2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 25-29, 2020, Las Vegas, NV, USA (Virtual)

A Concept of a Miniaturized MR Clutch Utilizing MR Fluid in Squeeze Mode

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Abstract— **This paper presents a novel design concept of a miniaturized Magneto-Rheological (MR) clutch. The design uses a set of spur gears as a means to control the torque. MR clutches with various configurations such as disk-, drum-, and armature-based have in the past been reported in the literature. However, to the best of our knowledge, the design of a clutch with spur gears to use MR fluid in squeeze mode is a novel concept that has never been reported previously.**

After a brief description of the MR clutch principles, the details of the mechanical design of the spur gear MR clutch are discussed. The distribution of the magnetic flux inside the MR clutch is studied using finite element analysis in COMSOL Multiphysics software. Preliminary experimental results using a prototype MR clutch that validates the new concept and the results therein will be presented next. To clearly show the performance of the proposed design, we compared the torque capacity of our MR clutch obtained experimentally with that of a simulated disk-type MR clutch of a similar size.

I. INTRODUCTION

The use of magnetorheological (MR) clutches and brakes is increasingly receiving attention for their distinctive characteristics such as fast response, low power consumption, high torque to weight ratio, precision in torque control, and intrinsic compliance of such devices.

In robotics, MR clutches can be used to achieve safety and the intrinsic compliance of the robot joints [1], [2], [3], [4], [5]. This opens up a new possibility for the development of compliant grippers similar to a concept shown in Fig. 1. Such end-effectors will be extremely desirable devices in agriculture, medicine, and haptic applications. The compliant-joint devices allow addressing some of the issues encountered in dealing with soft tissues and objects such as fruits, live organs, food, etc.

To this effect, conventional MR clutches with disk or drum configurations cannot be used in the design of compliant-joint end-effectors or robotic hands, because the delivered torque of these types of clutches reduces significantly as the diameter of the clutch becomes smaller.

The goal of this research is to evaluate the feasibility of an innovative design of an MR clutch based on planetary gear mechanism allowing the miniaturization of an MR clutch for a given torque value. We will present the details of the design for the construction of a miniaturized MR clutch. The detailed mathematical modeling of the device is out of the scope of this paper.

The contributions of this work are as follows:

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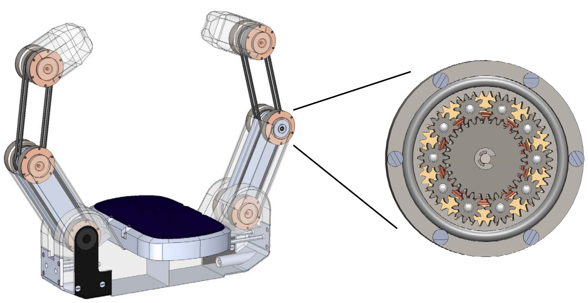


Fig. 1. Visualization of a robotic gripper concept with the miniaturized MR clutches used for the actuation of the joints.

- An innovative design concept of an MR clutch using squeeze mode of MR fluid is described.
- The distribution of the magnetic flux inside the MR clutch is simulated and analyzed.
- A prototype of a miniaturized MR clutch is developed and preliminary experimental results that validate the proposed design are presented.

II. OVERVIEW

A. Working Principles of MR clutches

The functional principle of an MR clutch (MR brake) is based on variable viscosity of magneto-rheological fluids. The MR fluid is a two-phase fluid, containing micron-sized spherical iron particles floating in a carrier fluid. Due to the ferromagnetic properties of iron, the particles can be easily magnetized with an external magnetic field. The tiny magnetized particles attract each other and form chains along the magnetic field lines. The direction of the chains determines the anisotropic properties of the fluid. The strength of these chains depends on the strength of the magnetic field. The viscosity of the MR fluid depends on the number of created chains and their strength. As a result, the viscosity of MR fluid can be precisely controlled by varying the magnetic field with a response time of less than 1 ms.

There are four known MR fluid operation modes that can be used in MR-based devices: Valve mode [6], shear mode [7], [8], squeeze mode [9], [10], and pinch mode [11]. Most types of MR clutches use MR fluids in shear mode [12], [13]. Also, there are several designs developed that utilize other approaches such as the use of compression plus shear mode [14], the use of small steel rollers as large size magnetic particles [15], the use of arc form shape of the clutch rotor [16].

