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Investigation of the Energy Saving Capability of a Variable Inertia Magneto-Rheological (MR) Flywheel

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Abstract— This research focuses on a theoretical and experimental analysis of a variable inertia magneto rheological flywheel (VIMRF). The objectives of the present study were to design and fabricate the prototype of a VIMRF and perform characteristics of energy saving capability of it. The moment of inertia has been calculated under different angular speeds and excitation currents. The prototype was designed and manufactured to verify the effectiveness of the proposed VIMRF. Simulations are primarily done to find variable characteristics of the moment of inertia of the VIMRF under certain conditions. The primary simulation shows that the moment of inertia of the VIMRF can semi-actively be tuned.

Keywords: *Magnetorheological, variable inertia, flywheel*

1. INTRODUCTION

Flywheels are showing immense promise in the field of the energy storage system. A flywheel is a mechanical device designed to store rotational energy efficiently. One topic of interest within this field is the energy-saving capability of variable inertia MR flywheel. The flywheel is an electromechanical, readily available energy storage system of rotating mass. The flywheels' size varies in size depending on the system requirements and cost-efficiency. Various research from all over the world developed a flywheel mechanism to a modern established level to cope with any system. But the fourth industrial revolution brought a new era of scientific achievement in communication, robotics, and electronics. Flywheel has been utilised for several applications, usually for energy storage or to minimise the angular velocity fluctuation of a shaft. Some energy storage applications include flywheel hybrid vehicles, cyclic alternative energy sources such as wind turbines, uninterrupted power supplies, and space power systems. The internal combustion engine, AC generators, industrial machinery such as camshafts etc., are some applications of flywheel for smoothing angular velocity fluctuations.

Within the plan of a system with a conventional flywheel utilised to minimise changes in angular velocity, the flywheel is measured on a coefficient of variance, characterised as the alter in angular velocity amid a cycle isolated by the normal angular velocity. A significant moment of inertia is required to achieve a low coefficient of fluctuation. An adjustable inertia flywheel can play a significant role in this case. Moreover, there are few research papers concerning the contribution of MR liquids within the flywheel area, which is also one of the primary reasons that trigger this extension to work.

2. RESEARCH METHODOLOGY

Over the past few decades, a wide range of work on variable inertia flywheel has been done on its energy saving capability. Jauch [1] has proposed a flywheel energy storage that is an integral part of a wind turbine rotor. Figliotti & Gomes [2] have proposed a design for a spring-connected variable inertia flywheel directly coupled to the vehicle in their study. Van de Ven [3] presents a self-governing fluidic variable inertia flywheel that can keep its angular velocity constant over a wide range of energy storage. A centrifugal pendulum in the

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double mass flywheel has been adopted by Ishida et al. [4]. James et al. [5] proposed a novel self-governing fluidic variable inertia flywheel that can maintain a constant angular velocity across a range of energy storage. Yuan et al.[6] designed of a diesel generator set under the pulse load, which can replace the traditional fixed inertia flywheel of the variable inertia flywheel. Bao [7] introduced a novel type of flywheels with the variable equivalent mass moment of inertia and without a fixed connection with the input shaft to the machine. Matsuoka [8] proposed a new vibration suppression device that utilises variable inertia mass by using a fluid that acted as a series of inertia mass. But the use of magneto rheological fluid to achieve variable inertia in a flywheel has not been widely done. The energy saving capability variable inertia magneto rheological flywheel (VIMRF) in comparison to its counterparts is yet to be explored.

The research methodology starts with an extensive literature survey of the existing and ongoing works on variable inertia flywheels. Then developing a CAD design of the prototype. Following CAD design, fabricating the prototype according to the design begins. After the prototype is fabricated, the testing phase starts. The final step is to perform experiments to find the energy saving characteristics of the VIMRF.

