reduction achieved. Also, the natural frequency shifts from the torsional transmissibility curve for a current (0 A – 3 A) (Fig.16).

Introduction

- ☐ World widely, the industrial sector plays an important role in energy consumption by more than 50% (Fig. 1) [1].
- ☐ Oil & Gas is the main source of energy and economy in the GCC countries and in Qatar. The extraction of natural gas from underground requires very advanced drilling machines and operations onshore and offshore.
- ☐ Such long structures are prone to be subjected to massive and severe vibrations in three modes [2].
- ☐ Magnetorheological Elastomer (MRE) is a type of smart composite material consisting of a polymer matrix embedded with ferromagnetic particles (Fig. 2). In the presence of an external magnetic field, its mechanical properties, such as stiffness, change due to the interaction between the magnetic particles, which have applications in vibration isolation [3, 4].
- ☐ In this work, a semi-active vibration isolator using MRE is proposed for a potential application in a drilling system to isolate the torsional vibration.
- ☐ The MRE was fabricated with a 35% mass fraction (MF) consisted of silicon rubber and iron particles. It was fitted with aluminium couplers and attached to the shaft (drill string) to study its efficiency in vibration isolation under a magnetic field.

Analytical model for the prototype drilling system

- ☐ The system is vertically oriented to represent a drilling process.
- ☐ The 3D isometric view of the system used in this study is shown in Fig. 4 (a).
- ☐ The shaft is 25 mm in diameter and 600 mm in length.
- ☐ The whole length of the system does not exceed 1 m.
- ☐ The transmissibility of the whole system will be a combination of three different rotations in terms of $\theta(t)_1, \theta(t)_2$ and $\theta(t)_3$ as in Fig. 4 (b) and Eq. (2).
- ☐ Fig. 4(a) shows the system and a zoomed snap for the MRE coupling as in Fig. 4 (b).
- ☐ The main concept of this analysis is to obtain the angular displacement transmissibility from the mathematical model to isolate the torsional vibration isolation in drilling using MRE.
- ➢ The angular displacement (torsional) transmissibility
- $$TT = \frac{output\ angulardisplacement}{input\ angular\ displacement} \quad (1)$$
- ➢ The torsional transmissibility (TT) of points 1 and 3 can be expressed by:
- $$TT_{1,3} = TT_{1,2} \times TT_{2,3} = \frac{\theta(t)_2}{\theta(t)_1} \times \frac{\theta(t)_3}{\theta(t)_2} = \frac{\theta(t)_3}{\theta(t)_1} = \frac{\theta(t)_{\mathrm{out}}}{\theta(t)_{\mathrm{in}}} \quad (2)$$
- ➢ The equation of motion that describes the system performance and behaviour:
- $$J(\ddot{\theta}_{out}) + c_{mre}(\dot{\theta}_{out} - \dot{\theta}_{in}) + K_{mre}(\theta_{out} - \theta_{in}) = 0 \quad (3)$$
- ➢ The angular displacement (torsional) transmissibility factor
- $$TT = \left|\frac{\theta(\omega)_{out}}{\theta(\omega)_{in}}\right| = \left|\frac{\theta_{out}}{\theta_{in}}\right| = \sqrt{\left[\frac{(c_{mre}\omega)^2 + (K_{mre})^2}{c_{mre}\omega)^2 + (K_{mre} - J\omega^2)^2}\right]} \quad (4)$$


MRE fabrication along with a coupling → Prototype design for drilling shaft → Testing

