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Controlling the Variable Inertia of Flywheel: A Scientific Review

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Abstract— Due to the variation of the moment of inertia, flywheels, a well-known mechanical system, can balance the energy output by preventing fluctuations in rotational speed. Examples of prevalent applications are the engine with internal combustion and industrial apparatus. A flywheel with a considerable moment of inertia is mandatory to accomplish reduced angular velocity variations. A flywheel with a variable moment of inertia can be recommended for specific applications to obtain sustainable energy savings. Variations in the masses' radii from the flywheel axis can yield the concept of true inertia. Still, the control techniques for the variable inertial flywheel (VIF) are relatively complex. This paper critically analyses the available literature on VIF control methods and focuses on their application.

Keywords: *VIF, MR Fluid, Flywheel, Smart Material.*

1. INTRODUCTION

Even though flywheels as mechanical devices have been used for many years to store brief energy spurts, it wasn't until the last century that they could store energy for relatively long durations. This device, which utilized the flywheel as its energy source, produced naval torpedoes with a high velocity and a long range. In addition, it was extremely precise due to the centrifugal stabilization, produced no disturbance, and did not modify trim [1]. The efficacy of flywheels has increased considerably over the past few decades, primarily due to the availability of anisotropic materials with improved strength-to-weight ratios. Since the energy-to-weight ratio of a flywheel is a direct consequence of the strength-to-weight ratio of the material used in its production [2], there has been a great deal of recent interest in the development of flywheel topologies that could best utilize the new family of anisotropic materials.

The energy-to-cost ratio of modern flywheels has also increased. Airspace organizations have completed a program that included flywheels made from unique, low-cost materials with a reasonable strength-to-weight ratio. Although in many low-cost flywheel applications, the weight or capacity of the flywheel has little impact on the system, the energy densities for the extremely low-cost flywheel program ranged from 22 to 44 Wh/kg [3]. Applying a large moment of inertia to a flywheel may cause difficulties during machine initiation. Any rotating machine with a large moment of inertia at start-up will have a high moment of inertia torque, which is inefficient. During high-speed, steady-state operation, this system's large moment of inertia conserves energy. Numerous published works propose a variable inertia flywheel to solve this issue.

The design of a flywheel with variable inertia must necessarily be more complex than that of a flywheel with constant inertia. The change of momentum of mass causes a change in inertia force that causes unwanted energy loss, resulting in a vibrating operation. Thus, as the reduction of stability, the unstable forces on the body cause undesirable vibration, which, depending on the machine configuration, can be torsional, linear, or bending. Vibration is a significant problem in any mechanical system that can impact the machine's service life, reduced quality, lack of safety, etc. [4]. Consequently, minimizing and controlling instability due to vibration is a crucial undertaking. The fundamental components of change in system stability are the spring components, used masses, and damping force of a damper. Important to the modelling of an effective vibration isolation system [5]-[6] includes the steps- the effective planning, system performance optimization, and accurate fabrication of these

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three components.

Vibration is typically undesirable when it causes annoying commotion, results in peril, or dissipates energy. As a result, researchers have always been interested in vibration control. In the past few decades, vibration controlling, including passive systems and active or semi-active systems, were the primary focus of research. In these systems, system rigidity has a significant impact on the response of the system. The main consideration is to reduce the response time and to include a dynamic working range. The main benefit of a semi-active controlling system is the requirement for less external energy, which acts as the control energy and is sometimes considered an extra stability than that of active control. Therefore, semi-active control systems are fascinating and utilized in numerous engineering disciplines. For semi-active control, variables can be mass, rigidity, or damping [7]- [8].

A magnetic field may be used to regulate the viscosity of a family of intelligent materials known as magnetorheological (MR) materials [9]. These materials 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.

2. PAPER STRUCTURE

The variable inertia flywheel is a significant innovation that has revolutionised several industries because of the development of advanced technologies and cutting-edge methods. This paper aims to examine the variable inertia flywheel's structure, Control technique, application, simulation, challenges, and future potential.

