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An Innovative Device for Multi-Degree of Freedom and Positional Stability-Spherical Smart Brake

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ABSTRACT

Recent days the science and technology have made too much development in the design of electronics and mechanical engineering using standard materials that are popularly known as "Mechatronics". Such type of materials have the ability to change in configuration like shape or size simply by adding a little bit of heat, or to change from a liquid to a solid almost instantly when near a magnet; these materials are called smart materials. Smart materials have one or more properties that can be dramatically altered. Most everyday materials have physical properties, which cannot be significantly altered; for example if oil is heated it will become a little thinner, whereas a smart material with variable may turn from a liquid state which flows easily to a solid. Each individual type of smart material has a different property which can be significantly altered, such as viscosity, volume or conductivity. Varieties of smart materials already exist, and are being researched extensively. These include piezoelectric materials, magnetorheostatic materials, electrorheostatic materials, and shape memory alloys. Some everyday items are already incorporating smart materials (coffeepots, cars, glasses) and the number of applications for them is growing day by day. In case of controlling of degree of freedom in spherical joint, there are so many inventions for 2-degree of Freedom, 4DOF, etc. But multidegree of freedom is need of many of the applications such as joystick; however the designed joint does not exhibit self-control. Through the paper a spherical type brake applying smart fluid will be designed and analyzed is explained. This type of brake will be useful to be adopted in the applications demanding positional stability and multi degree of freedom. Finite element analysis and exponential validation of the proposed brake will form the major future part of the work.

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I. INTRODUCTION

Now-a-days, science and technology made development with the combination of electronics and mechanical engineering which popularly known as "Mechatronics". The smart material is one of them which include the mechanical and electronic technology together with change in configuration like shape or size simply by adding a little bit of heat, or to change from a liquid to a solid almost instantly when near a magnet called as smart device. Smart materials have one or more properties that can be dramatically altered. In

Most day-to-day materials used, have physical properties, which cannot be significantly altered; for example when oil is heated it will become a little thinner, whereas a smart material with variable may turn from a liquid state which flows easily to a solid. Each individual type of smart material has a different property which can be significantly altered, such as viscosity, volume or conductivity. Varieties of smart materials already used, and are being researched. These include piezoelectric materials, magnetorheostatic materials, electrorheostatic materials, and shape memory alloys.

Controllable fluids are materials that respond to an external excitation field. When exposed to an electric or magnetic field, their rheological behavior exhibits remarkable changes. These smart materials are commonly referred to as Magnetorheological (MR) fluids, Electrorheological (ER) fluids and ferrofluids. Amongst these smart fluids, MR fluids gain more attention since they can produce the highest stress, which can be applied into many applications. An MR fluid is a suspension of micron-sized magnetically soft particles in a carrier liquid, which can exhibit dramatic changes in rheological properties. The change from a free-flowing liquid state to a solid-like state is reversible and is dependent on the presence of a magnetic field. Iron powder is the most popular material used as particle inclusion due to its high saturation magnetization. Under the influence of a magnetic field, these iron particles are arranged to form very strong chains of “fluxes” with the pole of one particle being attracted to the opposite pole of another particle. Once aligned in this manner, the particles are restrained from moving away from their respective flux lines and act as a barrier preventing the flow of the carrier fluid.[1,2,3]

Whereas the spherical joint is used for joining two circular shaft and others having multi degree of freedom. Also used in mostly for robots, joysticks liked devices where multi degree of freedom and positional stability required. Through paper the proposed work, details regarding these spherical smart brake is explained

II. LITERATURE REVIEW

Jong-Seok Oh, Young-Min Han, Sang-Rock Lee and Seung-Bok Choi discussed on 4-degrees-of-freedom (4-DOF) haptic master using an electrorheological (ER) fluid which is applicable to minimally invasive surgery (MIS) systems. By using a controllable ER fluid, the master can easily generate 4-DOF repulsive forces with the advantages of a simple mechanism and continuous force control capability. The proposed master consists of two actuators: an ER spherical joint for only 3-DOF rotational motion and an ER piston device for 1-DOF translational motion.[1]

