Design, Manufacture and Experimental Characterization of Magnetorheological Rotary Brake Based on an Peristaltic Pump System

Tomasz Korona

University of Catania Faculty of Engineering: Università degli Studi di Catania

Pawel Kowol

University of Catania Faculty of Engineering: Università degli Studi di Catania

GRAZIA LO SCIUTO (✉ grazia.losciuto@unict.it)

University of Catania Faculty of Engineering: Università degli Studi di Catania <https://orcid.org/0000-0001-9384-7232>

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Design, manufacture and experimental characterization of magnetorheological rotary brake based on an peristaltic pump system

Tomasz Korona¹, Paweł Kowol¹ and Grazia Lo Sciuto^{2,1*}

¹Department of Mechatronics, Silesian University of Technology,
Akademicka 10a, Gliwice, 44-100, Poland, Gliwice.

²Department of Electrical, Electronics and Informatics
Engineering, University of Catania, Viale Andrea Doria, 6,
Catania, 95125, Italy, Catania.

*Corresponding author(s). E-mail(s): grazia.losciuto@unict.it;
Contributing authors: tomasz.korona@op.pl;
pawel.kowol@polsl.pl;

Abstract

In this article the design and manufacture of the innovative MR rotary brake based on peristaltic pump inspired by the concept model of the pliers and the Rochester Pean forceps are presented . For the calculation and analysis of created structure comprehensive of roller, housing and pliers, simulations concerning the stress and strain are conducted to investigate the deformation and possible failure of part or assembly. Experimental tests including measurements of compression force and magnetic field were conducted to evaluate the performance of proposed designed MR rotary brake based on peristaltic pump system constituted by tube containing MR fluid and pliers with arm responsible of the movement and arm completely hold on bench vise

Keywords: Magnetorheological fluid;rotary brake;peristaltic pump;measurements of current;force;magnetic field

1 Introduction

The major manufacturing organizations want to reduce the risk of harm to people, equipment, or the environment. An intelligent risk-reduction strategy protects personnel, machines, and the environment, increases productivity, improves efficiency and increases uptime. The technology available for E-Stop and holding applications are commercially requested. Rotary brakes are designed for many applications including medical surgeries, haptics, automotive, vehicle and driving. Analytical and mathematical models are developed using the magnetic circuit analysis to determine the braking torque and to describe the rotary torque of the brake. The "brake" is mainly associated to phenomenon of friction forces in vehicle safety. The active element of the system is pressed against a braked element, such as a bicycle wheel. The control of such a phenomenon takes place with the participation of a hydraulic, mechanical, pneumatic or electric support mechanism. The braking component is composed of metal elements typically equipped with the friction materials called brakes lining that ensure effective high dynamic coefficient of friction. The brake system is used for: speed regulation, mechanical arrest and measurement of the braking torque. A rotary brake is called a maintenance-free and ready-to-install brake system [1]. In automation, rotary shock absorbers are available in an adjustable or fixed setting and to attenuate in both directions. Single-acting systems are also used in specialized modeling. The material of housing depends on the intended use and operating conditions of the brake. The transmission of force and torque takes place through a clutch or rack, which allows a smooth and uniform movement of the system. Rotary dampers ensure controlled opening and closing of flaps, covers, compartments and drawers. They can brake directly in the pivot point or linear through the gear rack to obtain a steady and smooth delayed movement, ending with the stopping of the system. Rotary dampers are filled with a medium that is pushed through a slit or a gland. The braking torque depends on the fluid viscosity and the inductance section. New kind of brake and brake system for braking process based on magneto-rheological fluid (MR) offer performance advantages over conventional hydraulic brake systems for automotive industry. An MR rotary disc brake has the property that its braking torque changes quickly in response to an external magnetic field strength [2]. MR fluid brake is more efficient than conventional braking system in terms of the weight reduction, and response time [3]. Perfluorinated polyether (PFPE)-based MR fluid is investigated for the prosthetic knee that uses MR fluids to actively control its rotary stiffness. [4]. MR actuator is used in a leg exoskeleton that can function as a brake or a clutch controlled to provide appropriate assistive torque and adapt to various working conditions or environment [5]. The exoskeleton and humanoid robots are expected to behave similar to the human neuro-muscular system, using variable damping actuators along with variable stiffness actuators and MR brakes that can provide variable damping in a relatively small actuator volume [6]. The designed magnetorheological elastomer peristaltic pumps allow