The variable inertia flywheel is a mechanical device designed to store and discharge energy as efficiently as feasible. In contrast to conventional flywheels in a fixed moment of inertia, the variable inertia flywheel allows the user to alter the moment of inertia dynamically. Due to this characteristic, the device can adapt to different scenarios and optimize energy preservation and discharge based on specific applications' needs [10].

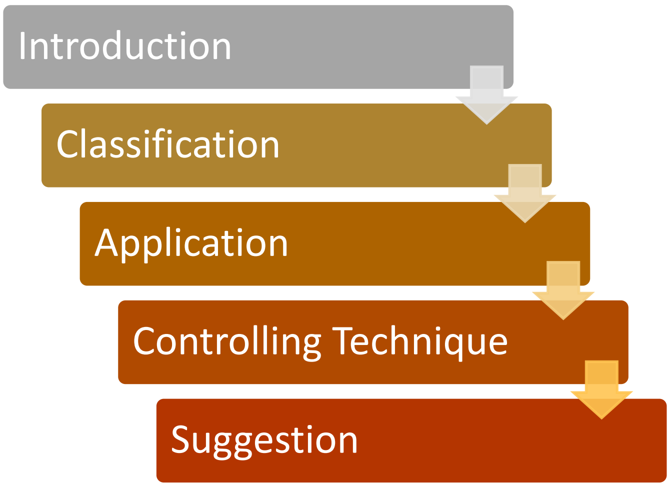

Fig. 1. Structure of the paper

Due to the coordination of its mechanical and control systems, the flywheel with varying degrees of inertia can execute its functions. A motor that can alter the location of the mass distribution is a component of a mechanical system that also consists of bearings and a rotating disc. The control system is accountable for moderating the motor's speed and position, as well as making any necessary adjustments to the flywheel's moment of inertia. This dynamic adjustment allows for exact control in the storage and discharge of energy.

3. CLASSIFICATION OF FLYWHEEL

A description of "VIF" and "FIF" are utilized to indicate two separate kinds of flywheels defined by the inertia characteristics they possess when discussing the classification of flywheels. Following is an explanation of the terms "Variable Inertia Flywheel" (VIF) and "Fixed Inertia Flywheel" (FIF). Flywheels with energy storage are sometimes incorporated into rotating apparatus to withstand sudden load changes.

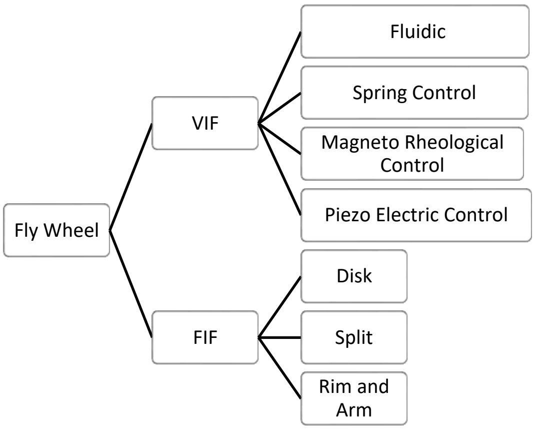

Fig. 2. Types of Flywheels according to inertia

Flywheels with fixed inertia (FIF) and flywheels with variable inertia (VIF) are the two primary varieties of flywheels used to store energy. Despite its widespread use due to its simplicity, FIF's high inertia causes machines to recover to their original speeds slowly. Researchers have debated and investigated the concept of VIF for many years. The control effects of VIF are substantially more potent and of much smaller magnitude than those of FIF. Its limited utility is due to its intricate construction and exacting maintenance. Reduced speed fluctuations in rotating apparatus are a relatively new research and application field [11]. Adaptive attitude control in spacecraft and the storage of electrical energy are two typical applications of VIF today.

3.1 Variable inertia flywheel (VIF)

The Inertia that varies in a Flywheel, as the name suggests, is a flywheel that allows for the dynamic adjustment of its moment of inertia. The resistance of a flywheel to a change in its spinning motion is its moment of inertia, which is determined by the distribution of the flywheel's mass. VIFs may have their moment of inertia modified to suit better their needs or the conditions in which they operate [12]. The flywheel's malleability in terms of its moment of inertia has several advantages. It allows for fine-grained management of energy storage and release, improving power transmission and the overall energy efficiency of a wide range of uses. VIFs may dynamically respond to changes in load or speed, enhancing the system's overall efficiency and responsiveness.