DorukSenkal and HakanGurocak introduced a position controlling system for a hybrid actuator using position, velocity and pressure feedback loops as well as a force-blending algorithm. The actuator uses combination of a spherical MR-brake and three air muscles to create motion in two degrees-of-freedom (DOF). The spherical MR-brake is developed for rotating along three axes and restricts all motion when engaged. The controlling system helps prevent overshoot and instability in the air muscles by engaging the MR-brake when necessary. It also gives the significant improvement in response time by making high-gain PID control of air muscles possible. [4]

Another worked a new 2-DOF hybrid actuator concept is explored as a powerful and compact alternative to conventional haptic actuators. The actuator is a combination of a spherical MR-brake and three air muscles and is integrated into a joystick that can apply forces in two degrees-of-freedom. The air muscles are used to create high active forces in a compact volume and the brake compensates for the “spongy” feeling associated with air muscles. [5]

In another research a passive haptic interface is explored as a surgical help for dental implant surgery. The placement of a dental implant is critical since positioning mistakes can make to permanent damage in the nerves controlling the lips, long lasting numbness, and failure of the implant and the crown on it. Haptic feedback to the surgeon in real time can decrease dependence on the surgeon's skill and experience for accurate implant positioning and increase the overall safety of the procedure. [6]

Also introduced the research explored design of a magnetorheological (MR) spherical brake as a multi-DOF actuator. The general goal was to design a compact but powerful brake using the serpentine flux path approach. An optical position measurement system was also designed to eliminate the gimbal mechanisms that are typically used in spherical joints for position measurement. [7]

In this first prototype, the commonly used pen-based haptic devices [8] were taken as the basis. Hence, three joints were actuated with MR-brakes for creating the haptic feedback and the remaining three joints at the wrist were left un-actuated to provide motion in 6 DOF. In essence when the MR brakes are activated, the position of the base of the hand-piece is constrained, whereas the orientation of the hand-piece is not. In the future prototypes, the last 3 DOF need to be actuated if orientation also needs to be constrained. This can be accomplished by using smaller MR brakes at the wrist. However since rotary MR brakes are 1 DOF devices, a gimbal mechanism need to be employed with 3 rotary MR brakes to create the spherical joint at the wrist.

A two-DOF joystick was developed for haptics applications [9]. The design integrated 2-1-DOF MR disc brakes into a joystick using a gimbal mechanism. The MR disc brakes had 78 mm diameter. The overall prototype joystick had a base of about 160 mm × 160 mm and provided up to 10 Nm braking force to the joystick handle. Another multi-DOF device was designed using two groups of MR actuators to simulate virtual forces in 2D [10]. The system used four MR rotary brakes each with 170 mm diameter and 10 mm height. The overall system size was 630 mm × 540 mm × 970 mm. The maximum output torque on the handle was 10 Nm. Two other multi-DOF devices were reported that used electrorheological (ER) fluids. The first device used both clutch and brake mechanisms to achieve active and passive force feedback [11].

The device integrated four AC motors with a spherical ER joint at the centre.The spherical joint assembly had an estimated diameter of 110 mm. When the motors were included, the system took up about 45 cm × 45 cm area. A complex controller was implemented resulting in about 7 N force output on the joystick handle from the spherical joint.

The second device consisted of a metal sphere which was concentrically mounted in a metal half sphere [12]. The gap between them was filled with ER fluid. The spherical joint had 102 mm diameter. At 2.8 kV/mm electric field strength, the device produced 1.2 Nm output torque.

Through the paper another alternative, by designing a spherical smart brake. The spherical brake allows motion about any arbitrary axes. When it is activated, it restricts motion around all three DOFs simultaneously. To the best of our knowledge, this is the first ever multi-DOF and positional stability for spherical brake using smart material.

