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Improving Rotational Stability and Enhancing Efficiency with Variable Inertial Flywheels and Magneto-Rheological Fluids

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Abstract—Variations in the rotational speed of a flywheel are naturally resisted by the moment of inertia. A high moment of inertia must be maintained to minimize angular velocity variations. Conversely, a significant moment of inertia makes it difficult to start spinning machines. A flywheel with a variable moment of inertia has been suggested to solve this issue. Although fluctuations between the masses' radii across the flywheel's axis may be used to approximate true inertia, the variable inertial flywheel's (VIF) control mechanisms are somewhat complex. Magneto-rheological (MR) Fluids can be utilized to avoid the complexity of the VIF. The applied device parameters determine the design and construction of the VIF system using a relatively simple control technique. To determine the relation between the semi-active VIF control system and the input parameters of a rotating electrical machine to decrease energy losses, adequate data from a VIF coupled with an induction motor (IM) system is gathered in this study. An analysis was done on the system, and the outcome showed a possible improvement in the performance of IM. This study significantly reduces power consumption and smooth speed build-up possibility for the proposed system.

Keywords: *Variable inertia flywheel, Semi-active control, Energy Saving, Inertia Control*

1. INTRODUCTION

The flywheel is one of the most straightforward energy storage or restoration options, among many others. Because of their cheap capital costs, long cycle durability, high power density, and ability to store energy for short periods (seconds to minutes), flywheels have replaced other energy storage methods in numerous applications [1]-[4]. The primary functions of flywheels in these applications are energy storage and dampening of shaft angular velocity fluctuations. Energy storage may be used in various contexts, including flywheel hybrid vehicles, intermittent power supplies, wind turbines, and space power systems. Flywheels are often employed in AC generators, camshafts, and internal combustion engines to dampen oscillations in rotational speed [5]. The design of a flywheel with variable inertia has to be more complex than that of a flywheel with constant inertia. To have a regulated moment of inertia around its spin axis, a flywheel has to have a flexible geometry around its spin axis, and altering the geometry requires moving elements within the flywheel [6].

While the complexity of a VIF may make it heavier per unit of energy stored than a fixed inertia flywheel, the device may have a better energy density than a constant inertia flywheel if it is assumed that the VIF is replacing both the flywheel and the gearbox. Most studies in [15] focused on the design and execution of VIF in the sphere of power savings and stability. Still, they neglected to account for the effect of high system stability. There is a risk of instability and system failure due to virtual inertia control in load disturbances. This is the major drawback of the previously suggested approaches. Until now, no virtual inertia design or approach has been able to provide steady control free of device-induced fluctuations. Therefore, a robust adaptive control system must be adopted in addition to virtual inertia control to manage changes in a machine with substantial stability and energy savings.

The energy-saving potential of this flywheel has garnered a lot of interest during the last several decades. Jauch [15] suggested incorporating flywheel energy storage technology inside the rotor of a wind turbine. Figliotti and

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Gomes [16] claim to have developed a vehicle-mounted flywheel with a changeable moment of inertia and a spring connection. Van de Ven [18] presented a fluidic variable inertia flywheel that can keep its angular velocity constant throughout a broad range of energy storage. The double-mass flywheel has a centrifugal pendulum similar to Ishida et al.'s [19]. James et al. [22] propose a fluidic variable inertia flywheel that can keep its angular velocity constant throughout a broad range of energy storage. According to Yuan et al. [20], a variable inertia flywheel may be used instead of a conventional fixed inertia flywheel. In this research, Bao [24] created flywheels with a movable equivalent mass moment of inertia and no permanent connection to the machine's input shaft. Matsuoka [22-23] presented new vibration suppression mechanisms using a fluid that behaved like a sequence of inertia masses. However, magnetorheological fluid has not been extensively implemented in flywheels. It has not been determined whether or not VIMRF (variable inertia magnetic rheological flywheel) can save more energy than its competitors. New approaches are emerging as research advances.

1.1 Motivation

Variable inertia to optimize the flywheel's output has been a common technique for the past few years. Many researchers addressed this issue in their research, and as a result, new techniques were introduced to control VIF. MR fluid is a recent invention used in damper control in different vibrating systems. This analysis will quantify the possibility of utilising this type of fluid to control the inertia of a VIF and will be used to improve the application system's performance.