3.2 Fixed Inertia Flywheel (FIF)

In contrast to variable inertia flywheels, fixed inertia flywheels have an inertia moment that does not change while the flywheel operates. FIFs cannot dynamically adjust their inertia characteristics, and once their mass distribution is determined, it cannot be altered [13].

FIFs are often employed as a solution in applications that need a continuous and predictable spinning behavior. They provide dependable rotational energy storage and can serve as a kinetic energy reservoir, both supporting the effective operation of a range of systems. FIFs are often utilized when a fixed inertia is sufficient to meet the system's demands, such as internal combustion engines, industrial machinery, and power production [14].

4. 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 variable inertial flywheel. When the flywheel speed is zero, the springs are initially at their free length and contact the hub. Here, gravity's impact is disregarded. The springs can only be compressed; they cannot expand farther [15].

Elliott et al. presented a particular kind of VIF in which the mass block's displacement could be changed by the centrifugal force and its position could be fixed by the control system using primarily a hydraulic fluid along with a control system including a valve [16]. Thus, a flywheel with variable inertia can increase the stability of equipment at high speeds by starting with a little inertia; on the other hand, a high-speed rotation with a large inertia but requires a suitable controlling system, where the moment of inertia is protected by the inserted hydraulic fluid. Another VIF introduced, which gain the variation of inertia by controlling the valve of fluid flow, was suggested by Dugas [17]. By filling and emptying, Jayakar et al. [18] found that the VIF's inertia could be altered by utilizing any viscous fluid characteristics.

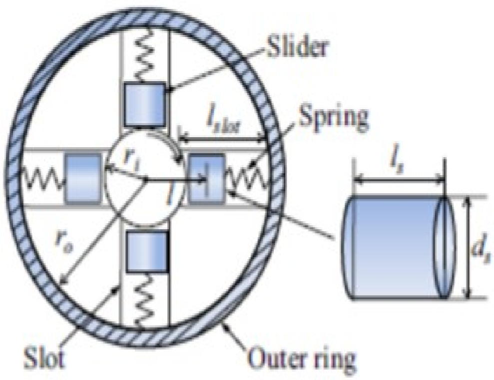

Fig. 3. Schematic presentation of VIF[15]

The VIF can reduce fluctuations in the speed of the engine brought on by the power demand change by managing the fluid in the chamber, but this is challenging since fluid must be filled and managed. The idea of a flywheel with a variable moment of inertia has been demonstrated using a container with an engineered shape; as the liquid inside disperses at increasing speeds, the moment of inertia changes from that of a disk-type flywheel to a hoop-type flywheel, all three of which are constrained to the same mass and outer radius. The percentage of extractability improves by more than 10%, even if the amount of energy that can be extracted within the specified speed range is equivalent to that of a flywheel with a hoop-like design.

Additionally, the amount of wasted energy that remains below the lower speed restriction is cut in half. Despite the demonstration flywheel's limitations in terms of practicality, J. Barid et al.'s Design of a Liquid-Based Variable Inertia Flywheel provides a design technique and numerous future factors. [19]. 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

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

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

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

$J_{slot} = m_{slot}\{\frac{1}{12}(d_s^2 + I_{slot}^2) + (r_0 + .5I_{slot})^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$ [15]

A pre-compressed spring is set between the piston and the frame. The coil is entangled in the double ring groove of 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

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

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

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machine to reduce energy consumption by simulation [22]. The addition of MR fluid can improve the research as well. However, there hasn't been much practice using magnetorheological fluid to create changing inertia in a flywheel. Variable inertia magnetorheological flywheels (VIMRF) have yet to be fully investigated regarding their potential for energy savings.