a potential application of conveying stress sensitive fluids [7]. Peristaltic pumping systems are widely adopted in the primary mass transport, heat transport and in microfluidic systems. The peristaltic pump is a positive displacement pump used for pumping a variety of fluids. The fluid is contained inside a tube within the pump. The pumping principle, called peristalsis, is based on alternating compression and relaxation of pipe that generates vacuum sucking the product and consequently a constant delivery. Each peristaltic pump is equipped with a tube which allows the pumping with high abrasion resistance for easy flow of solids and high viscosity. The pump flow is proportional to the speed, making it suitable for dosing. In peristaltic pumps, the tube is compressed by the rollers during rotation, creating the vacuum to aspirate the liquid through the tube. The liquid comes into contact only with the tube preventing the contamination, thus eliminating the risk that the pump contaminate. The advantages of this type of pumps are a delicate pumping preventing oxidation, emulsions, crushing of berries and seeds, and contacts between the product and mechanical parts. Peristaltic pumps are ideal for use with corrosive and viscous fluids, as the only part of the pump to come into contact with the fluid is the tubing. In medical device industry or in the laboratory, peristaltic pumps are used in a variety of applications: processing sterile fluids, for treatment of liquids aseptically and at low stress, dialysis, filtration, or for wastewater treatment, in the presence of highly abrasive and viscous fluids in mining industry or biogas plants or condensate removal in gas analysis applications or in agriculture for dispensing food or beverages, vitamins, or chemicals. A variety of pumps has been widely developed with associated applications and fabricated in laboratories using 3D-printing [8]. A design for a miniature self-priming peristaltic pump consisting of a Delrin acetal plastic body with two integrated valves, a flexible silicone tube, actuated by a motor, a shape memory alloy, and manually actuated is presented in [9]. The comparison of positive displacement pumps and the silent pumping mechanism of valveless moving chambers of propagative peristalsis pumps in nature and the technical adaptation in engineering inspired by the biological role models is presented in [10]. In [11] open-source peristaltic pump constructed with a combination of three dimensional (3D)-printed parts and common hardware, which is amenable to deployment with microfluidic devices for point-of-care diagnostics is programmed with the Arduino IDE to generate custom responses to an operator controlled switch. A biomimetic tubular pump actuated by eight silicone-based pneumatic ring actuators with an elliptical inner conduit longitudinal diameter of 2 cm allowing for a simple, quiet and safe transport of a wide variety of Newtonian and non-Newtonian fluids with variable viscosity has been developed in [12]. Combining the peristaltic pumping models with the perspective from passive, capillary effect-driven microfluidics, quasi-1D lumped element model gives a first-order understanding of the working mechanism of discrete actuation pressure pulse-driven peristaltic pumps in discrete flow regime which targets the initial filling process of liquid into microfluidic channels as described in [13]. For the greatest accuracy and controllability, a

Fig. 1: Realized rotary brake MR based on peristaltic pump

self-priming peristaltic pump is driven directly by stepper motors with 2 or 3-roller rotor and single-phase DC or BL and AC brushed motor. The roller assembly is either driven directly from the motor shaft or via a gearbox between the motor and peristaltic pump head. Usually, DC and BLDC motors used together with a gearbox allow to precisely control and set direction and the peristaltic pump speed depending on the flow need . Stepper motor speeds can be regulated by using an external controller board.

In this paper we present the design and manufacture of small peristaltic pump whose significant advantages is to work in the system as a rotary brake, in addition gears, mechanical valves, motors are eliminated to avoid friction and non-essential elements. The designed pump system has been implemented in 3D using the dedicated program Autodesk Inventor Professional 2021. Stress and Strain analysis are conducted to investigate possible failure of part or assembly and identify critical part.

In particular the modeling elements were assembled into one coherent model with moving element in the entire mechanism. The main assumption is to realize peristaltic pump system operating in a closed circuit. The element causing the movement in experimental set-up inside the pump is not traditionally an electric motor, but the movement caused by the external force. For this purpose, the pliers have been designed useful to transfer the linear movement to the rotary movement inside the positive displacement pump (Fig. 1).