III. SELECTION OF SMART MATERIAL

a In the earlier development, most eras of technological development have been connected to utilize and alter the use of materials such as the stone, bronze and iron ages. Until relatively recent years, the vigorous technological change in many respects has switched towards information technology. These changes are generously demonstrated by the ability of microprocessors to control daily domestic appliances. However, the generation of the information technology has stimulated material sciences and led to a new family of engineered materials and structures. Smart materials are materials that have multiple properties (chemical, electrical, magnetic, mechanical and thermal), or can transform energy (photovoltaic, thermo-electric, piezoelectric, photoluminescent, and electrostrictive) which can be altered or tuned using external fields. In general, smart materials can be divided into many categories based on their stimulus and response as shown in Table .1 [2, 13].

TABLE 1: CLASSIFICATION OF THE SMART MATERIALS & THEIR RESPONSE

MR materials are field responsive rheology under smart materials, where their properties may be controlled by the execution of an external magnetic field. The materials are currently enjoying renewed interest within the technical community in terms of the fundamental and applied research. Usually, MR materials comprise of MR fluids, foams and elastomers. The focus on MR fluids makes possible numerous applications in the automotive, aerospace and other sectors of technology and has attracted much interest of many researchers in recent years. [13]

A. Field Responsive Fluids

Field responsive fluids are materials that undergo significant responses leading to consequent rheological changes upon the influence of an external field. There are two main classes of smart fluids; MR fluids and ER fluids under the influence of applied magnetics and electric fields, respectively. The fluids comprise a carrier liquid, such as a dielectric medium, including mineral oil or hydrocarbon oil, and solid particles. MR fluids require the use of solid particles that are magnetizable, and ER fluids make use of solid particles responsive to an electric field. In addition, ferrofluids (magnetic liquid) also can be categorized as smart materials. In the presence of a magnetic field, colloidal magnetic fluids retain their liquid properties.

TABLE 2: COMPARISON THE PROPERTIES OF MR FLUIDS, ER FLUIDS & FERROFLUIDS.

Sr No	**Items**	**MR fluids** [16]	**ER fluids** [17]	**Ferrofluids** [18]
1	Particulate material	Ferromagnetic, ferrimagnetic, etc	Polymers, Zeolites, etc	Magnetite, hematite, etc
2	Particle size	0.1 – 10 µm	0.1 – 10 µm	< 10 nm
3	Carrier fluid	Water, synthetic oils, non-polar and polar liquids, etc	Oils, dielectric gel and other polymers	Aqueous paramagnetic salt solution
4	Density (g/cc)	3-5	1 -2	1-2
5	Off viscosity (Pa.s^{-1} @ 25 °C)	0.1 to 0.3	0.1 to 0.3	0.002-0.05
6	Required field	~3 kOe	~ 3 kV/mm	~ 1 kOe
7	Yield strength (Field)	100 kPa	10 kPa	$\Delta\eta$ (B) /η (0) ≈ 2
8	Device excitation	Electromagnets and / or permanent magnet	High Voltage	Permanent magnet

They do not generally exhibit the ability to form particle chains or develop a yield stress. However, ferrofluids experience a body force on the entire fluid, and this force

Stimulus	**Material Class**	**Response**
Temperature	Shape Memory Alloys	Mechanical strain
	Pyroelectrics	Electric polarization
Electric Current	Piezoelectrics	Mechanical strain
Electric Field	Electroluminescent Materials	Light emission
	Electrochromic Materials	Color change
	Electrorheological Materials	Rheology change
	Electrostrictors	Mechanical strain
Electric Field / pH	Electroactive Polymers	Mechanical strain
Magnetic Field	Magnetorheological Materials	Rheology change
	Ferrofluids	Rheology change
	Magnetostrictors	Mechanical strain

causes the fluids to be attracted to regions of high magnetic field strength. Table 4.2 shows the comparison of some of the properties between them. In a general manner, MR and ER fluids demonstrate specific advantages or disadvantages which can be considered as complementary rather than competitive. They have their own markets and applications in different fields. For instance, one of the advantages of MR fluids is higher stresses that they can withstand, while the major advantage of ER fluids is a smaller size of the systems that they can be developed with them[14, 15].