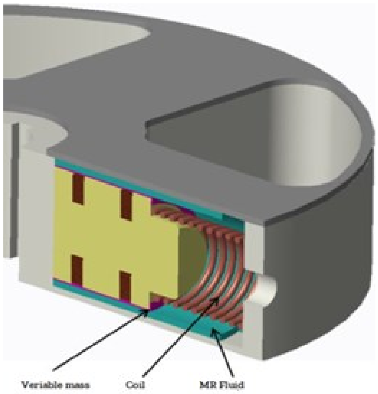


Fig. 4. VIF with MR Fluid[20]

The VIF prototype is shown in Fig. 5. There are sixteen sliding rods inserted around the flywheel's center, with a mass block and a spring on each sliding rod, spaced every two rods. The mass block is connected to the flywheel center via the spring. When the sliding rod is placed into the mass block's holes, the mass block may move easily. The viscous damper of the mass block is formed by the airtight plate, and the viscous coefficient of the mass block is adjusted using the air holes on the side cover [23].

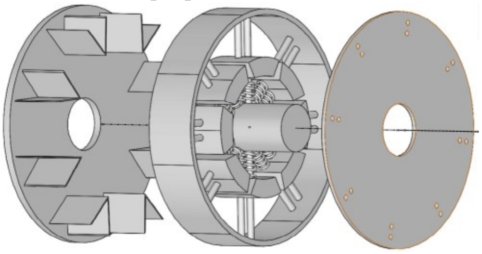


Fig. 5. VIF used for DG [23]

WEH consists mostly of the transmission system, mechanical motion rectifier, generator connected with VIF, circuitry, and ancillary components in Fig. 16. While operating in the ocean, the buoy's up-and-down motion in response to wave excitation is considered the transmission module's vibration input. The ball screw transmission module transforms recompensing vertical motion to recompensing rotation. During transmission, the mechanical motion rectifier turns the reciprocating rotation to a one-direction rotation via clutches and boosts the angular velocity. The VIF can store or release energy to stabilize the generator's speed and enhance its effectiveness. Lastly, the AC generator produces electricity, which either powers the load or is stored in a capacitor.

4.1 VIF In Wave Energy Converter

The VIF's inertia is the wheel's constant and the mass blocks' variable. Spring-pushed mass blocks and four cantilever sliders lessen initial torque. The mass blocks' rotation radius r rises when accelerating due to centripetal force and decreases when decelerating due to spring force, resulting in a smoother velocity shift and longer overrunning phase. When modelling the increased output voltage of the WEH after including the VIF, it is important to account for the overrunning period of the mechanical motion rectifier. The rotational speed, m, of the generator at a single instant, T, is modelled. (Fig. 6). The WEH overrunning phase without VIF varies between 0.11 T and 0.32 T for 0.50 Hz and 25 mm amplitude and between 0.03 T and 0.40 T with VIF. The duration is lengthened, and its velocity diminishes gradually. Due to overrunning, it is estimated that the mechanical motion rectifier contributes 16% to the rise in output voltage, while the VIF puts up an added 25%. So, the output benefits from the VIF's ability to cut down on velocity attenuation in a streamlined fashion.

The WEH has been tested both with and without VIF setup to determine its effectiveness. The input force is measured with and without VIF during the meshing phase. However, during the overrunning period, the rise in input force with VIF is slowed (Fig. 6a) because the overrunning period with VIF is longer than without VIF.

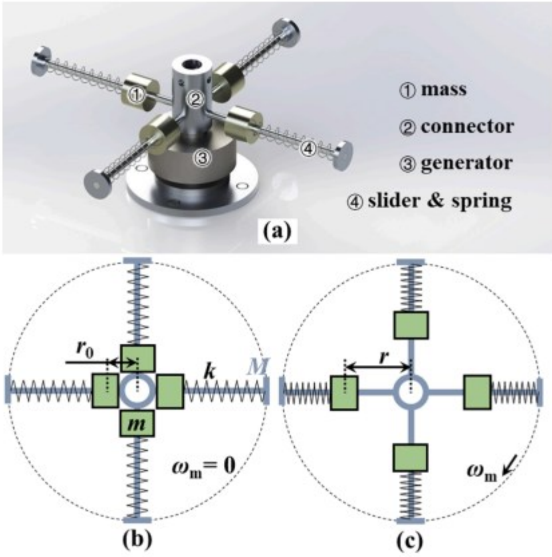


Fig. 6. Design of the VIF. (a) The structure of the VIF. (b) Normal state
(c) Operating state [24]