The new design of the MR clutch presented in this work uses the MR fluid in squeeze mode. This mode is expected to generate higher torque than a similar size conventional MR clutch.

We briefly describe the design of a conventional disk-type MR clutch to provide a basis for subsequent discussions.

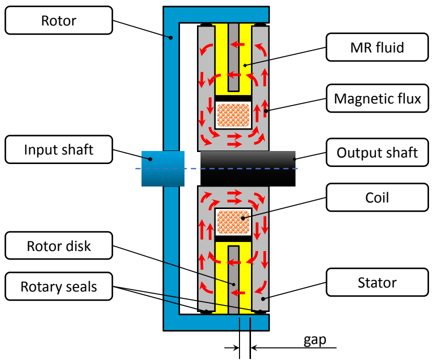


Fig. 2. Cross-section view of a single-disk MR clutch.

The MR clutch shown in Fig. 2 consists of a single ferromagnetic disk mounted on the rotor that is driven by the input shaft. Also shown in the figure is the stator, which is comprised of two ferromagnetic disks and an electromagnetic coil, that drives the output shaft. The gap between the stator disks and the rotor disk is filled with magneto-rheological fluid. The electromagnetic coil generates a magnetic field in order to change the viscosity (yield stress) of the MR fluid in the gap. The shearing in MR fluid due to the rotation of the rotor disc (input) relative to the stator (output) causes the stress that transmits the torque. The amount of torque transmitted by each surface element of the disk is given by,

$$dT = 2\pi r^2 \tau dr \tag{1}$$

where r is the distance from the shaft axis of rotation to the element (radius), and τ is the MR fluid shear stress obtained using Bingham visco-plastic model as follows [17],

$$\tau = \tau_y(B) + \eta\omega r/l_f, \tau > \tau_y \tag{2}$$

in that $\tau_y(B)$ is the yield stress dependent on magnetic field, η is the Newtonian viscosity of the MR fluid, ω is the angular velocity of the rotor disk relative to the stator, and l_f is the fluid gap size.

Due to the limited achievable yield stress of the MR fluid (around 100 kPa [18]), the torque-to-weight ratio of an MR clutch cannot be improved indefinitely. In practical applications, the highest ratio achieved is close to 60 Nm/kg [19].

A complete comparison of various MR clutch configurations can be found in [20], [21], [22].

III. Design of miniaturized MR clutch

A. Design objectives

This study is triggered by the need for a miniaturized MR clutch with sufficient torque characteristics that can fit into the fingers of a prospective compliant gripper, such as a concept shown in Fig. 1. The outer diameter and the width of the desirable MR clutch are set to be not more than 20 mm and 10 mm respectively. Chosen dimensions allow to incorporate a pair of antagonistically actuated clutches into a joint of a reasonably small finger that is comparable in size with a human finger.

The "classical" disc-type clutch design is used as a starting point to estimate the value of the torque that can be transmitted by such a small device.

B. Disk-type MR clutch

In this section, we explore the design of a disk-type MR clutch and its torque characteristics, for the given size requirements. We use a previously verified model of MR clutch [22] based on Finite Element Analysis in COMSOL Multiphysics software to evaluate the design.

Fig. 3 shows a disk-type MR clutch with the outer diameter of (OD) 19 mm and width of 9 mm. It is assumed that the construction of such a clutch poses no extreme requirements for the precision of the manufactured parts.

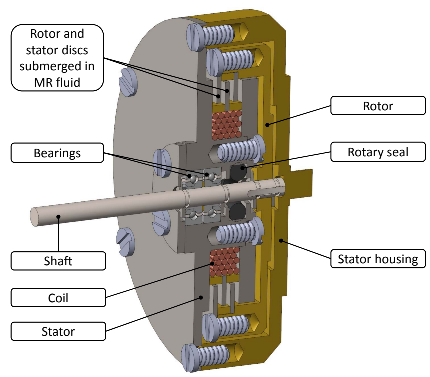


Fig. 3. Construction of the miniaturized "Disk" MR clutch.