The control of peristaltic pump without gear motor is carried out with an internal magnetic field with the goal to work as an hand that is blocked grabbing the object. The movement of the system is controlled by the viscosity of the material inside the tube of rotary brake based on peristaltic pump .

Therefore detailed kinematic and impact of force analyses, magnetic measurements, simulation models are presented as well as experimental measurements which demonstrate suitable performance for future applications in robotic hand exoskeleton including functions such as touching, holding and grasping object during its manipulation. The mechanism was developed and tested.

Fig. 2: Peristaltic pump: the liquid being sucked into the pump tube, then trapped by the head roller and expelled as the next roller passes over the tube. When the rollers rotate, a vacuum is generated in the tube which leads to the suction of the liquid, ready for the passage of the next roller on left side and realized rotary brake MR based on peristaltic pump (a), sample of pump with three rollers (b), designed rollers with diameters of 14 mm and 15 mm (c).

The stress-strain analysis is calculated for a part and assemblies of rotary brake pump system. The paper is organized as follows: the Section 2 introduces the design and structure of rotary brake based on peristaltic pump, simulation analysis and properties of MR fluid used in the realized device. The Section 3 describes the developed experimental set-up. The Section 4 discusses the performed experiments and the obtained experimental results. The Section 5 closes with the conclusions and future works.

2 Methodology

2.1 Design of rotary brake based on peristaltic pump

The novel small peristaltic pumps has been designed and manufactured requiring an accurate modelling and simulation.

2.1.1 3D Design and Geometric Model

Among the various types of positive displacement pumps, a peristaltic pump was characterized by flexible hose inside the pump with the possibility of pumping high viscosity fluids and easy control of a constant amount of fluid pumped during the rotation of the impeller. The components include in the designed peristaltic pump are:

- Pliers with a fixed arm and mobile actuating arm
- Pump housing
- Rollers with the shaft
- Gear
- Sleeve
- Forcing hose
- Fastening elements

Fig. 3: Combination of pliers drawing used to build the model such as scorpion's pincers and the Rochester Pean forceps pliers (a) and assembly of the designed layout (b)

2.1.2 Conceptual Design

The design and manufacture of the innovative brake rotary based on peristaltic pump is inspired by the concept model of the pliers.

Based on appearance and functionality derived from the natural environment, the shape of the designed pliers is supposed to resemble the two claws of a crustacean, closest to the position of the hands and fingers in the case to drive the system. The complicated solution of pliers structure is modelled on the Rochester Pean forceps. The peans are used to arrest haemorrhage and are commonly used to occlude /clamp vessels to control bleeding. Their characteristic structure may have a significant impact on their handling during work or tests when used in the drive of a hydraulic pump system. Moving the pivot point (also known as fulcrum) closer to the center of the pliers redefines how the pliers are gripped between the fingers (Fig. 3(a)) In order to select the best solution for appropriate design of pliers to work with a positive displacement pump, the criteria have been considered :

- Low complexity of the pliers construction
- Convenience of use
- Compressive strength
- Simplicity of connection with the pump
- size of the arm opening angle,
- Possibility to modify the construction of the pliers
- Minimum weight of the pliers
- High stiffness

The construction of the pliers has fitted properly in the fingers to limit the risk of failure. Taking into account the forces acting on the pliers and application of force, the pliers didn't deform when compressed and resist to compression without cracks or deflection.

Fig. 4: Models of plier fixed (a) and movable arm (b), realized plier fixed (c) and movable arm (d)

The construction of the structure has required sufficient amount of material to make the pliers stiff. The distance between the arms and the pivot point of the pliers didn't cause some unwanted breakdowns. The perfect solution of shape and design of pliers is reported in Fig. 3(b).

All elements of small peristaltic pump inspired by Rochester Pean forceps and the two claws of a crustacean were printed using the XYZprinting Da Vinci PRO 1.0 open 3D printers working in FFF technology (FUSED FILAMENT FABRICATION) with a maximum print size of 200 x 200 x 200 mm. The printer is equipped with an improved laser engraving system and the material used for engraving was PLA.