2. PROBLEM FORMULATION AND SCOPE ANALYSIS

Whereas a variable inertial flywheel's (VIF) balancing mechanisms are relatively complex, the principle of variable inertia may be used by altering the location of the masses relative to the flywheel's axis. Furthermore, while there is abundant research on VIF control strategies, little of it concentrates on the application side. Characterizing the link between the VIF and the VIF coupled machine is crucial for reducing complexity and obtaining more effective control for the VIF that manages a broad variety of various rotating machines.

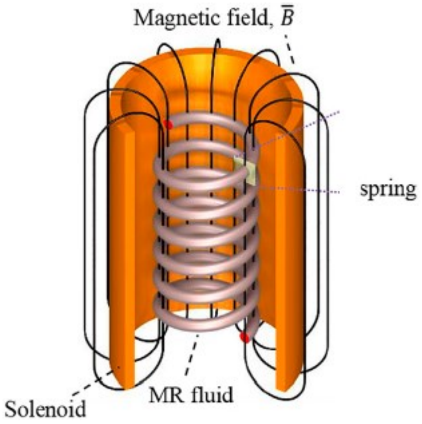


Fig. 1. Spring-solenoid system and generated magnetic field

In both the rotating flywheel and the inertia of mass, vibration is a common motion phenomenon that often oscillates around a balanced point. Because it produces obtrusive noise, uses energy, causes mechanical wear and structural stress, and raises danger, vibration in VIF is typically unwanted. Because of this, specialists have spent a lot of time researching vibration control. "Vibration control" in this context refers to lessening vibration to minimize undesirable oscillations in a protected structure. This is often achieved using a small connecting device composed of a spring, damper, or mass [14].

The primary emphasis of research over the last several decades has been on passive, active, and semi-active vibration control systems. The reaction time and operational frequency range of these systems are significantly impacted by system stiffness. Semi-active control is more stable than active control and needs less outside energy to operate as control energy. Compared to passive control, it is more versatile and works across a more extensive frequency range. As a result, semi-active control systems are pretty intriguing and are used in many different technical fields. Variables for semi-active control include damping, stiffness, or mass [15]- [16].

Non-Newtonian fluids like MR and ER transform their observable properties when subjected to magnetic or electric fields. Micron-sized iron particles suspended in a carrier fluid (water, petroleum-based oil, or silicon-based oil) change the rheological features of the fluid by aligning in chain-like patterns along the flux lines of a magnetic or electrical field. Both magnetically reversible (MR) and electrically reversible (ER) materials may undergo a phase transition from a viscous fluid to a semi-solid state when exposed to a magnetic or electric field [17].

The VIF's mechanical and control components work together to allow it to operate with MR fluid with different degrees of inertia. A mechanical system of bearings, and a spinning disc also includes a motor that can move the mass around to a new spot. Finally, an MR VIF's effectiveness is responsible for regulating the motor's speed and stability and modifying the flywheel's moment of inertia. Since dynamic adjustment permits precise control over energy storage and discharge, understanding MR VIF's performance analysis is essential.

3. VIF APPLICATION AND TECHNIQUE

In a flywheel with variable inertia, the slider's passage through the slot causes the flywheel's inertia to change. Fig. 3 depicts the conceptual design of the VIF. As the flywheel speed counted zero, the inserted springs are at free length initially and contact the hub. Here, gravity's impact is disregarded. The springs can only be compressed; they cannot expand farther. [18].

An engineered container has been used to demonstrate the concept of a flywheel with a variable moment of inertia; as the liquid inside the container spreads out at higher velocities, the container's moment of inertia shifts from that of a disk-type flywheel to that of a hoop-type flywheel, despite their shared mass and outer radius. Even though the quantity of energy extracted within the defined speed range is comparable to that of a flywheel with a hoop-like construction, the percentage of extractability increases by more than 10%.
Moreover, below the lower speed limit, wasted energy is reduced by 50%. There are several restrictions to the demonstration flywheel, but a design method and many potential parameters have been offered in Design of a Liquid-Based Variable Inertia Flywheel by J. Barid (2014) [19]. To combine the issues, the MR VIF is constructed to remotely control the mass and reduce vibration sufficiently.