The clutch is comprised of two carbon steel rotor disks and one stator disk with a thickness of 0.25 mm each. The gaps between the disks are 0.25 mm. The electromagnetic coil is wound on the carbon steel stator and has 25 turns of AWG 28 wire. The rotor is made of brass and mounted on the stainless steel shaft. The shaft is 1 mm in diameter and is mounted on two ball bearings with 3 mm OD. The rotary seal is used to isolate the volume containing MR fluid inside the clutch. The brass stator housing is tightly attached to the carbon steel stator. Miniature screws used for the assembly are 2 mm long with M1 thread each.

The geometry of the magnetic core was optimized to avoid saturation in the local areas as it was reasonable taking into account the small size of the device and manufacturability of the parts. Fig. 4 shows the magnetic flux density of the described MR clutch for input current of 3.6 A.

Using this model, the maximum torque capacity of the clutch for the maximum input current of 3.6 A was calculated to be 20.3 N·mm. The transmitted torque could be further improved by increasing the number of disks and reducing the size of the gaps between them. However, this could be difficult to achieve due to the high tolerance required, the

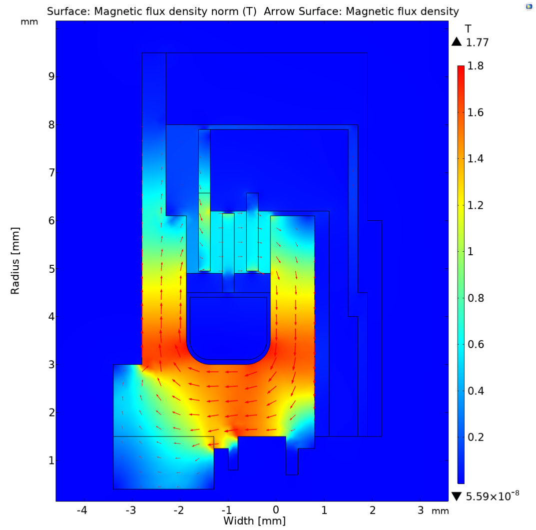


Fig. 4. Magnetic flux density contour map in the miniaturized disk-type MR clutch (coil wire current 3.6 A, total coil current 90 A for 25 turns of wire).

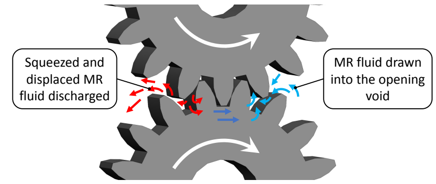


Fig. 5. Process of squeezing MR fluid between the teeth of rotating spur gears in mesh.

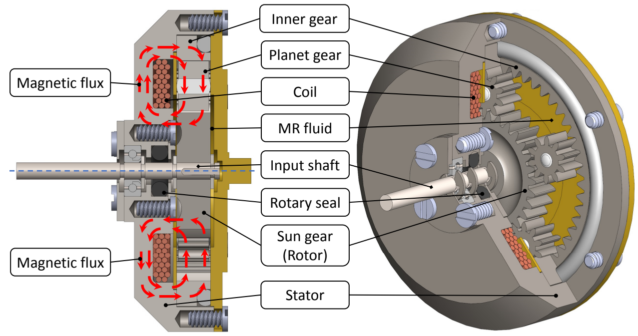


Fig. 6. Construction of the MR clutch.

complexity, and miniature of the parts. Further optimization of the core shape cannot substantially increase the torque.

C. "Planetary" MR clutch

In order to improve the torque capacity of an MR clutch, an alternative design is proposed for the miniaturized clutch. Rather than utilizing a pure shear mode, as is done in conventional disk-type and drum-type clutches, the idea is to make use of more effective squeeze mode. While the behavior of the MR fluid in this mode is still not fully understood, the forces generated within small displacement at squeeze mode are grossly larger than that in pure shear mode [10]. It is therefore hypothesized that an MR clutch operating in squeeze mode can have larger torque capacity than other similar designs working in shear mode.

To this end, it is proposed to use the rotating cogwheels (gears) in mesh to squeeze the MR fluid from the space between the teeth.