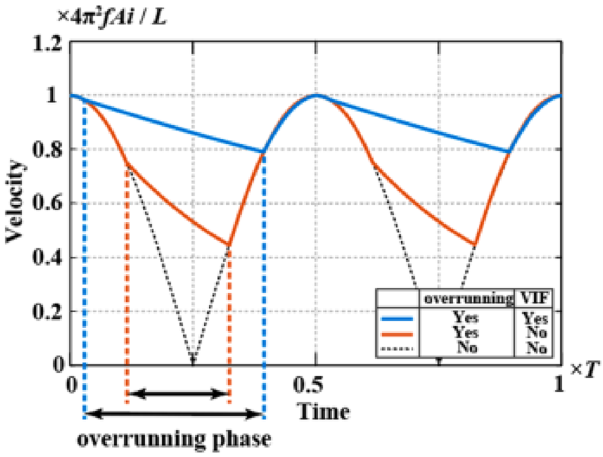


Fig. 7. Simulated angle of rotation of the generator [24]

In addition, the output voltage with VIF is greater than in the absence of VIF during the overrunning period (Fig. 6 b). After integrating the voltage curve (Figure 6b), the expansion of the overrunning period raises the output voltage by 8.2%, while with VIF, it increases by 13.5% in output power and 25.5% in efficiency. The highest output power is 2.15 W, the average output power is 1.17 W, and the efficiency is 51.54%.

4.2 VIF in Power Utility

A flywheel with balanced positioned dampers was utilized in a ball screw-type power takeoff system. Due to their ability to change inertia, small mass spring dampers can be cost-effectively adapted to the system's conditions. In addition to the passive configuration, partially active and active configurations are proposed to improve the system's efficiency and expand its functional extent [25].

4.3 VIF In Spacecraft System

In the design of a diesel-producing unit that experiences pulsed load, the traditional fixed inertia flywheel (FIF) is replaced by a variable inertia flywheel (VIF). FIF is commonly utilized due to its easy-to-build design, however, its high inertia causes the speed to restore steadily to its original value. VIF's size is significantly reduced but its control effects are much increased in comparison to FIF. However, its complicated design and laborious routine maintenance prevent it from seeing widespread use. Presently, VIF is mostly applied to the adaptive attitude control of spacecraft and the storage of electric energy; it is rarely employed to reduce the speed fluctuations of spinning gear [26].

4.4 VIF In Wind Energy Converter

A wind turbine's rotor blades are loaded with mass that increases the rotor's moment of inertia. This flywheel's inertia can be adjusted by repositioning the weights near to the center of the flywheel. It has a traditional drivetrain with a transmission and a rapidly spinning generator. In the literature, different designs of these wind power generators are explained in considerable attribute. Simulating the beginning part-load operation with constant wind speed shows the flywheel system's behavior. In the second situation, the turbine operates at partial load when wind speed temporarily meets its rated value. Comparisons are made with and without the flywheel. In the third instance, the same approach is followed when the turbine is operating at full load, and a temporary fall in wind speed causes the wind turbine's output to diminish. The wind power generator operates at a partial load while the speed of the wind remains constant. For the flywheel to turn, its mass must be transferred from the smallest to the biggest radius and then back to the smallest [27][28].

4.5 VIF In Breaking System

Figliotti and Gomes proposed a VIF mechanism for bicycle restorative braking systems. Most transportation energy storage methods are either chemical or electrical in nature. Most purely mechanical energy conservation systems are capable of absorbing and releasing small amounts of energy over extremely brief timeframes. These systems are ideally suited for use as restorative decelerating systems for vehicles for high-rate energy transfer. Bicycles with regenerative braking systems were created using springs. However, flywheels are more desirable than mechanical springs because they may be configured to have larger power densities [29].

