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

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Abstract

In this article the design and manufacture of the innovative MR rotary brake based on a 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 and testing of compression force and magnetic field were conducted to evaluate the performance of proposed design 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 manufacturing strategies include the promotion of health and safety in the workplace, providing the improvement of the efficiency and profitability. Emergency stop devices or E-stop function are essential in applications necessary for the safety. Rotary brakes (RB) are designed for many applications including medical surgeries, haptics, automotive, vehicle and driving. Analytical and mathematical models are developed for rotary and braking torque. A rotary brake is maintenance-free and ready-to-install brake system [1]. New kind of brake and brake system for braking process based on magneto-rheological fluid (MR) offer many advantages in the automotive industry. The torque of MR rotary disc brake commutes rapidly under an external magnetic field. [2]. The MR fluid brake is more efficient than the conventional braking system in terms of the weight reduction, and response time [3]. The MR fluid is investigated to control the rotary stiffness in the prosthetic knee. [4]. MR actuator is used in a leg exoskeleton that can function as a brake or a controlled clutch to provide appropriate assistive torque and adapt to various working conditions or environment [5]. The humanoid robotic and exoskeleton anticipate the behaviour and movement alike to the human neuromuscular system, depending on MR brakes and variable damping actuators characterized by stiffness. [6]. MR elastomer peristaltic pumps are used for stress sensitive fluids [7]. Peristaltic pumping systems are widely adopted in the primary mass transport, heat transport and in microfluidics. systems. 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 (Fig. 2(a)). The liquid comes into contact only with the tube, preventing the contamination, thus eliminating the risk that the pump contaminates. The advantages of pumps are related to a delicate pumping preventing oxidation, emulsions, crushing of berries and seeds, and contacts between the product and mechanical parts. Peristaltic pumps are used in the presence of highly abrasive and viscous fluids, to avoid the contact of fluids in the tubing.

Generally the self-priming peristaltic pump is driven directly by stepper motors with 2 or 3-roller rotor and AC brushed motor or single-phase DC that are used to control the direction and speed depending on the flow. The roller system is exactly controlled by motor shaft or via a gearbox between the motor and peristaltic pump head [8].

In this paper the design and manufacture of small peristaltic pump are presented 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 the possible failure of part or assembly and identify critical part [8].

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

In particular the modeling elements were assembled into one coherent model with the moving elements 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 is 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 a 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 objects during its manipulation. The mechanism was developed and tested.

The stress-strain analysis is calculated for a part and assemblies of the 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.

Fig. 2: Peristaltic pump (a), design of peristaltic pump using 3 rollers (b), realized rollers with diameters of 14 mm and 15 mm (c).

The number of rollers adopted in peristaltic pumps plays an important role on fluid handling. Two or three rollers lead to higher flow rates.

2 Methodology

2.1 3D Design and Geometric Model of rotary brake based on peristaltic pump

The novel small peristaltic pumps have been designed and manufactured, requiring an accurate model and simulation. 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.

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

The design and manufacture of the innovative brake rotary based on peristaltic pump are 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

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

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. (Fig. 3(a))

All elements of the 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 designed pliers comprise two arms connected each other. The fixed arm of the 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)).

Simulations of the plier arms in the rotary brake system were performed to obtain the resistance to compression strength. 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 stiffness of pliers. 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 most important stress exists 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) that emphasizes the stress level. After performing stress analysis of entire drawing model in defining technological conditions, the maximum stress value for model reaches 9.84 MPa. In the housing and roller of system the maximum stress value for each model is respectively of 1.137 MPa and 0.0188 MPa (Fig. 5(c),(d)) The maximum values have suggested no negative impact on functional parts and no effect on the quality of the final product.

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

2.2 Peristaltic pump construction and visual stress analysis

A peristaltic pump is considered a positive displacement pump used for pumping a variety of fluids. The fluid is contained inside the tube of the pump. A rotating roller mounted on a shaft passes along the length of the tube, creating a temporary seal between the suction and discharge sides of the pump.

As the roller moves over the tubing, it expands and creates a vacuum to allow more fluid to enter.

By combining of these suction and discharge principles, a powerful self-priming action is obtained.

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 adopted in peristaltic pumps plays an important role in fluid handling. Two or three rollers lead to higher flow rates. 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 simulations perform 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

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).