An example of a configuration with two cogwheels is shown in Fig. 5. The top cogwheel is assumed to rotate counter-clockwise and driving the bottom cogwheel clockwise, or vice versa. As the teeth of the two gears approach and come in contact, the MR fluid is trapped and then forcefully squeezed out from the space between them. As the rotation progresses, the contacting teeth of the cogwheels start to depart and the fluid is pulled into the opening void with low pressure that is left behind the separating teeth.

To implement this squeezing method in the construction of the MR clutch, we then propose to use a mechanism similar to a planetary (epicyclic) gear train. The details of the proposed design are shown in Fig. 6. In this design, the sun gear of the planetary mechanism can act as the input (or rotor) and the ring gear will act as the output (or stator). The planet gears are immersed in MR fluids.

The proposed "Planetary" clutch has a similar number of parts as its disk-type counterpart. In this design, the stator carries the electromagnetic coil. The stator also contains an inner gear (the so-called ring gear in a planetary mechanism). The inner gear is stationary and is fixed inside the stator cutout. A number of planet gears are in mesh with the inner gear and with the sun gear in the center of the mechanism. The sun gear plays the role of a rotor and it is fixed to the input shaft using snap rings and a key. The stator, the sun, and the planet gears are all made of carbon steel. The input shaft is mounted on one bearing only (1st shaft support). The function of the 2nd shaft support is performed by the planet gear mechanism working as a "roller" bearing. A rotary shaft seal isolates the volume containing MR fluid inside the clutch. The brass stator lid covers the planetary mechanism and prevents the rotation of the inner gear inside the stator. Miniature M1 screws are used as fasteners for the clutch assembly.

IV. MAGNETIC FLUX DISTRIBUTION

The distribution of the magnetic field density was simulated for the proposed MR clutch design using the Finite Element Method in COMSOL Multiphysics software. Several cases were studied with 1, 2, 3, 4, and 5 planet gears in the planetary gear mechanism. Fig. 7 and 8 show the map of the magnetic flux density for the cases with 2 and 5 planet gears.

As seen in figures 7 and 8, the density of the magnetic flux is the highest in the regions where the ferromagnetic planet gears are currently located. This is the intended region for the MR fluid to undergo the squeeze mode. One can expect that increasing the number of planet gears will increase the number of fluid squeeze regions and result in larger torque capacity of the clutch. On the other hand, a higher number of planet gears can reduce the flux density by providing multiple parallel paths for the magnetic flux. There is clearly a trade-

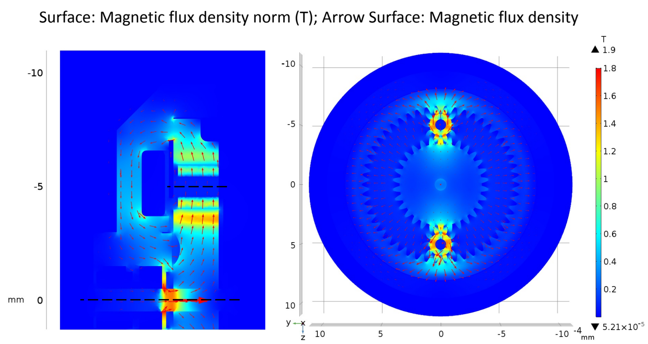


Fig. 7. Magnetic flux density contour map in the miniaturized "Planetary" MR clutch with 2 planet gears (coil wire current 3.6 A, the total coil current 90 A for 25 turns of wire).

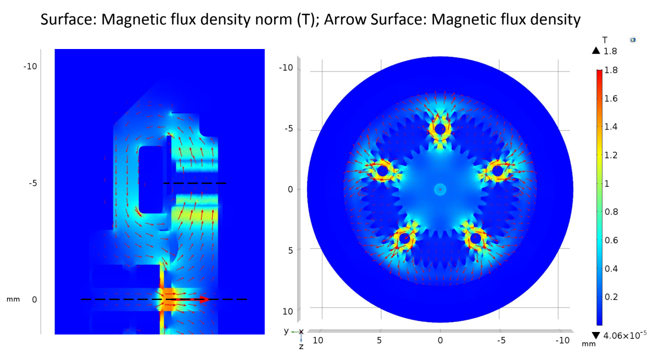


Fig. 8. Magnetic flux density contour map in the miniaturized "Planetary" MR clutch with 5 planet gears (coil wire current 3.6 A, the total coil current 90 A for 25 turns of wire).

off between the number of planet gears and the magnetic flux density. However, it is difficult to mathematically calculate the exact relationship between the value of the magnetic flux passing through each gear and the number of gears in the system. In order to evaluate this relationship more precisely, a set of 12 virtual Domain Point Probes are used in COMSOL Multiphysics as shown in Fig. 9.