4.6 VIF In Vibration Reducer

In order to improve the effectiveness of passive vehicle suspension, it is proposed to employ a vibration absorber based on a two-terminal mass (TTM) with a variable moment of inertia (VMI). Sliders in a hydraulically powered flywheel do the VMI for the system. In reaction to strong vertical oscillations, the vehicle's moment of inertia grows, while weak vertical oscillations cause the moment of inertia to shrink. By means of a hydraulic mechanism, the system transforms the linear motion between the two suspension terminals into a rotational motion of the flywheel. Due to centrifugal force, the sliders inside the flywheel travel away from the flywheel's Centre when the vertical oscillation of the vehicle is greater, increasing the moment of inertia. When a car's oscillation is weaker, the opposite is true. Therefore, the moment of inertia can be adjusted to suit the conditions of the road. Dynamic modelling, simulation, and experimental investigation have been used to study the performance of the proposed TTM-VMI absorber. Besides sinusoidal excitations, the proposed VMI system exceeds its constant moment of inertia equivalent regarding response time, road handling and safety, ride comfort, and suspension bend [30].

4.7 VIF in Engine Performance Enhancement

Electrical landing gear of aerospace system drives, outfitted via traction motors, enable the tires of single-aisle passenger aircraft to be powered, allowing them to travel on the runway. The implementation of powered wheels addresses the issues of low engine efficiency, excessive fuel consumption, and elevated pollutant levels in the aircraft during the taxiing operation. The powered wheel electric drive system comprises an electric traction motor, a set of planetary gear assemblies, and a wheel. This research aims to enhance the torque output of the powered wheel by optimizing the characteristics of the planetary gear assembly in the electric drive system. Subsequently, two testing protocols are devised to quantify the torque of the powered wheel electric drive system.

These two test schemes utilize moments of inertia and resistance loading to simulate the real vertical load of the aircraft on the powered wheel during the taxiing procedure. The initial plan uses a mass block to replicate the mass of the typical aircraft. In contrast, the second scheme utilizes a flywheel with an adjustable moment of inertia to approximate the bulk of sizable commercial aircraft. [32].

Table 2. Variable Inertia Flywheels and their applications

VIF Components	Applications	Enhancement
Mass spring damper based VIF	Power hydraulic motor system	Motor efficiency increment
4 Slider based VIF	Diesel Generator Unit under Pulsed Load	Diesel Generator output power quality and efficiency improvement
Actively controlled VIF	Wave energy converter	Energy harvesting and performance acceleration
Band VIF	Urban transit bus	Efficiency increment
Four cantilever sliders base VIF	Wave energy harvester	Energy harvesting and performance acceleration
Mass spring damper based VIF	Regenerative Braking on A Bicycle	Breaking system performance enhancement
4 Slider based VIF	Hybrid Power Systems	Power quality and efficiency improvement
Mass spring damper based VIF	Hydraulic drive	Motor efficiency increment
4 Slider based VIF	Passive Vehicle Suspensions	Improvement of suspension system

5. CONTROL STRATEGIES FOR VARIABLE INERTIA

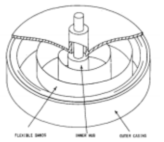
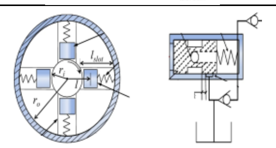
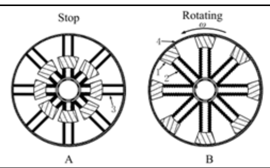
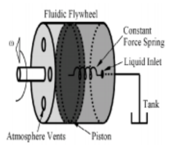
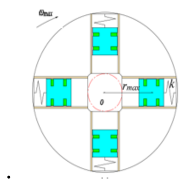
Small mass spring dampers may be used to change the equivalent mass and associated parameters of economically and dynamically adaptable systems with variable inertia and mass amplification effects. In addition to the passive configuration, semi-active and active configurations are also provided to improve performance and widen the proposed VIF system's functional range. The dynamics of a flywheel with variable inertia have been revealed by numerical simulations, which have also shown its potential and confirmed its ability to adapt to different wave conditions.