2.1 Design of the Variable Inertia Magneto-Rheological Flywheel

2.1.1. Modelling of variable inertia flywheel

The inertia of the flywheel varies as the slider moves through the slot in a variable inertia flywheel. When the flywheel speed is zero, the springs are at their full length in the extended position, touching the hub. Gravity isn't taken into account here. The springs can only be compressed and not extended any farther. The slider's moment of inertia around its own mass centre and the fixed structural part's moment of inertia around the shaft centre are both expressed as

$$J_s = \frac{1}{4} m_s \left(\frac{d_s^2}{4} + \frac{l_s^2}{3} \right),$$

Where m_s, d_s, l_s and Ns = 4 are the slider mass, slider diameter, slider length and number of slots, respectively, Jscd = 12mscd(ri2 + ro2) is the polar moment of inertia of a solid flywheel of uniform thickness, m_{scd} is its mass, J_{shaft} is the polar moment of inertia of the shaft, and r_i and r_o are the inner and outer radius of the circular disk, respectively, and the lost inertia of the removed material from each rectangular slot

$$J_{slot} = m_{slot} \left\{ \frac{1}{12} \left(d_s^2 + l_{slot}^2 \right) + \left(r_o - 0.5 l_{slot} \right)^2 \right\},$$

where m_{slot} and l_{slot} are the mass of the removed material from each slot of the circular disk and the length of the slot, respectively. The slider moves along the slot while it rotates along with the flywheel. The equation of the motion of the slider can be obtained using Lagrange's approach. The Lagrangian is expressed as

$$L = T - U$$

where T and U are the kinetic and potential energy of the variable inertial flywheel, respectively. The kinetic energy can be formulated from radial and tangential velocity components of the ith slider, l_i and li$\dot{\theta}$, respectively, as

$$T = \frac{1}{2} \sum_{i=1}^{4} m_s \left(\dot{l}_i^2 + l_i^2 \dot{\theta}^2 \right) + \frac{1}{2} \left(J_f + 4J_s \right) \dot{\theta}^2,$$

where l̇i and $\dot{\theta}$ = ωf are the instantaneous linear velocity of the ith (i = 1.0.4) slider and angular velocity of the flywheel, and J_f is the flywheel's polar moment of inertia, respectively. The slider's potential energy U is introduced as well as the Rayleigh dissipation function D for resistive losses, ignoring gravity.

$$U = \frac{1}{2} \sum_{i=1}^{4} k_{fs} \left(l_i - l_{\min} \right)^2$$

$$D = \frac{1}{2} c_\theta \dot{\theta}^2 + \frac{1}{2} c_{line} \dot{\theta}^2 + \frac{1}{2} \sum_{i=1}^{4} c_l \dot{l}_i^2,$$

where k_{fs}, is the spring stiffness of the variable inertia flywheel, l_{min}, denotes the free length of the spring, c theta is the combined viscous damping co-efficient for loss at the bearings and viscous drag on the flywheel, c_{line} is the coefficient of line resistance of the circuit and cl is the viscous damping between the slider and the slot. The radial and tangential components of acceleration of the ith slider are $a_r = \ddot{l}_i - l_i\dot{\theta}^2$ and $a_\theta = 2\dot{l}_i\dot{\theta} + l_i\ddot{\theta}$, respectively. The normal reaction on the slot from the slider is m_{sa} and this reaction gives a part of the load torque. The Lagrange's equations of motion in generalised coordinates are given as

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{l}_i}\right) - \frac{\partial L}{\partial l_i} + \frac{\partial D}{\partial \dot{l}_i} = F_{ci},\ i = 1 \dots 4;$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} + \frac{\partial D}{\partial \dot{\theta}} = T_m - T_l,$$

2.1.2. Flywheel design

MR variable inertia flywheel and inner structure are shown in Figure 1. The MR variable inertia flywheel consists of a frame and four magnetorheological dampers with four identical slots. Each damper includes a cylinder, piston, MRF and spring. The middle of the frame is provided with a hole and a keyway for fixing the connection with the rotating shaft. The frame is set in a radial direction with four rectangular grooves and the cylinder is settled in the rectangular groove of the frame. A pre-compressed spring is set between the piston and the frame. The coil is entangled in the double ring groove of the piston. The non-woven fabric with MRF is placed in the gap between the piston and cylinder. Nonwoven fabrics are made from hygroscopic fibres and can store MRF. Its structural principle is like that of magnetorheological foam, which can simplify the damper structure and avoid leakage of MRF without sealing.