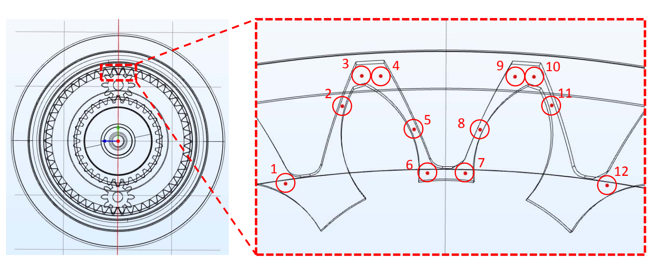


Fig. 9. Location of the Domain Point Probes in the MR fluid between the teeth in the COMSOL model.

The probes are positioned between the teeth of the sun gear and one of the planet gears for all simulation cases (i.e. with 1, 2, ..., 5 planet gears).

The results of the magnetic flux density norm measurements at each probe are tabulated in Fig. 10. The average flux density norm for each simulated case is also calculated in the rightmost column.

	Magnetic flux density norm at the probe (T)												Average flux density norm (T)
Number of Planet gears	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Probe 9	Probe 10	Probe 11	Probe 12	
1	0.277	0.552	0.217	0.193	0.480	0.244	0.263	0.576	0.197	0.240	0.471	0.288	0.333
2	0.269	0.540	0.212	0.188	0.471	0.238	0.256	0.563	0.193	0.243	0.461	0.281	0.326
3	0.258	0.524	0.206	0.182	0.458	0.227	0.247	0.546	0.186	0.234	0.448	0.270	0.315
4	0.246	0.506	0.198	0.175	0.444	0.219	0.237	0.529	0.180	0.226	0.435	0.259	0.304
5	0.234	0.489	0.190	0.168	0.426	0.207	0.225	0.511	0.173	0.216	0.416	0.245	0.292

Fig. 10. Magnetic Flux Density measurements at Domain Point Probes.

Based on average flux density, the approximate magnetic flux passing through a part of the planet gear surface ($8.61\ mm^2$) is calculated. For each simulated case the magnetic flux through a single planet gear and through all planet gears in the clutch are plotted in Fig.11. The results show a slight reduction of the magnetic flux through each gear (orange) as the number of planet gears in the system increases. However, the total magnetic flux through all planet gears (blue) increases almost proportionally to the total number of the planet gears.

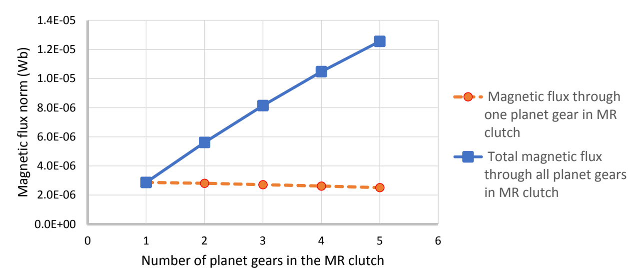


Fig. 11. A plot of the relation between the number of planet gears in the clutch and the magnetic flux passing through the gears.

The small reduction observed in the magnetic flux despite increasing the number of planet gears can be described as follows. Increasing the number of planet gears reduces the flux density in each gear. On the other hand, increasing the number of planet gears decreases the total reluctance of the magnetic circuit which in turn results in larger total flux in the clutch. As such, the magnetic flux through a single gear is only slightly reduced, while the total magnetic flux through the circuit increases almost proportionally to the number of gears.

V. Preliminary Experimental Results

In order to prove the feasibility and to evaluate the performance of the proposed "Planetary" MR clutch design, a prototype of the device was built as shown in Fig. 12.