DA VINCI 1.0 PRO 3D Printer from XYZprinting is supplied with software that allows to adjust the print parameters. The ability to modify head retraction settings allows to print models without streaks or stains that occur in the printing process. The 3D printer allows to adjust the temperature settings for the extruder nozzle and aluminum work table in order to use various filaments with a diameter of 1.75 mm. The automatic filament loading function ensures correct feeding of material to the head without loading it. The printer is equipped with a first generation EEPROM chip, which is attached to the bottom of the filament cartridge. XYZware software is included in the set with the 3D printer DA VINCI 1.0 PRO and allows to adjust basic and advanced print settings such as: layer thickness, filling, print speed, wall thickness, automatic building of supports, etc. and more advanced settings. The designed pliers comprise two arms connected each other. The fixed arm of pliers is intended to properly grab and hold as shown in the design of Fig. 4(a),(c).

The second plier arm of the drive system includes a mobile arm. The task of this arm is to perform a linear movement, caused by the applied user force and to convert linear motion to rotary motion (Fig. 4(b),(d)).

The developed solution for transferring linear motion to rotary motion regards the use of a gear wheel and a suitable shape inside the movable arm that have allowed to achieve the desired effect for the entire system. The Fig. 6(d) shows the described element with the key on the gear wheel. As the pliers will be used by various users, the compressive strength of the fingers is a significant criterion for their construction. Grip strength is typically measured in pounds, kilograms, or Newtons by squeezing a type of muscle strength testing equipment, known as a dynamometer, about three times in each hand.

Fig. 5: Simulation of pliers for man's hand (a), Stress analysis of pliers (b), Stress analysis of housing (c) and roller (d).

Men aged 20-30 typically have the greatest strength, while women over 75 have the lowest. In people aged 20-29 years old, average grip strength is 46kg for men and 29kg for women. The pliers can operate with two fingers or grasp with whole hand and squeeze with all strength. For verifying the accurate construction three dimensional stresses and strains build up in many directions for experimental production. Simulations of the plier arms were performed to obtain the resistance to compression strength. In this case simulations of a woman and man handshakes are conducted. The strength of the user's hand muscles in the simulations affects the movable element-arm of the pliers and it does not negatively affect their shape. The forces of 504N and 310N in Fig. 5(a) have caused a deformation of 0.4 mm and 0.15 mm, respectively. Despite the small dimensions, such results ensure the pliers sufficiently stiff. For the calculation and analysis of created structure, simulations concerning the stress [MPa] in all main directions (X,Y,Z), planes (XX,XY,XZ,YY,YZ,ZZ) are conducted relative to complex structure comprehensive of roller, housing and pliers. The stress analysis environment allows analyzing assembly and part design under used materials, loads and constraints (boundary conditions). After defining the materials, loads, and constraints for the condition the stress analysis was established in order to test the realized device. For the model of housing and the roller was defined a loading force of 100N, and for the nippers was defined a loading force of 580N. The most important stress exist in the ZZ set for the pliers, because the force is directed in the Z axis and has the greatest impact on z-axis as in the Fig. 5(b) is emphasized the stress levels. After performing stress analysis of entire drawing model in defined technological conditions, the maximum stress values for model reaches 9.84 MPa. In the housing and roller the maximum stress value for each model reaches is respectively of 1.137 MPa and 0.0188 MPa (Fig. 5(c),(d)) Maximal consequential values suggests that there is no negative impact on functional parts assuming that there won't be negative effect on quality of final product.

Fig. 6: 3D printed roller (a), simulation model of roller with application force of 30 N to shaft (b), housing created in Inventor (c) simulation model of housing with an acting force of 100 N (d).

2.2 Peristaltic pump construction and visual stress analysis

A peristaltic pump considered self-priming works using positive displacement. Fluid is fed through the tubing by rollers that rotate slowly squeezing and compressing a flexible tube against the pump housing. As the roller mounted on a shaft moves over the tubing, it expands and creates a vacuum to allow more fluid to enter. During operation, at least one roller closes the tubing. The rollers are turned either directly by a motor or a gearbox.

The effect of the hose with the tubing causes a negative pressure at the top part, but at its end it causes an over pressure.