The moment of inertia of the slider about its own mass center and that of the fixed structural part about the shaft center, respectively, are expressed as

$$J_s = \frac{1}{4} M_s \left(\frac{d_s^2}{4} + \frac{I_s^2}{3} \right) \dots\dots\dots\dots\dots\dots\dots\dots\dots . (1)$$

$$J_F = J_{shaft} + J_{scd} - N J_{slot} \dots\dots\dots\dots\dots\dots (2)$$

where,

$J_{scd} = \frac{1}{4} M_{scd}(r_s^2 + r_0^2)$ is the polar moment of inertia of a solid flywheel of uniform thickness

J_{shaft} is the polar moment of inertia of the shaft

$J_{slot} = m_{slot}\{\frac{1}{12}(d_s^2 + I_{slot}^2) + (r_0 + .5 I_{slot})^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (3)$ [18]

A spring is inserted between the frame and the piston. The coil set to excite the fluid is inserted in the middle of the double-ring groove surrounded by the piston.
If we consider friction force F_f, the spring force F_0, MR damping force F_{mrf}, sin w is a sign function related to the radial slip velocity of piston and k is the spring constant

$$J_{slot} = m_{slot}\{F_0 + (F_{mrf} + F_f) Sin\, w + k \frac{r_i}{m_{slot} w^2 - k} \dots\dots\dots\dots (4)[20]$$

A fluid was used to operate as a succession of inertia masses in S M Salam [21] and L. Islam's [22] proposal for a novel vibration suppression system that uses changeable inertia mass.

Fig. 2. VIF with MR Fluid

3.1 Inertia Controlling with Smart Material

A magnetic field may be used to regulate the viscosity of a family of intelligent materials known as magnetorheological (MR) materials [23]They are made up of magnetically sensitive, non-colloidal particles, often iron or iron-carbide, suspended in a magnetically inert matrix material. A magnetic field causes the magnetic particles to form chain-like formations, raising the matrix's effective viscosity.

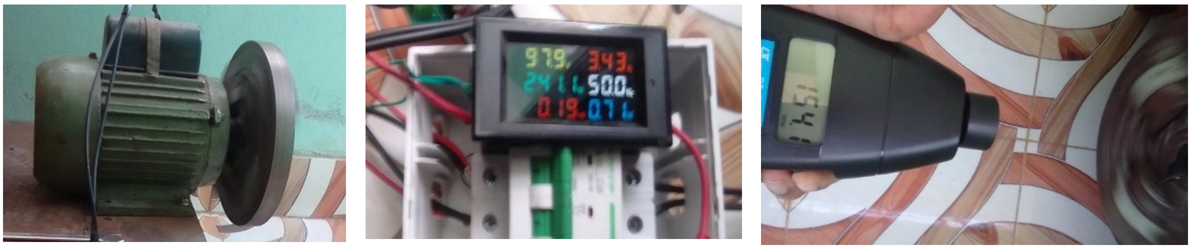
Magneto-rheological fluid (MRF) is the term used to describe the resulting combination most often [24]. A fluid. Elastomers may also be employed as the matrix material because of their increased viscosity when there is no magnetic field [25]. There are also magnetorheological foams, in which a spongy substance, such as a metal foam, is soaked in an MRF or MR elastomer. [26]. The magnetic particles, base fluids, and additives are the three primary elements of MRF [27]The magnetically active component consists of magnetic particles that, when exposed to a magnetic field, produce patterns resembling chains. The base fluid serves as a carrier and lubricant and also offers traditional damping.

Numerous qualities, including friction, corrosion, sedimentation, and viscosity, are improved by using additives. The behavior of the fluid in both its off-state and on-state is impacted by all three of these elements [28].

4. EXPERIMENTAL SETUP AND DATA COLLECTION

In this research, we used semi-active material MRF 140 CG, which has a viscosity between 0.31 to 0.27 Pas at 30^{o} C, and for MR properties, an externally induced magnetic field is used to excite the fluid. Initially, an experimental setup was developed for data collection. A single induction motor applies and operates the flywheel system. A multimeter has measured the electrical system's parameters, and a converter regulates the system's speed. In order to alter velocity, the converter modifies both current and voltage.