The dimensions of the prototype MR clutch were based on the design requirements described in Section III. The total weight of the prototype clutch filled with MR fluid MRF-140CG [23] was measured to be 10 g.

The prototype was first tested with a set of 2 planet gears (Fig. 13 a), and then with a set of 3 planet gears (Fig. 13 b).

For the experiments, a milling machine Craftex CX-600 was used to rotate the MR clutch at a constant speed of

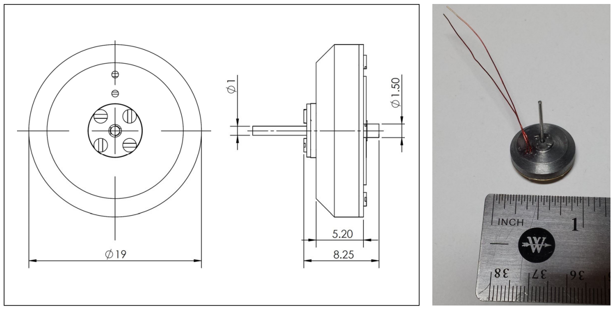
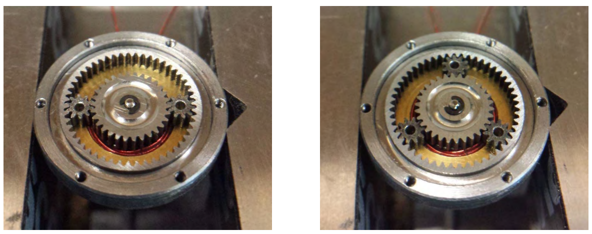


Fig. 12. An assembled prototype of the "Planetary" MR clutch and its basic dimensions.



(a) MR clutch with 2 planet gears

(b) MR clutch with 3 planet gears

Fig. 13. Pictures of the "Planetary" clutch prototype with the 2 and 3 planet gears installed.

50 rpm. A power supply TTi EX752M was used to supply current to the electromagnetic coil. A 50 mm 3D-printed shoulder was attached to the clutch. The torque was measured using a micro load cell CZL616C connected to an acquisition board Phidgets PhidgetBridge RB-Phi-107. The test setup is shown in Fig. 14.

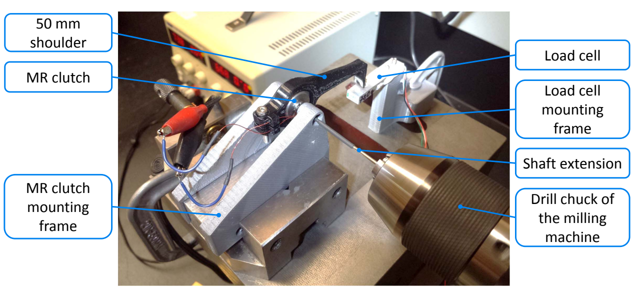


Fig. 14. Experimental setup with the MR clutch installed.

During the tests, a constant current of up to 3.6 A with an incremental step of 0.2 A was applied to each prototype MR clutch. For each value of the current, the transmitted torque was recorded during 4 seconds at 0.1 seconds intervals and then averaged. The results of the tests are shown in Fig. 15 in blue and green solid lines.

The graphs illustrate the actually transmitted torque for two "Planetary" MR clutch configurations with 2 and 3 planet gears respectively. It can be observed that the torque capacity of the "Planetary" MR clutch increases nearly proportionally to the number of planet gears used. Therefore, the torque of the planetary clutch with multiple planet gears can be calculated as the multiplication of the one-gear clutch

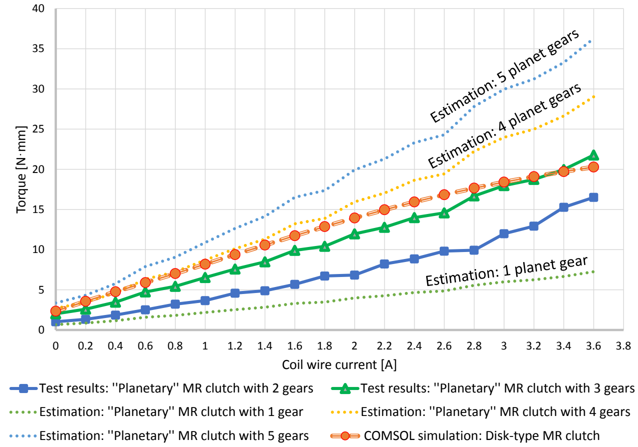


Fig. 15. Comparison of the experimental results for the "Planetary" MR clutch and disk-type MR clutch.

torque by the number of gears. Based on the obtained test results, the torque values for the "Planetary" clutch with 1, 4, and 5 planet gears are estimated and included in Fig. 15 in dotted lines.