Fig. 5. Experimental work methodology flowchart

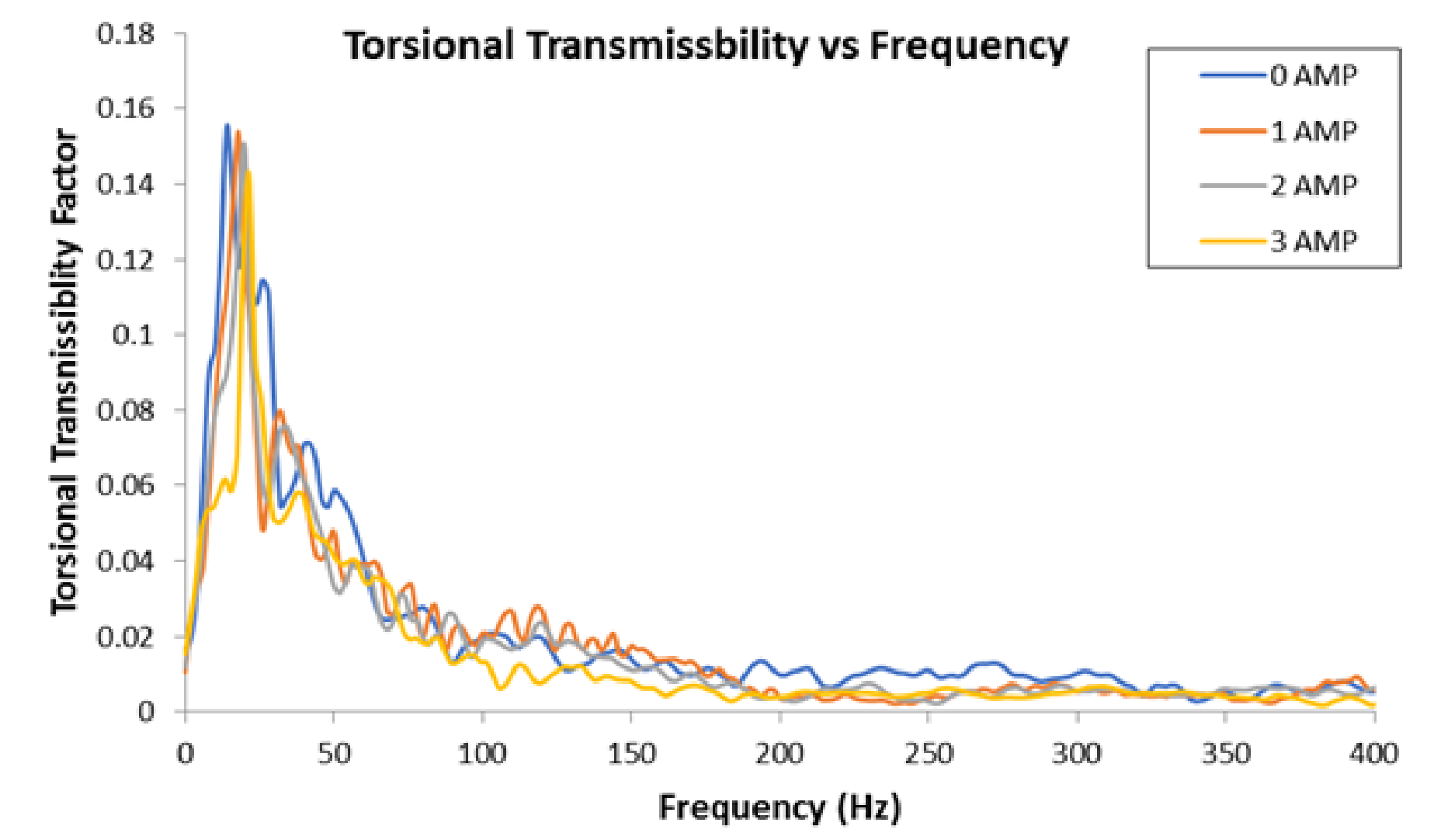

Fig. 10. TTF vs frequency.