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

liquid displacement inside the hose. A larger roller exerts more force on the tube. (Fig.6(b)). Due to the small size of housing in which the pump operates, the differences between each variant shaft are small (Fig.6(c)).

The resistance to compressive strength of the rollers has been considered. On each roller, a simulation was performed using 3 different values of forces acting on the roller during the operation. The force was applied to each roll separately. The entire axis, on which rollers are placed, was held 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 a maximum value of a force of 100 N.

The deformations caused by the action of the hose on the shaft are very small, although the shaft has smaller 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 elements of a pump are 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. Due to the light weight, the device uses a circular 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 braking applications, exhibiting highest stress, and consisting of magnetic particles in a carrier fluid. The suspension of micrometer-sized iron particles changes from liquid to semi-solid state spontaneously under the influence of a magnetic field.

The increase of flow resistance, especially the apparent viscosity, is proportional to the magnetic field also equally proportional to mechanical energy required to break the forces of interaction between the dipoles.

When the magnetic field is not activated, the fluid has the behaviour of the Newtonian fluid and the particles float freely.

Consequently, the strength of the material is strictly dependent on the entity of the applied magnetic field, i.e. the applied field and yield stress are directly related, enabling control and precision. An energy-efficient arrangement involves the particles to join together in order to form chains parallel to the magnetic flux lines.

In addition, the rapid response and the controllable yield stress in MR fluids ensure an appropriate interface between the electronic control and the mechanical system. Especially controllable fluids respond to an external excitation as an electric or magnetic field presenting extraordinary changes [9], [10].

During 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 was inspected with the Keyence VHX-7000 4K High Accuracy digital Microscope able to capture 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 rotary brake based on a peristaltic pump system containing MR fluid inside the tube with high viscosity. Experiments were carried out to test the implemented system applying pressure force to one arm of plier and characterize the behavior of MR fluids at various magnetic field intensities.

The purpose of this test is to perform repetitive opening and closing movements with no object to grasp. Magnetic stimuli were provided to test the maximum aperture and closure of arms.

3 Experimental Set-up

3.1 Test Set-up

Experiments were conducted to evaluate the proposed design of RB 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 setup used to investigate the realized 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 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 sensing 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 has been placed perpendicular to the movable arm of the 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 with 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 system in bench vise mounted directly to workbench, determining a point of force application in the movable bar (arm) of rotary brake based on peristaltic pump system and measuring the magnetic field strengths of the coil generated by variable currents in the pump system. Specifically, as shown in Fig. (Fig.7(b)) one pliers arm of realized 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, in particular, ensuring the movement of the movable bar in the

manufactured system parallel to the fixed arm in the bench vise as shown in Fig.8.

At the compression forces applied on the RB based on pump system, the MR device is activated in order to solidify inside the flexible tube under the effects of the magnetic 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 applied magnetic field. The basic steps of conducted research have included:

- Testing of rotary brake based on a 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 a 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 a 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 were conducted in the absence of magnetic field and without the presence of MR fluid in the RB pump system's tube (Fig.10) The

Fig. 9: Test conducted to determine the strength of the proposed pump with roller diameters respectively of 14mm and 15mm in absence of magnetic field and no presence of MR fluid in the tube

dynamometer is used to test the strength of moveable arm in the realized system which has roller diameters of 14mm and 15mm (Fig.9).

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

As a result, performance tests were conducted to evaluate the force applied to the pliers' mobile arm in the implemented system, which has a roller diameter of 15mm. In this case the MR fluid did not entirely fill the tube, so the external values of voltages rated with DC Regulated Power Supply were applied (Fig.11).

External values of current rated with DC Regulated Power Supply are applied to electromagnetic coil generating the magnetic B-field. When an external B-field is carried out, for increasing magnitude of currents, the MR fluid viscosity and yield stress increase considerably so that the strength applied on movable arm increase significantly as shown in Fig.12 for the used two diameters of RB pump system. The Force [N] applied to arms of pump in function of coil currents and after the inserting of MR fluid inside the realized pump

Fig. 11: In the presence of MR fluid, test conducted to determine the response of force in the rotary brake system with roller diameter of 15 mm

Fig. 12: The Force [N] in function of current [A] for RB system pump with the tube filled of MR fluid and roller diameters respectively of 15mm and 14mm

system for roller diameters respectively of 15mm and 14mm (Fig. 2(c)). The force applied to the system with roller diameter of 14 mm is less than the force applied to it with roller diameter of 15mm. The Magnetic B-field in function of Force is reported in Fig.14 for roller diameters respectively of 15mm and 14mm of RB based on peristaltic pump system .