In the pump the important feature to consider is the size of the rollers and shaft to ensure pump accuracy. Manufacturers involved in the production and design of peristaltic pumps offering models with two or more rollers, even twelve rollers used for medical purposes and laboratory purposes due to the high accuracy. The number of rollers used in peristaltic pumps has a major effect on fluid handling. For higher flow rates only two or three rollers are used.

Three rollers have been selected and realized in the presented peristaltic pump model as shown in the created sketch Inventor Professional 2021 Fig. 6(b),(d). Stress, displacement and strain analysis can help to find the best design alternatives for a part or assembly. In Stress and displacement analysis structural loading conditions are evaluated. The simulation performs the geometric modeling and determine structural design. Further the analysis of displacement can define the movement of individual points on a structural pump system due to various external loads.

The rollers were combined with the shaft into one integral element. The entire element has been printed using the 3D printer maintaining all oval contours Fig. 6(a)

The roller size at the end of the drive shaft also affects the performance and efficiency of the pump. The roller presses the flexible tubing causing the liquid displacement inside the hose. A larger roll exerts more force on the tube. (Fig.6(b)). Due to the small dimensions of housing sizes in which the pump is to operate, the differences between each variant shaft are small (Fig.6(c)).

Force [N]	10	30	100
Roller1 [mm]	0.000053	0.0002	0.00066
Roller2 [mm]	0.00048	0.00018	0.0006
Roller3 [mm]	0.000043	0.00016	0.00055

Table 1: Acting force and deformation of roller

The resistance to compressive strength of the rollers has been considered . On each rollers, a simulation was performed for 3 different values of forces acting on the roller during operation. The force was applied to each roll separately. The entire axis, on which rollers are placed, was hold back. The Tab. 1 below presents the obtained deformation values that can be observed during the functioning of the entire pump at various loads with maximum value of force of 100 N.

The deformations caused by the action of the hose on the shaft are very small, although the shaft has small dimensions. During the tests 3 shafts were used appropriately to work in the rotary brake system.

Peristaltic pumps have a single mechanism of action. The distinguished element of a pump is the housing, the shape, size, color and even position in relation to the entire system. Square ,round and hexagonal housings are used for special applications.also Due to the light weight, the device uses a round housing with an outer diameter of 40 mm and protrusions for the two ends of the flexible hose.The walls of the housing are 2.5 mm thick. The height of the element is 15 mm. Such dimensions are sufficient to hold a pump with a three-roller shaft.

The modeling process of all elements in Autodesk Inventor Professional 2021 has proceeded to assembly into one coherent set of elements consisting of: 2 pliers arms, rollers, case and flexible hose.The assembly is presented in Fig.3 .

2.2.1 Properties of MR fluids

Magnetorheological (MR) fluids offer many engineering solutions and applications exhibiting highest stress. MR Fluids consist of magnetic particles in a carrier fluid. In the presence of a magnetic field, the suspension of micron-sized particles changes from a fluid state to a semi-solid instantaneously. The flow resistance (apparent viscosity) of the fluid is intensified by the particle chain. When the magnetic field is removed, the fluid just as quickly returned to its natural original state which is known as Newtonian fluid. Furthermore, the degree to which the fluid changes to a semi-solid is proportional to the strength of the magnetic field, giving the fluid infinite controllability and precision.As a result, a yield stress is developed in the fluid. The changes of solid-liquid state 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 the rapid response interfaces between electronic control or sensor and mechanical system outputs for appropriate utilization of MR fluids in the design and fabrication of mechanical clutches, brakes damping devices

and torque and gripping/latching devices . Controllable fluids are materials that respond to an external excitation field. When exposed to an electric or magnetic field, their rheological behaviour exhibits remarkable changes [14], [15].

The benefit of the controllable yield stress in MR fluids is often realized in devices such as MR dampers for the ability to respond quickly while providing large dynamic force.

In this investigation the commercial MR fluid type Lord MRF-132DG (Lord Corporation, Cary, NC, USA) is contained in a flexible tube fitted inside the realized peristaltic pump casing. The MR material has been inspected using the digital Microscope Keyence VHX-7000 4K High Accuracy capable of capturing high resolution images (Fig.7(a)).