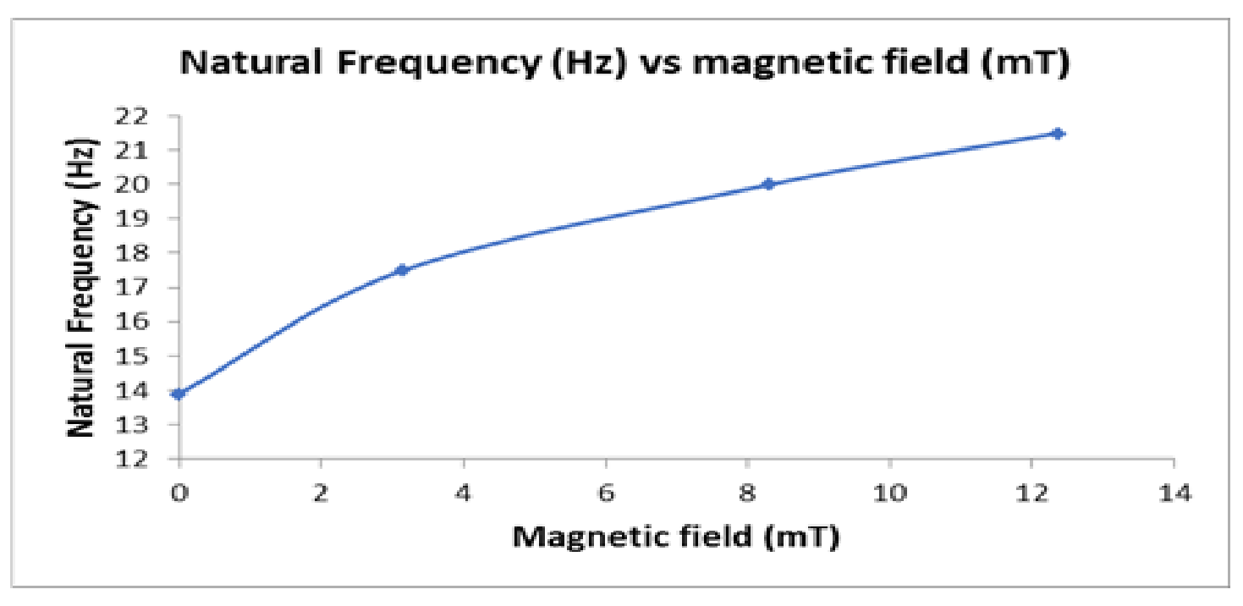

Fig. 12. Natural frequency vs magnetic field.

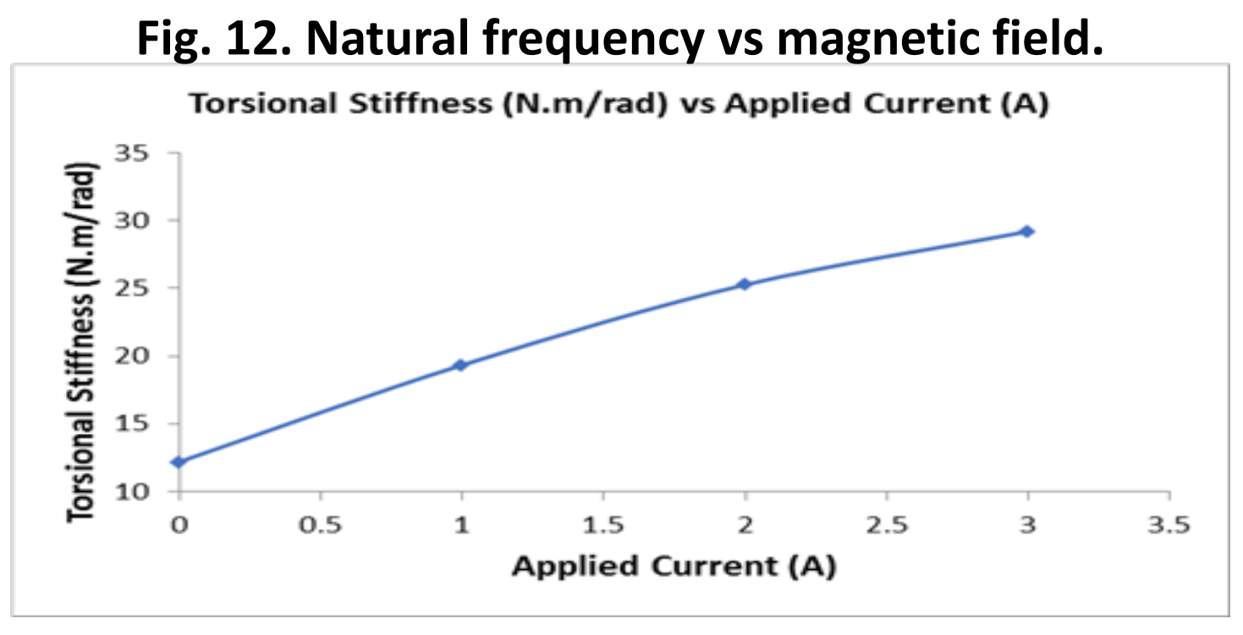

Fig. 13. Torsional stiffness vs applied current.