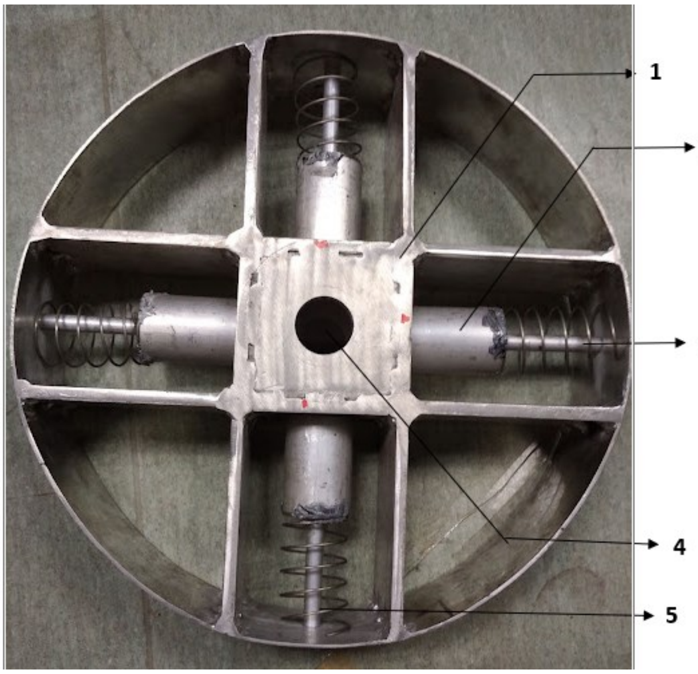

Fig. 1. Prototype of the flywheel (1) Rim of the block, (2) Mass block, (3) Spring, (4) Shaft hole and (5) Mass holding rod

2.2. Experimental Setup

This experiment involves the fabrication of a variable inertia magneto rheological flywheel (VIMRF). The design consists of four MR dampers used to adjust the rotational inertia of the flywheel. The flywheel will relate to the induction motor. An inverter will control the induction motor. A torque sensor will be placed between the motor and flywheel to obtain the experiment's output. Below is the schematic diagram of the system.

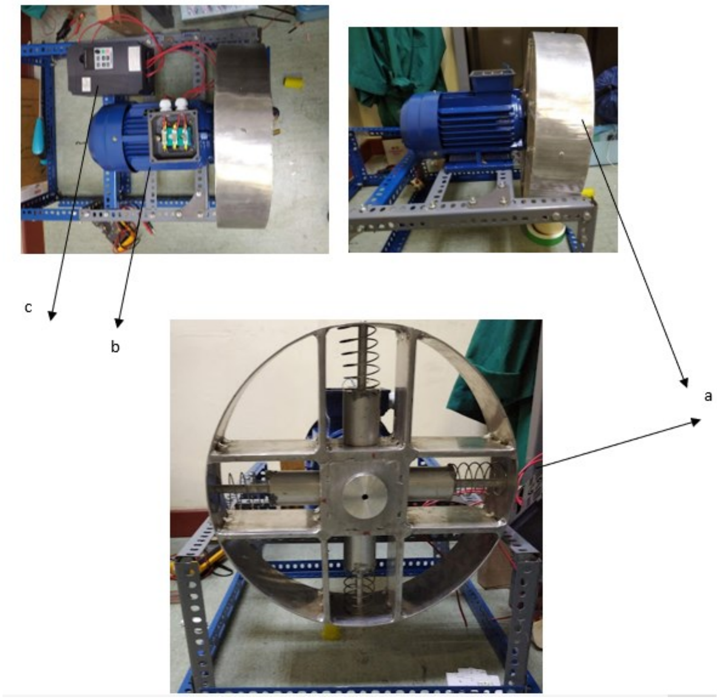

Figure 2 Experimental setup of the flywheel (a) Variable inertia flywheel, (b) Induction Motor, (c) Inverter

2.3 Results

The speed control system of the AC motor with VIF has been simulated using MATLAB. VIF is represented as an energy storage device in the internal feedback loop. VIF adjusts the system by releasing stored kinetic energy when the load torque increases. VIF will absorb excess energy from the system as load torque decreases. The constructed feedback loop uses the motor's angular acceleration as an input signal, and its output minimises the loading pulse impact. number.