Fig. 7: MR fluid under Digital Microscope Keyence (a) and realized MR peristaltic pump (b)

The aim of this research is to control the peristaltic pump system containing MR fluid inside the tube with high viscosity . Experiments were conducted to test the peristaltic pump system applying pressure force to pliers fixed arm and characterize the behavior of MR fluids at various magnetic field strength.

The aim of this test is to perform the movements of opening and closing repetitively without any object to grasp. Magnetic stimuli were delivered to test the maximal aperture and maximal closure of arms.

3 Experimental Set-up

3.1 Test Set-up

Experiments were conducted to evaluate the proposed designed rotary brake based on peristaltic pump system constituted by pliers with arm responsible of the movement and arm completely hold on bench vise.

For this purpose, the experimental set-up used to investigate the system shown in Fig. 8 consists of probes for measuring magnetic fields, magnetic sensor, DC Regulated Power Supply, force gauge, cooling fan, electromagnetic coil, and Tested pump.

Smart magnetic sensor model SMS 102 TEL-Atomic is used to measure axial or transverse magnetic fields up to 2000.0 mT with Measurement Probes of 12.5mm long and it operates on the basis of the Hall effect. This means that it generates an output signal when its sensitive area is affected by a magnetic field produced by a permanent magnet.

The indispensable tool of dynamometer FORCE GAUGE 5 Kg full scale, Model:FG-5000A LUTRON ELECTRONIC is provided for compressive force measurements. The gauge is equipped with a maximum reading pointer and the gauge has a flat tip with a dial diameter of 1 1/2 inches. In the conducted test the tip of gauge perpendicular has been placed to the movable arm of pump system in order to apply compression (push) force and carry out measurements of force.

The magnetic field in the electromagnetic small copper coil EM42/3349 with turns $N=1400$, is generated by the current produced and regulated by DC Regulated Power Supply (GOPHERT CPS-6003 0-60V 0-3A) and a Hall probe has been used to measure magnetic field strength fairly accurately. The electromagnetic coil is equipped by part of flexible tube containing MR fluid fitted inside the pump casing and sealed with metal gaskets on top in a closed circuit. The measuring probe was placed inside the system to precisely measure the values of the electromagnetic field. The fan has been used to cool off the heat of the system during the measurements.

The tests were conducted, firstly, fixing the rigid bar of the designed peristaltic pump system in bench vise mounted directly to workbench, determining a point of force application in the movable bar (arm) of peristaltic system and measuring the magnetic field strengths of coil generated by variable currents in the pump system. Specifically as shown in Fig. (Fig.7(b)) one pliers arm of realized pump system was held by bench vise ensuring the angle higher than 90° between the movable arm and fixed arm of pliers attached to a workbench. The tip of the dynamometer has been placed close to the mobile arm in order to measure the force necessary to carry out the movement of the arm ensuring the movement of movable arm of pump system parallel to the fixed arm in bench vise.

At the requested of compression force applied on rotary brake based on pump system, the MR device is activated to solidify inside the flexible tube under the effects of the passing electromagnetic field generated by the electromagnetic coil element, and creates the required mechanical locking action to maintain the system composed by pliers in locked position.

As in the case of MR fluid actuators, the locking mechanism strength provided by the pump system design is proportional to the strength of the applied magnetic field.

The basic steps of conducted research have included:

- Testing of rotary brake based on peristaltic pump system without MR liquid contained in the flexible tube fitted inside the pump system and the application of electromagnetic field

- Testing of rotary brake based on peristaltic pump system with MR liquid inside the tube fitted inside the pump system, with application of different values of electromagnetic field

Fig. 8: Measuring station for MR rotary brake based on peristaltic pump including pump, coil, regulated DC power supply, force gauge, magnetic field measurement probe and fan

4 Experimental Results

4.1 First Testing campaign

The performance tests have been defined in absence of magnetic field and no presence of MR fluid in the tube of rotary brake pump system (Fig.10) The dynamometer is used to test the strength of mobile arm in the realized pump system with diameters of 14mm and 15mm (Fig.9).

Therefore performance tests have been conducted to obtain the force applied on mobile arm of pliers relative to peristaltic pump whose diameter is 15mm. In this case the MR fluid didn't fill completely the tube and the external values of voltages rated with DC Regulated Power Supply are applied (Fig.11).