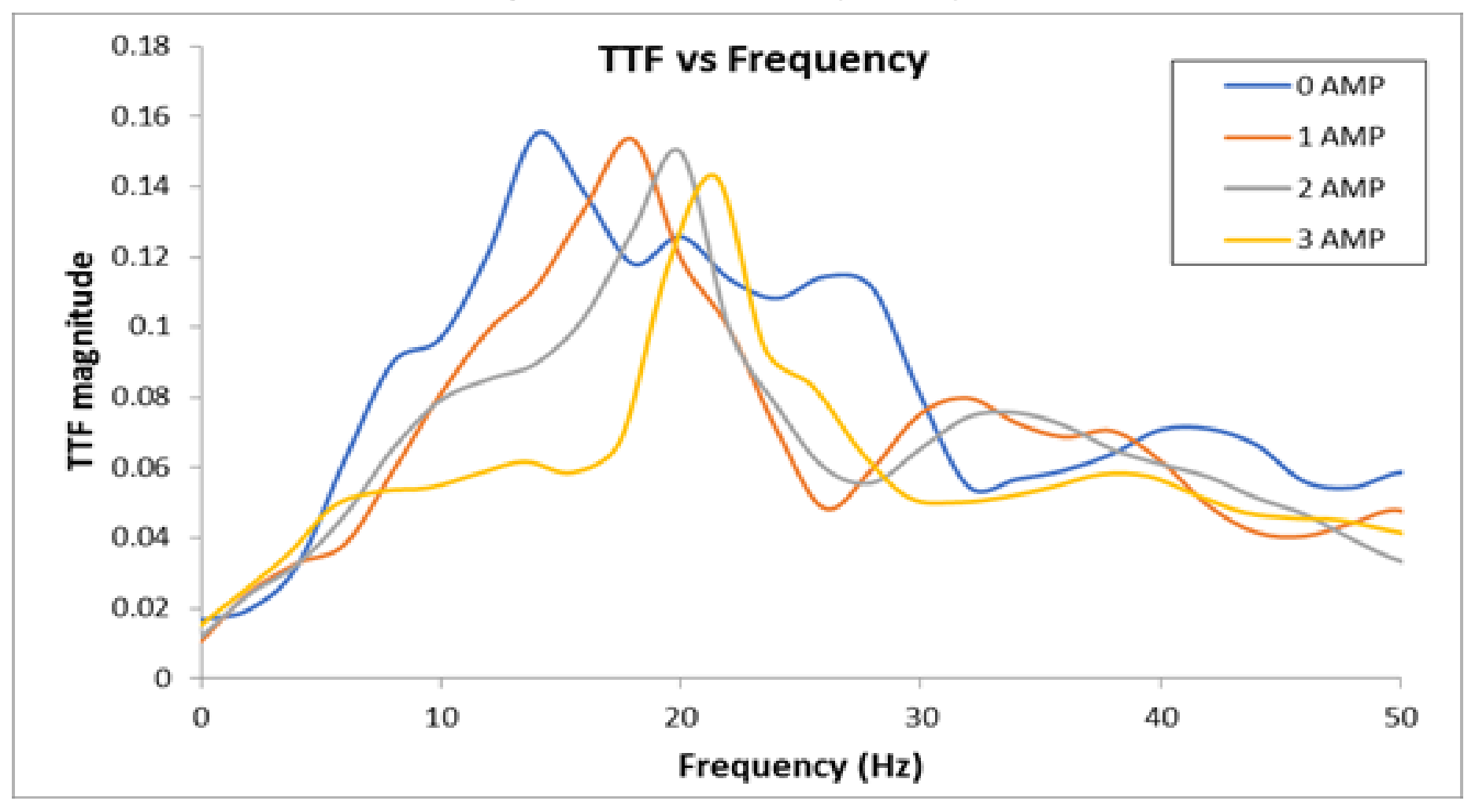

Fig. 11. TTF vs frequency at low frequency range.