The flywheel is initially put through its paces using a fixed load to ensure stability and eliminate undesirable vibrations. In the second scenario, a spring is installed to avoid the mass's damping force and prevent unwanted vibration. Power use data is kept for different speeds to be compared afterwards. At long last, MR fluid has been introduced to the system. Here, Variable Inertia cylinders filled with MR fluid are subjected to an external magnetic field to measure the resulting change in viscosity, and the resulting variations in power consumption at different speeds are recorded.



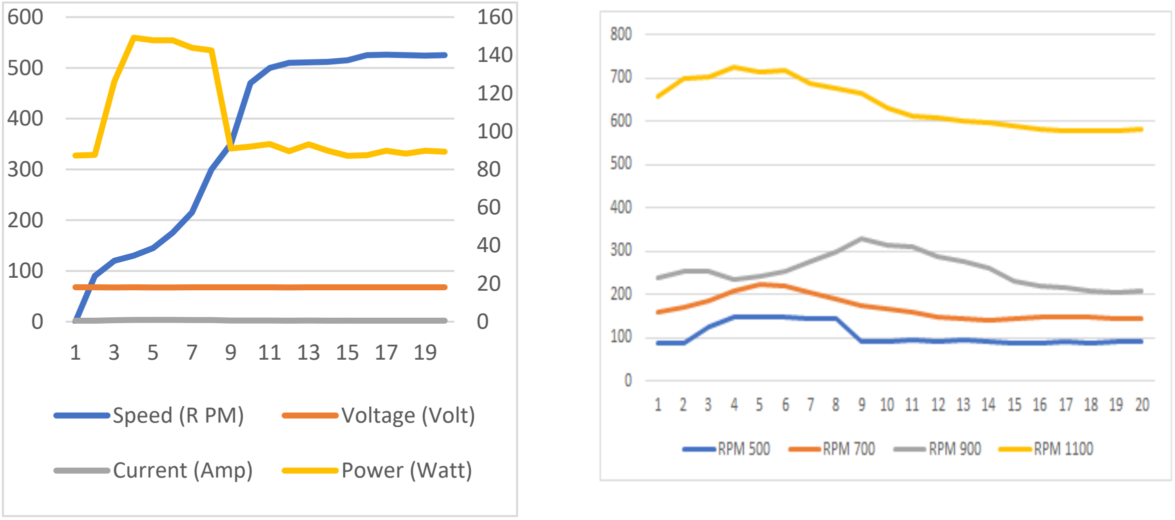
(a) (b) (c)

Fig. 3. Experimental Data collection (a) moving flywheel (b) electrical parameter measurement (c) speed measurement

4.1 Case Study 1: VIF with Spring Setup

Initial measurements have been made using a VIF with a spring configuration and a fixed voltage. Figure 5 (a) depicts the granular data for the 500 RPM speed, showing that power usage rises at startup but stabilizes shortly afterwards. The rate of current consumption changed throughout time. In this case, the current consumption is close to 6.8 to 7 amperes.

Figure 5 (b) compares the power usage at 700, 900, and 1100 RPM. As is the norm, initial power usage is more significant than average but drops down with time. Case Study 1's overall performance analysis results are reported in Table 1. High consumption values are proportional to increases in speed, whereas low speeds result in lower average consumption.



(a)

(b)

Fig.4. Power consumption analogy with speed increment for different speeds with spring set up.

Table1: Analysis of different parameters of Case 1

Speed	Consumption (W)			Stable Time (S)	
(RPM)	High	Average	Low	Speed	Consumption
500	149.18	105.64	87.2	12	9
700	221.2	167.85	142.8	10	12
900	328.6	255.58	204.5	9	15
1100	689.8	638.84	576.2	6	11

Higher speed levels take less time to stabilize than lower ones. In contrast to the features of motion, the stabilization of power consumption exhibits an inverse tendency.

4.2 Case Study 2: VIF with MRF

In the second case study, the system was operated using MR fluid within the variable inertia cylinder. Power consumption, speed stabilization, and viscosity increase while the system operates in a magnetic environment. The viscosity of the MR fluid is measured to be 0.29 Pas, and the motor is driven at several speeds. Figure 5 displays the overall performance curve in relation to the spring configuration and Figure 6 shows the Comparative study of speed build-up for 900 RPM speed.