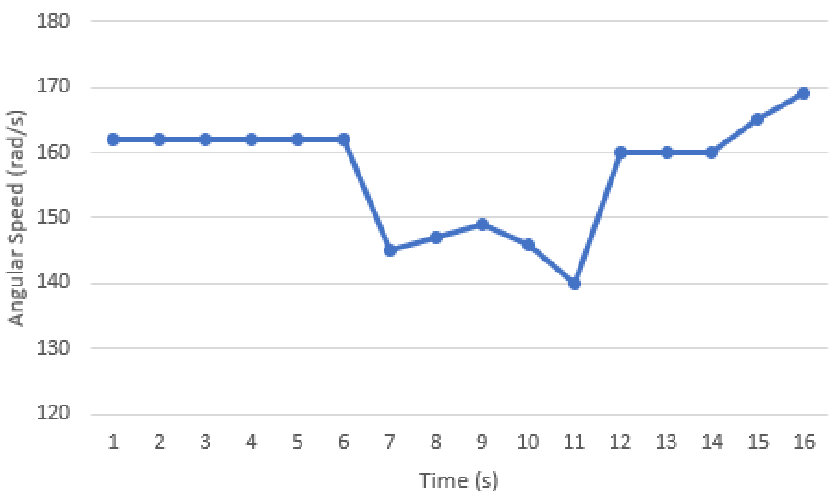

Fig 3 Angular speed of the motor(rad/s)

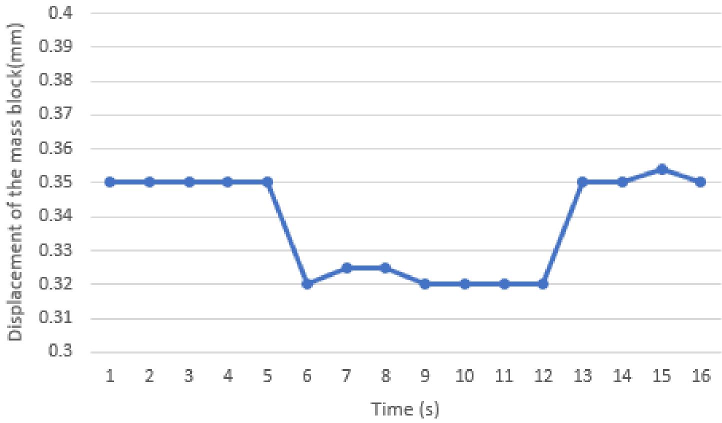

Fig 4 Displacement of the mass block(mm)

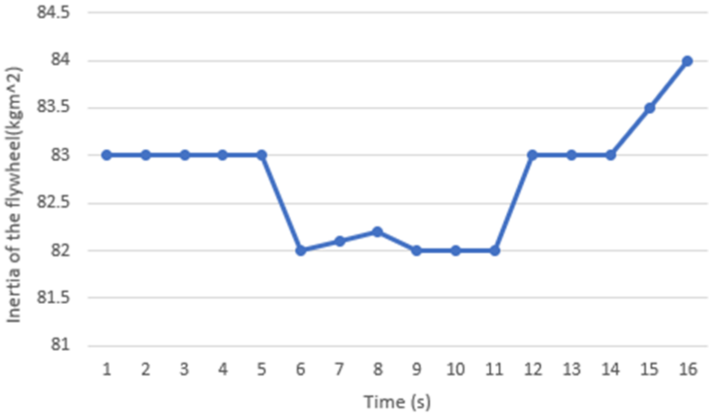

Fig 5 Inertia of the flywheel(kgm^2)