External values of current rated with DC Regulated Power Supply are applied to electromagnetic coil generating the magnetic B-field. The magnetic B-field [mT] is in function of current applied to coil as shown in Fig.12. The recorded values of magnetic B-field [mT] and currents [A] are in accordance to theory of MR and physics. When an external magnetic field is applied, for increasing magnitude of currents, the MR fluid viscosity and yield stress increase considerably so that the strength applied on mobile arm increase significantly as shown in Fig.13 for the two diameters of rotary brake pump

Fig. 9: Test conducted to measure the strength of the designed pump (diameter of 14mm and 15mm) in absence of magnetic field and no presence of MR fluid in tube

Fig. 10: Test conducted in absence of MR fluid on right side and Test conducted in presence of MR fluid on right side

system. The Force [N] applied to arms of pump in function of current of coil and after the inserting of MR fluid inside the peristaltic pump for diameter 15mm and diameter=14mm . The force for d=14 mm is a less than the force applied to system pump with diameter 15mm.

The Magnetic B-field in function of Force is reported in Fig.15 for diameter 15mm and diameter=14mm of designed rotary brake.

4.2 Second Testing campaign

In the second testing campaign the performance tests have been defined in the presence of the controlled magnetic field for the MR rotary brake pump system. A small socket is realized in the movable arm of system in order to guarantee the easily movement of dynamometer tips on the flat surface of the arm. By the way a Silikon+Teflon smar tf silikon PTFE coating has also been applied between the arms to eliminate the high friction coefficients. In addition the tube was filled completely with MR liquid placed part in the coil

Fig. 11: Test conducted to obtain the response of force for 15mm diameter of designed pump in presence of MR fluid

Fig. 12: The magnetic B-field [mT] as a function of current [A] for diameter of 14mm and 15mm of designed rotary brake system pump with the tube filled of MR fluid

and part in the rotary system pump. The tests conducted for voltage of 60 V have considered higher current values than 0.7 [A] so the cooling fan has been inserted to avoid excessive heating of the system.

The Forces, current and Magnetic B-field values obtained during the tests are linearly dependent each other. As the intensity of Magnetic B-field increases (Fig.17), so the necessary force enhances to move the arm of the system (Fig.16).

Fig. 13: The Force [N] in function of current [A] for diameter 15mm and diameter=14mm of designed rotary brake system pump with the tube filled of MR fluid

Fig. 14: Magnetic B-field as function of Force for diameter=15mm of designed rotary brake based on pump system

5 Conclusion and Future Works

The novel MR rotary brake based on peristaltic pump is designed and manufactured in this article. The numerical method is used to compute the stress and strain analysis of the device. The experimental tests were included the force acting on pliers arm of realized system held by bench vise and magnetic B-field measurements were carried out. The MR fluid has been used as smart material with property of changing its viscosity when exposed to a magnetic field. By placing this fluid into the tube of peristaltic pump with an electromagnet coil able to generate magnetic field, a controllable resistance motion can be created. The off-state viscosity controls the ability of the device to move freely in the absence of magnetic field. The designed MR rotary brake works with low power consumption and few included elements with advantages of simple construction and maintenance, high efficiency without brushless permanent-magnet DC motor based actuator. The subject of future specific application will be to study the MR rotary brake device based on peristaltic pump as

Fig. 15: Magnetic B-field as function of Force for diameter=14mm of designed rotary brake based on pump system

Fig. 16: The Force [N] in function of current [A] for diameter 15mm of designed rotary brake based on pump system

Fig. 17: Magnetic B-field in function of Force for different current values (d=15mm) designed rotary brake based on pump system

hand exoskeleton joint with more energy efficient and providing the sensation of holding a virtual object.

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- Consent to participate
The authors consent to participate.
- Consent for publication
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- Availability of data and materials
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- Code availability
Not applicable
- Authors' contributions
Tomasz Korona: conceptualization and developing methodology/manufacturing in laboratory ; visualisation; data analysis and investigations.
Paweł Kowol: Project administration, supervision, conceptualization and developing methodology/manufacturing in laboratory; data analysis and investigations
Grazia Lo Sciuto: writing-original draft preparation,supervision,data analysis and investigations in laboratory, review

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