In addition, the torque results for the disk-type MR clutch described in chapter III-B are also included in the plot in Fig. 15. The results were obtained through the simulation using the developed COMSOL Multiphysics model. It can be observed that the performance of the "Planetary" clutch with 3 planet gears is close to the torque capabilities of a disk-type clutch with 3 disks.

As conjectured, increasing the number of planet gears in the proposed design will lead to higher torque capabilities of the "Planetary" clutch. For the current MR clutch configuration, the maximum of 10 planet gears can be installed as shown in Fig. 16.

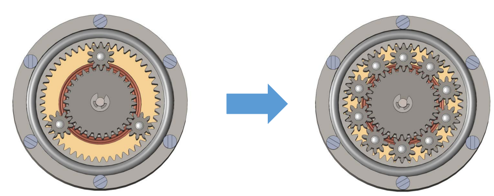


Fig. 16. "Planetary" clutch with 3 and 10 (the maximum possible number for current design) planet gears installed.

At 8 A/mm^2 current density (0.64 A wire current for 28 AWG) the clutch with 10 planet gears has torque-to-weight ratio approximated as 1.6. While the clutch with 3 planet gears has torque-to-weight ratio calculated as 0.5 for the same current density.

Similarly, increasing the number of disks will lead to improved torque capabilities of the disk-type clutch. However, while the planetary clutch can be easily improved just by inserting the additional planet gears, the disk-type clutch requires changes in the thickness of the disks and spacers.

Additionally, it is believed that the performance of the "Planetary" clutch can be further improved through optimization of the gear parameters such as the number of teeth, pitch diameter, modulus, pressure angle, tooth profile, and others.

VI. CONCLUSION

An innovative design of a magneto-rheological clutch based on planetary gear mechanism and using MR fluid in squeeze mode was presented and experimentally validated in this paper. The results ascertained the possibility of building a miniaturized MR clutch with similar or even better torque performance when compared with conventional disk-type MR clutch of similar size. It is observed that the value of the transmitted torque nearly proportionally depends on the number of planet gears installed. At the same time, according to the simulation in COMSOL Multiphysics, the magnetic flux passing through each planet gear decreases slightly with each additional gear introduced in the system.

The design of the "Planetary" clutch allows the improvement of the torque capabilities through the simple installation of the additional planet gears up to the maximum number allowed by the clutch configuration.

Clearly, there is room for further performance improvement through optimizing the gear parameters such as the number of teeth, pitch diameter, modulus, pressure angle, tooth profile, etc.

The detailed mathematical modeling is in the process of development and will greatly benefit in the optimization of the clutch as well as in determining the achievable limits of the design.

At the same time, some drawbacks of the proposed design are already identified and can be summarized as follows:

- Achieved torque values of "Planetary" MR clutch are still too low and need to be increased for use in a compliant robotic hand;

- The addition of planet gears in the clutch increases off-state torque of the device due to the remaining viscosity of the MR fluid. A more throughout evaluation of the dynamic range for the "Planetary" clutch needs to be performed.

- Uneven friction, observed during the testing, possibly due to the low quality of gear manufacturing and/or air bubbles trapped in MR fluid needs to be addressed.

- Difficulties in mathematical modeling of the "Planetary" clutch with complex shape of the gear teeth as well as with MR fluid working in squeeze mode impedes the optimization of the device.

Further work is planned to evaluate alternative designs of the MR clutch with cogwheels based on planetary gear train without inner gear and planetary gear train without sun gear.

Additionally, a linear MR clutch (MR damper) utilizing the squeeze mode of the MR fluid through the use of the rack-and-pinion mechanism is planned to be designed and tested.

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