The Flywheel's Variable Behavior Equivalent Mass m_a and Moment of Inertia I_{af}, With the input velocity, the equivalent mass ma will change. However, when the rotating speed is very low, the slider will remain in its initial position, and ma will be the smallest number. The spring in the slot will fully compress when the rotating speed reaches a specific threshold, and ma will reach its maximum value. To study the flywheel's overall behaviour, the input signal should be chosen so that the sliders do not stay at the two ends of the slot and are neither the minimum nor the maximum value. Because the sinusoidal velocity input signal with a frequency of 0.1 Hz and an amplitude of 0.0314 m/s is less sudden than the rectangular and triangular inputs, it is employed. This is also because the sliders will travel over the majority of the travel range in the slots when given a sinusoidal input of this frequency and amplitude. As a result, the change in equivalent mass can be noticed over a larger range of values. The varied position of the sliders, the variable moment of inertia, and the equivalent mass of the flywheel in response to the sinusoidal input (Fig. 6) are all shown in reaction to the sinusoidal input. Figures 7–9 depict the results, respectively. The moment of inertia and equivalent mass of the flywheel vary adaptively in response to the input, as seen in Figs. 8 and 9, but the variation frequency is doubled.

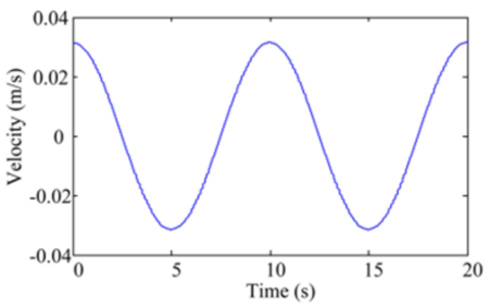

Fig. 6 Sinusoidal velocity input (frequency 5 0.1 Hz, amplitude 5 0.0314 m/s),

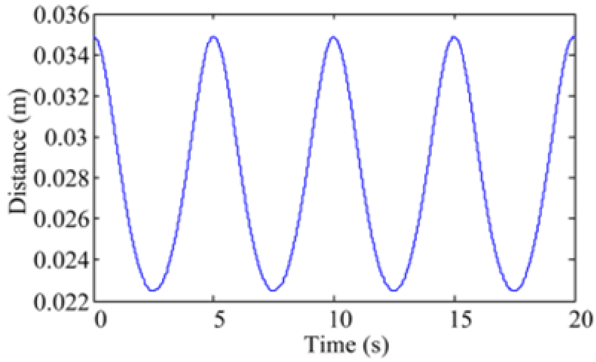

Fig. 7 Slider location that varies in response to the velocity input in Fig 6,

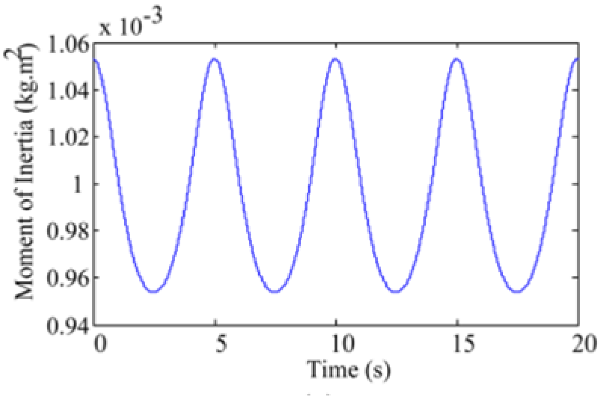

Fig. 8 The variable moment of inertia of the flywheel associated with the slider location presented in Fig. 7,

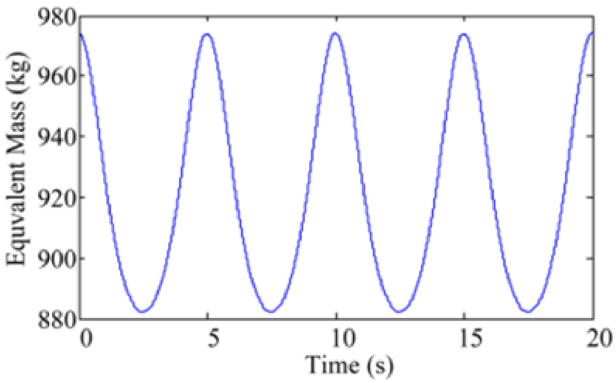

Fig. 9 The variable equivalent mass of the flywheel due to the location change of the sliders.