One benefit of these materials is that electromechanical actuators can be appropriately designed and fabricated. The utilization of MR or ER fluids can work to rapidly respond in active interface between sensors or controls and mechanical outputs. The fluids can be employed in vibration isolation systems as an example of precision surface shaping/polishing machines, mechanical clutches, brakes damping devices, building seismic isolators, torque/tension controllers, gripping/latching devices and fluid flow controllers [13].

B. Magnetorheological Fluids

MR fluids can be described as magnetic field responsive fluids which are part of a group of relatives known as smart or actively controllable fluids. The discovery of MR fluids is credited to Jacob Rabinow at the US National Bureau of Standard in 1948. MR fluids consist of magnetically permeable micron-sized particles dispersed throughout the carrier medium either a polar or non-polar fluid, which then influence the viscosity of the MR fluids. On the other hand, MR fluids are controllable fluids that exhibit dramatic reversible change in rheological properties (elasticity, plasticity or viscosity) either in solid-like state or free-flowing liquid state depending on the presence or absence of a magnetic field. In the presence of an applied magnetic field, the suspended particles appear to align or cluster and the fluid drastically thickens or gels. The flow resistance (apparent viscosity) of the fluid is intensified by the particle chain. When the magnetic field is removed, the particles are returned to their original condition, which lowers the viscosity of the fluid. The fluid structure is dependent on many factors such as volume fraction, magnetic field strength and carrier fluid. The fluid structure is also responsible for a rapid formation and is reversible either in solid-like state or free-flowing liquid state. The changes of solid-liquid state or the consistency or yield strength of the MR fluid can be precisely and proportionally controlled by altering the strength of the applied magnetic field. These characteristics provide simple, quiet and rapid response interfaces between electronic control and mechanical systems. [13]

Most of the researchers used carbonyl iron as particles scatter in oil medium, for instance silicone oil hydrocarbon oil, mineral oil and hydraulic oil. The material also can be produced at a relatively lower cost as compared to MR fluids that include hydrophobic-oil type fluids as a carrier fluid. Iron powder is the most popular material used as particle due to its high saturation magnetization about 2.1 T. Those particles are arranged in a proper order from one pole to another pole of a magnet to form very strong chains or fluxes. Initially, in the absence of the magnetic field, the iron particles in the space between two walls move unrestrained. In the presence of the magnetic field, the iron particles are organized along the direction of the applied magnetic field. These particles are constructed into a uniform polarity and connected to the walls. Once aligned in this manner, the iron particles are refrained from moving out of their respective flux lines and act as a barrier to an external force. The yield stress, in this case, symbolizes the maximum of the stress-strain relationship, and the chains will break when the stress has reached its maximum which allows the fluid to flow even if the magnetic field is still applied.

MR and ER fluids use feedback information such as rapid response interfaces between electric controls and mechanical systems to vigorously change the material behavior. By changing the material behavior, the performance of the devices is intensified to a certain level that unattainable using conventional materials and devices. MR fluids can be considered as unique smart materials because they produce milliseconds response time. The fluids may be used in both small and large displacement devices in order to generate very large forces and torques without reliance on the velocity of the working systems. The performance of the fluids depends on the fluids' structure in connection with many factors such as volume fraction, carrier fluid and particle size. The development and success of MR fluids in recent years are mainly due to the rapid research devoted to improving the technology into one that is commercially viable. Research studies done by industries such as Lord Corporation and Liquids Research Limited and all over the world have contributed to the MR technologies in order to be used in a wide variety of applications.[19]