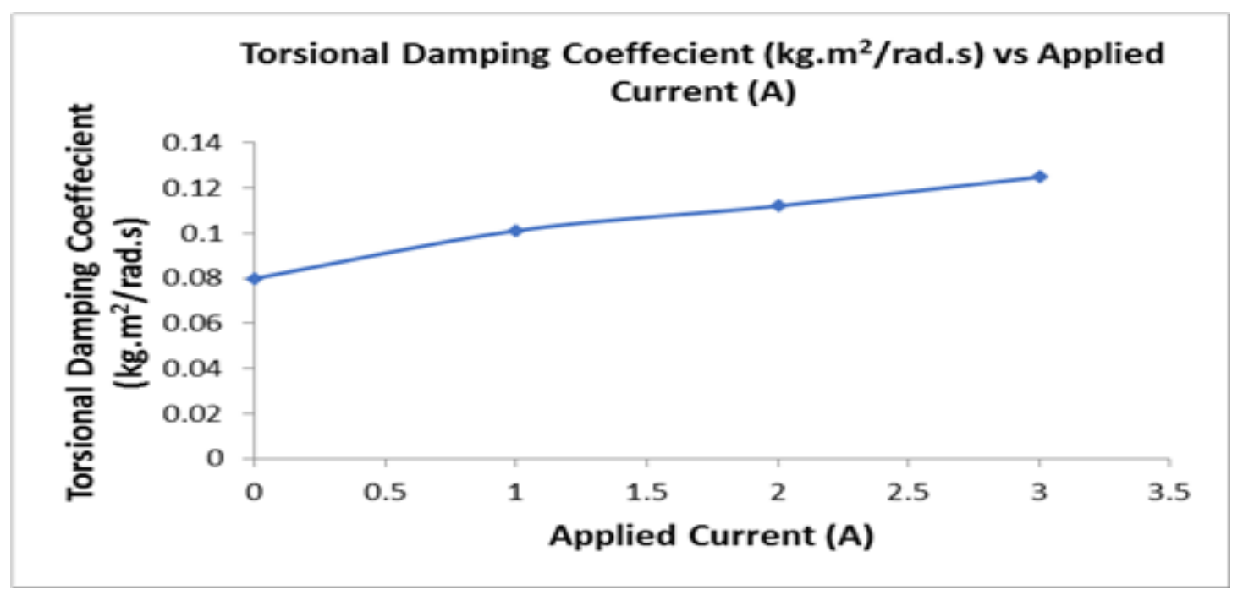

Fig. 14. Torsional damping coefficient vs applied current.

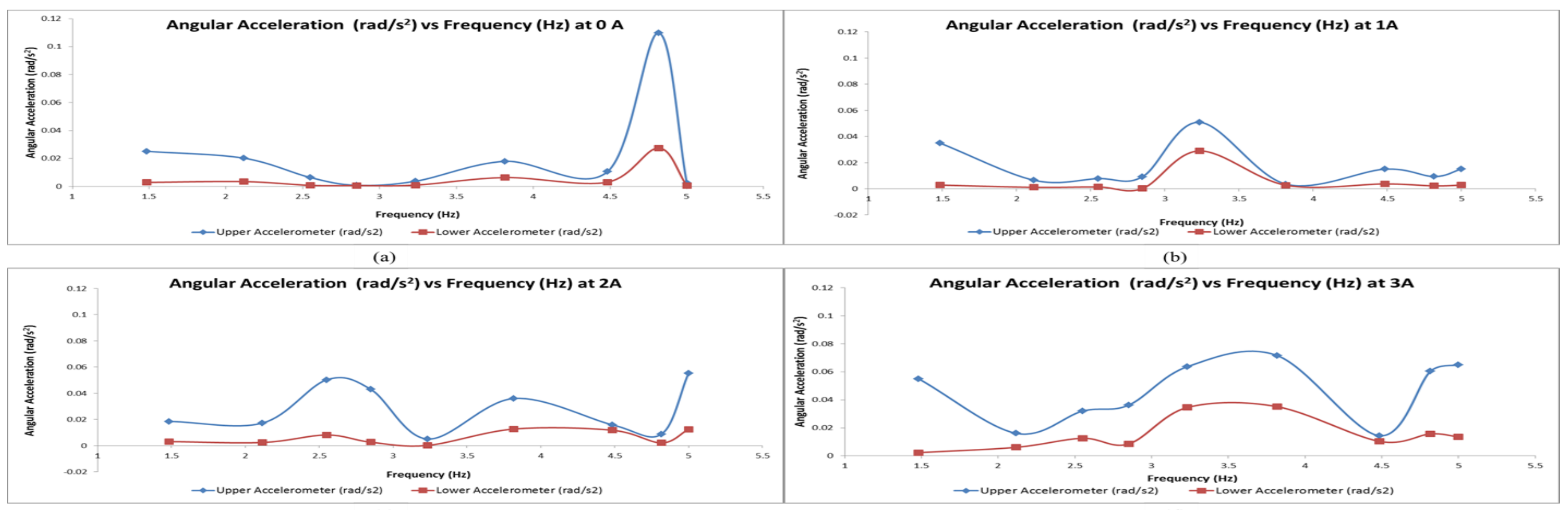

Fig. 15. Angular acceleration for upper and lower accelerometers (before and after MRE) for the applied current of (a) 0 A, (b) 1 A, (c) 2 A, and (d) 3 A.