In a passive design, mass-spring-dampers are evenly distributed throughout the flywheel plate; in a semi-active configuration, the mass may be temporarily locked at its origin; in an active configuration, the spring stiffness can be adjusted. Refer to Figure 6; the setups of VIF are described with different conditions especially passive, active, and semi-active state. Additional switches are introduced for the mass-spring dampers for the semi-active VIF. Semi-active VIF is like passive VIF while the switches are off; when the switches are activated, the mass will

Vol. 4 No. 1 2024
E-ISSN: 2785-8189

remain locked at its origin. The mass-spring dampers in symmetric places will be simultaneously locked to maintain the VIF's balance [33]. The Semi-active devices cannot directly input energy into the system they control. This crucial requirement ensures that system parameter changes do not result in parametric excitation [34]. When employing the word "semi-active" in literature, this is often not taken into appropriate consideration. It has been shown to function better than a passive control system and is utilized as one effective method to reduce unwelcome vibrations in many applications.

TABLE I: MAJOR VIF CONTROL TECHNOLOGIES.

Technology	Schematic Figure	Findings
Band-type variable inertia flywheel		BVIF-integrated systems save 30% on fuel. Regenerative braking reduces brake wear by five times.
Hydraulic flywheel system with two terminals for variable moment of inertia		The variable inertia flywheel was analyzed using a two-terminal hydraulic system. Experimentally determined hydraulic device and variable inertia flywheel parameters.
Spring		The variable moment of inertia flywheel stabilizes diesel generator speed under loads. SIMULINK simulations show that the variable inertia flywheel reduces diesel generator loading impact.
Fluidic Variable Inertia Flywheel		Experimental evidence suggests that the fluidic flywheel can keep its angular velocity constant despite having a mass moment of inertia that is one order of magnitude smaller than that of a traditional flywheel.
Magneto-rheological fluid based variable inertia flywheel		MRVIF is created and tested for semi-active adjustment. The maximum allowable range for adjusting inertia is 27.2%.

Active vibration control is, however, overshadowed by the system's relative expense, complexity, and instability [35]. Semi-active dampers are hydro-mechanical control mechanisms that can change how much energy they release while drawing just a small amount of electricity. Magneto-rheological fluid (MRF) is the term used to describe the resulting combination, which is most often [36] a fluid. Elastomers may also be employed as matrix material because of their increased viscosity when no magnetic field exists [37]. There are also magnetorheological foams, in which a spongy substance, such as a metal foam, is soaked in an MRF or MR elastomer [38]. Magnetic particles, base fluids, and additives are the three primary elements of MRF [39]. The magnetically active component is made up of magnetic particles, which produce patterns resembling chains when exposed to a magnetic field. In addition to serving as a carrier and lubricant, the base fluid also offers traditional damping. The use of additives improves numerous qualities, including friction, corrosion, sedimentation, and viscosity. The behavior of the fluid during active, semi-active or passive state has an impact on the improvement of these qualities [40][41].

VIF is one of the common concepts that utilized the effect of moment of inertia in a flywheel system. It is difficult to control the mass in the VIF as there is a change in momentum of the mass. Previously different fluidic VIFs is used for improvement in design of a VIF [16] [17] [18][42][45]. The main objective of these design variations is to save energy requirements. Some VIF concepts are also utilized to harvest energy [24], where the spring and semi-active fluid is used to get optimum output. Many literatures focus their research on reducing the unwanted vibration using VIF in diesel generation power production. Most of the systems used for VIF mass controlling are passive type and some are semi active. Only a few used with active control but little cost benefit achieved [43][44].

6. CONCLUSION

Though there are semi-active fluids like MR fluid that can be used to improve control, most of them used for energy harvesting and vibration control in power production. There is a new concept developed by Yang et al to use MR fluid for controlling the power consumption of rotating electrical machines but only theoretically proved. The application of electrical rotating machine power consumption optimisation can be another interesting topic for VIF application. Also, the utilisation of different smart material in MRF and ERF also explores a new horizon in the applied side. According to inertia control science, the semi-active Controller has potential applications that other vibration control does not. The most apparent are the civil construction and automobile industries, which currently employ controllers. There may be more that haven't been considered, however. Considering the prospect of utilising semi-active controllers as vibration absorbers for constructions whose inherent frequency varies over time is exciting. One example is vibration absorbers for VIF that adjust to the increasing mass when loaded. Finally, it seems that this is a promising field for the design of governing mechanisms in general and that it will help us better understand their limits.

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