VI. PROPOSED SPHERICAL SMART MR BRAKE

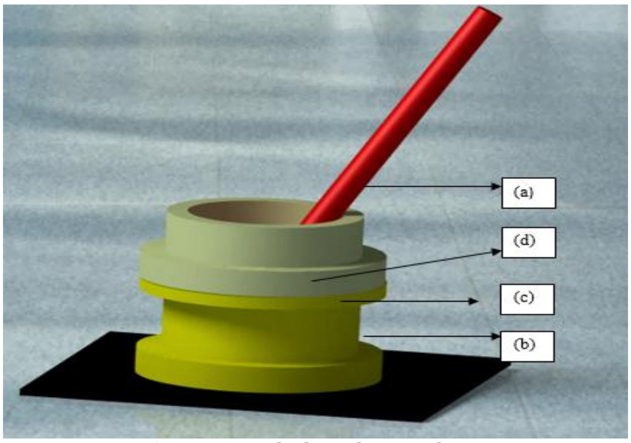

Fig. 1. ProposedSpherical MR Brake

Devices that use MR fluids have several advantages over devices with ER fluids. Yield shear stress of MR fluids is much higher than ER fluids, this leads to higher torque output. The ER fluids require potential differences as high in order to be activated, whereas devices that use MR fluids have much lower voltage requirements usually in the range of a few volts. This becomes even more important if the device is to be used in environments, such as haptic, where human interaction will be present. Failure in a high voltage circuit can be very dangerous to the user. A big challenge in designing devices that use MR fluids is routing the magnetic flux path through the fluid while keeping the overall device size compact and the output torque high. Both in ER and

MR fluids the fields that are applied to the fluid must be perpendicular to the fluid gap.

This requirement is satisfied easily with ER devices as applying a potential difference between any two surfaces would automatically create electric fields perpendicular to those two surfaces hence also perpendicular to the ER fluid in the gap. With MR brakes it is more difficult since a coil for an electromagnet must be housed in the brake and the resulting flux path must be guided through the fluid by carefully designing the magnetic circuit. Previously other designed single DOF rotary, compact and powerful MR brakes using a serpentine flux path concept. In this approach, aluminium and steel rings were employed to weave the magnetic flux path through the MR fluid gap. This led to activation of much more of the MR fluid in the same compact volume.

The same concept was adapted in the design CAD model (Fig. 1) of the MR spherical brake. The MR spherical brake consists of four main components: (a) Steel ball with rod, (b) Steel socket, (c) Coil, and (d) MR fluid between the ball and the socket. The static analysis done using FEM (Fig. 2) software which shows the chances of failure in steel ball connected with rod is validate with experimental work.

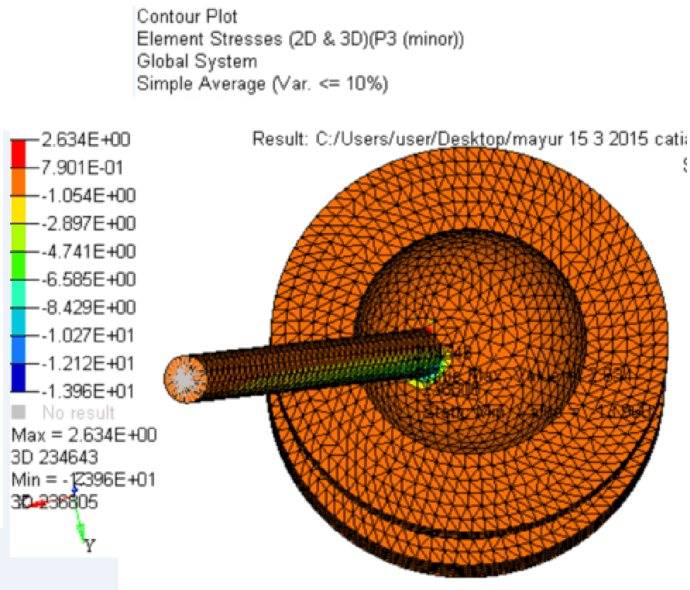

Fig. 2. FEM Analysis of MR Spherical Brake

V. Conclusions

Through the study of smart material, the magnetorheological fluid has been selected by studying its characteristics and properties with comparing it with another smart fluid like ferrofluids and electrorheological fluid. The selection of this smart material will help to obtaining the multidegree of freedom and positional stability, for that design the spherical smart break with analysis using FEM software and validate it by experimental work and test its performance for future study.

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