4.2 Second Testing campaign

In the second testing campaign the performance tests have been defined in the existence of the controlled B- field for the MR rotary brake pump system. A small socket is realized within the movable arm of system in order to ensure the easy 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 deposited on the arms to eliminate the high friction coefficients. In addition, the tube was filled completely with MR liquid placed part within the coil and part in the rotary system pump. The tests conducted for voltage of 60 V have considered

Fig. 13: Magnetic B-field as function of Force for RB system pump with the tube filled of MR fluid and roller diameter of 15mm

Fig. 14: Magnetic B-field as function of Force for RB system pump with the tube filled of MR fluid and roller diameter of 14mm

Fig. 15: The Force [N] in function of current [A] for RB system pump with the tube filled of MR fluid and roller diameter of 15mm

higher current values than 0.7 [A] so the cooling fan has been embedded 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, so the necessary force enhances to move the arm of the system (Fig.15).

5 Conclusion and Future Works

The novel MR rotary brake based on peristaltic pump is designed and manufactured in this article. The used numerical method computes the stress and strain analysis of the device. The experimental tests 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 ability of varying viscosity under magnetic field. By locating this fluid into the tube of the peristaltic pump with an electromagnet coil able to generate magnetic field, a controllable resistance motion can be created. The viscosity has a great role in the movement of the device without constraints and in the absence of magnetic field.

The design of MR rotary brake works with low power consumption and includes few elements without motor and actuators. The subject of future specific application will be to study the MR rotary brake device based on a peristaltic pump as hand exoskeleton joint with more energy efficient and providing the sensation of holding a virtual object.

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References

- [1] Sohn, J.W., Gang, H.G., Choi, S.-B.: An experimental study on torque characteristics of magnetorheological brake with modified magnetic core shape. *Advances in Mechanical Engineering* **10**(1), 1687814017752222 (2018)
- [2] Attia, E., Elsodany, N., El-Gamal, H., Elgohary, M.: Theoretical and experimental study of magneto-rheological fluid disc brake. *Alexandria Engineering Journal* **56**(2), 189–200 (2017)
- [3] Thanikachalam, J., Jinu, G., Nagaraj, P.: Design and analysis of magneto-rheological fluid brake (mrb). In: *Advanced Materials Research*, vol. 984, pp. 634–640 (2014). Trans Tech Publ
- [4] Gudmundsson, K., Jonsdottir, F., Thorsteinsson, F.: A geometrical optimization of a magneto-rheological rotary brake in a prosthetic knee. *Smart materials and Structures* **19**(3), 035023 (2010)

- [5] Chen, J., Liao, W.-H.: Design and control of a magnetorheological actuator for leg exoskeleton. In: 2007 IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 1388–1393 (2007). IEEE
- [6] Baser, O., Demiray, M.A.: Selection and implementation of optimal magnetorheological brake design for a variable impedance exoskeleton robot joint. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **231**(5), 941–960 (2017)
- [7] Wu, C., Zhang, Q., Fan, X., Song, Y., Zheng, Q.: Smart magnetorheological elastomer peristaltic pump. *Journal of Intelligent Material Systems and Structures* **30**(7), 1084–1093 (2019)
- [8] Korona, T., Kowol, P., SCIUTO, G.L.: Design, manufacture and experimental characterization of magnetorheological rotary brake based on an peristaltic pump system (2021)
- [9] Kowol, P., Szczygieł, M., Sciuto, G.L., Capizzi, G.: Modeling of magnetorheological fluids relative magnetic permeability by using a neural network approach. In: 2020 IEEE 20th Mediterranean Electrotechnical Conference (MELECON), pp. 25–28 (2020). IEEE
- [10] Kowol, P., Piłśniak, A., Ziolo, G., Lo Sciuto, G.: Stanowisko do badania przenikalności magnetycznej cieczy magnetoreologicznej. *Pomiary Automatyka Robotyka* **24** (2020)