Figure 10 depicts the centrifugal force, spring tension, mass block displacement, and inertia curve as a function of rotational speed. The centrifugal force, displacement, and spring tension change slowly when the speed is less than 1000 RPM in the first column. However, when the speed exceeds 1000 RPM, the quadratic equation values increase, indicating that the flywheel has a greater energy storage capacity at high speeds. The effect of gravity on the centrifugal force and friction in the second column is represented by positive and negative alternating high frequency signals so that gravity can be ignored. The normal force from the gravity of the mass block produces coulomb friction, and the friction surface varies in 360 degrees, resulting in a positive and negative alternating high frequency signal. Because the angular acceleration of the flywheel is constant at 1500 RPM, the friction created by mass block inertia is also constant, as seen in the third photo of the second column.

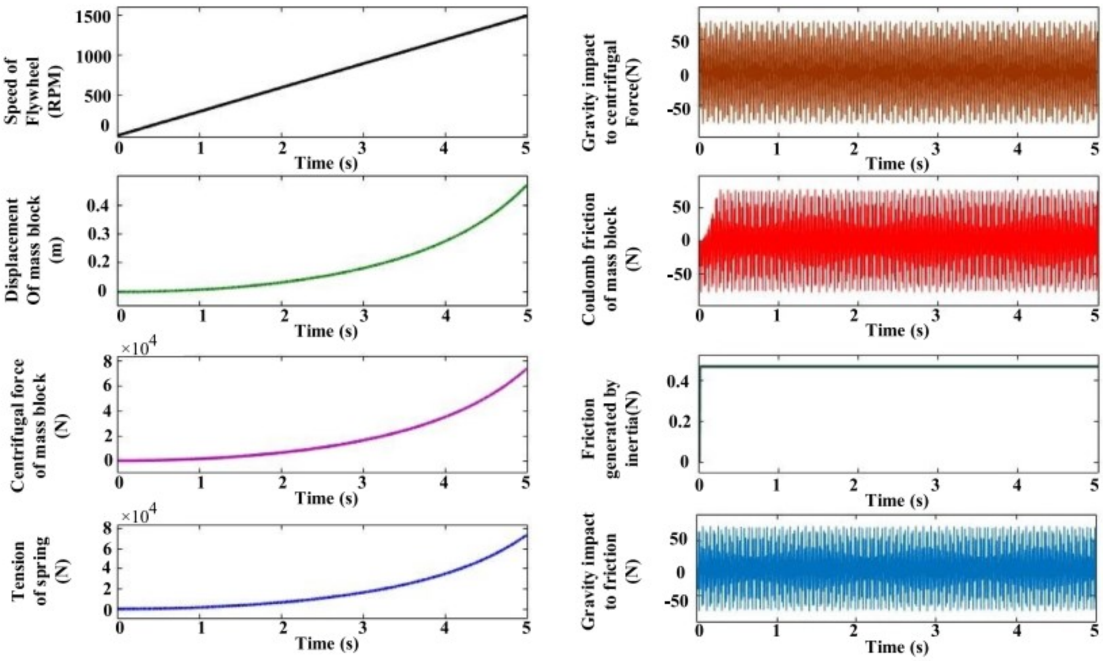

Figure 10. Simulation diagram of the flywheel

3. CONCLUSION

The objective of this research was to fabricate a prototype of VIMRF, do a simulation of the system and analyse and perform characteristics of energy saving capability of the VIMRF. The idea of storing energy in the rotating mass of a flywheel looks to be particularly enticing because of its simplicity. Closer inspection, however, reveals intricacies that make deploying an operating system significantly more challenging. One of the most challenging difficulties is transferring energy to and from the energy storage flywheel. This study looks at some of the research done on the topic of variable inertia flywheels. The experimental results are on good terms with the simulation results.

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