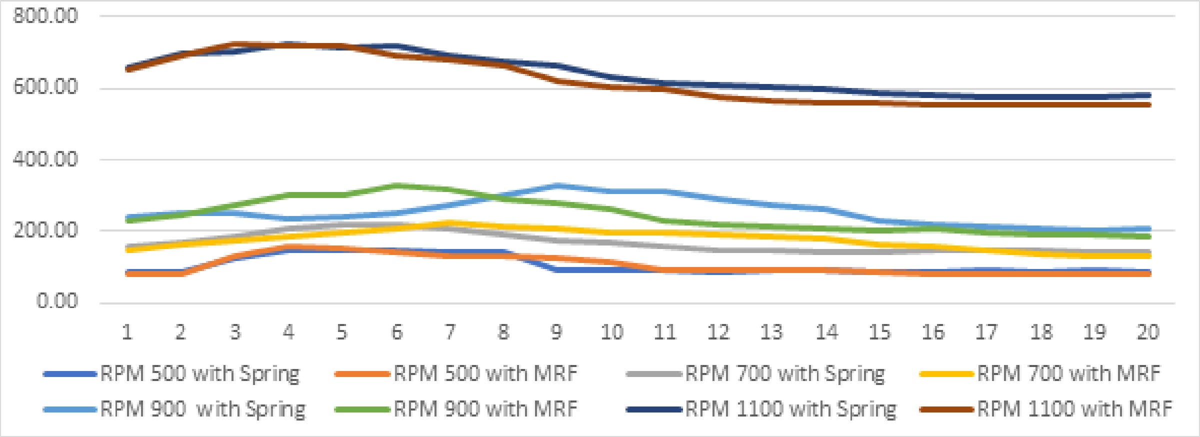


Fig. 5. Comparative study of power consumption with different speed

Table2: Analysis of different parameters of Case 1 and Case 2

Speed RPM	Consumption Spring (W)			Consumption MRF (W)		
*100	H	Avr	L	H	Av	L
5	149.1	105.64	87.2	155.7	105.4	81.1
7	221.2	167.85	142.8	222.1	165.1	133.2
9	328.6	255.58	204.5	329.3	243.2	187.7
11	689.8	638.84	576.2	726.1	619.3	554.7

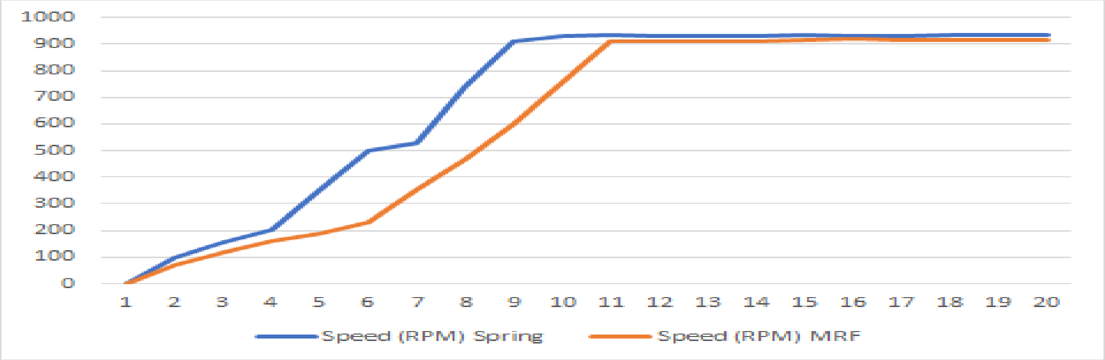


Fig. 6. Comparative study of speed build-up for 900 RPM speed

4.3 *Discussion*

When MR fluid is used, the overall power consumption drops, but the peak value is still more significant than it would be with a spring configuration, as shown in the comparison between cases 1 and 2. When comparing the two scenarios regarding speed, the second one has a more consistent velocity than the first. That issue can define the main reason for lower power consumption with MR fluid.

5. CONCLUSION

According to inertia control theory, the semi-active Controller might be used when traditional vibration control is ineffective. Two of the most obvious would be the car and civil construction sectors, both of which are heavily reliant on controllers in the present day. However, the application side was considered by power consumption fluctuation in this analysis. Therefore, any loaded induction motor's energy consumption may be recycled if the

MRF uses vibration absorbers for VIF. Finally, it seems this sector has great potential for shedding light on the practicality of energy-saving vibration control systems.

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