Conclusions and future work

- ☐ Drilling test rig was prototyped in order to utilize MRE as a semi-active vibration isolator in drilling.
- ☐ MRE samples were fabricated with 35% MF and cured in order to test it in vibration isolation.
- ☐ The mathematical model of the system was derived
- ☐ From the impact test, the natural frequency of the system is shifted from 13.9 Hz to 17.5 Hz.
- ☐ The torsional stiffness increases with the magnetic field while the torsional damping slightly increases
- ☐ Results showed that there is a vibration reduction by plotting the upper and lower accelerometers amplitudes while rotation.
- ☐ As a future work, one can study the MRE efficiency of MRE in axial and transverse modes in drilling.

Funding Acknowledgement

This work was partially supported by Qatar University International Research Collaboration Grant No. IRCC-2020-017 and partly supported by Qatar University Student Grants (QUST-1-CENG-2020-18). The findings achieved herein are solely the responsibility of the authors.

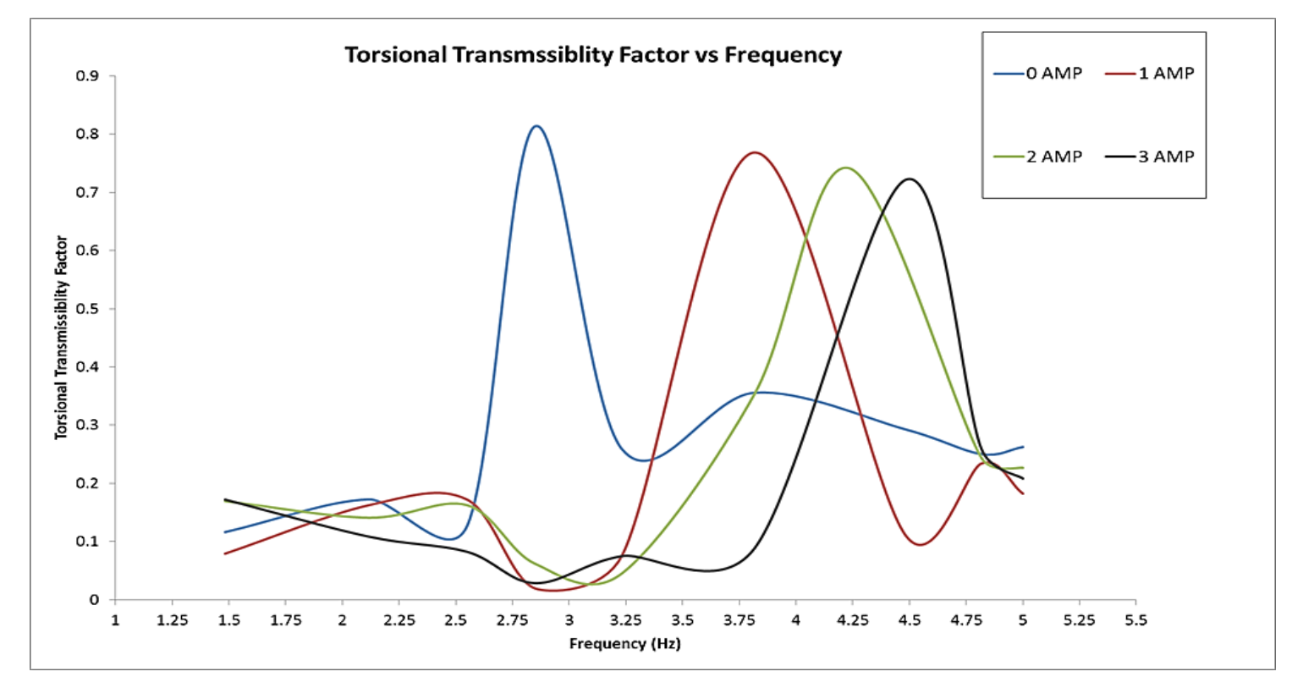

Fig. 16. TTF vs frequency in rotational test.

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