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COMPARATIVE ANALYSIS OF TWO MAGNETORHEOLOGICAL CLUTCHES WITH DIFFERENT GEOMETRIC CONFIGURATIONS

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Abstract. The paper focuses on the comparative analysis of two magnetorheological clutches with different geometric configurations. One magnetorheological clutch corresponds to cylindrical geometry (MRC-CG) while the second is selected with disk geometry (MRC-DG). Both experimental and numerical investigations are performed to determine magnetorheological clutch performances. The constructive solution is detailed for each magnetorheological clutch type. The numerical simulations are carried out to determine the distribution of the magnetic field. The magnetorheological clutch performances are investigated experimentally over a range of variable speeds between shafts from 50 rpm to 500 rpm. The torque for both geometric configurations is determined using the same magnetorheological fluid (MRF-132DG). The torque control range of the MRC-CG is limited by the response of the MRF to the variation of the magnetic field induced by the coil. MRC-DG covers a wider range of the torque control than MRC-CG due to the additional contribution of the gap geometry. MRC-DG provides twice the torque density of MRC-CG proving more compact solutions. The conclusions are drawn in last section.

***Keywords**:* magnetorheological clutch (MRC), cylindrical geometry (CG), disk geometry (DG), experimental investigations, numerical simulations, performance assessment, critical analysis.

1. INTRODUCTION

Magnetorheological fluids (MRFs) were developed for a clutch device designed by Rabinow [1] in early 1948. The advantages of using this kind of clutch device are as follows: the small electrical power to control it and its fast time response. Therefore, the magnetorheological devices are widely used in application such as dampers [2–6], brakes [7–12], clutches [13, 14], shock absorbers [15] and gas rotating gaskets [16].

Magnetorheological clutches are an important class of engineering applications that uses MRFs [17]. Magnetorheological clutches transfer mechanical power from an input shaft to an output shaft in a controlled manner via MRF [18, 19]. The modification of the mechanical power at the output shaft is obtained by reducing its torque and speed in relation to the input shaft. The difference in mechanical power between the input and output of the magnetorheological clutch is converted into heat. Usually, the amount of heat dissipated in magnetorheological clutches is limited due to the small differences in mechanical power between the input and output avoiding the cooling systems.

The performance of the magnetorheological clutch is correlated with the magnetorheological behaviour of the MRF inserted in the gap and its geometry. Different geometrical configurations of the gap (cylindrical referred to in the literature as a drum and bell, disk or combinations thereof) hosting the MRF can be selected in the design of the magnetorheological clutch to meet the requirements of the engineering applications in robotics and automation [20, 21], automotive [22–24] and high power transmissions [25, 26]. However, several requirements should be taken into account due to the technical and/or operational constraints (maximum speed and/or temperature, available volume, environmental conditions). Therefore, the aim of the paper is to explore the performances of two magnetorheological clutches with fundamental different geometrical configurations (cylindrical and disk) to highlight their main characteristics and limitations. The results obtained for these two magnetorheological clutches provide a critical insight into their performances with the aim to establish a selection criterion in relation to the requirements of engineering applications.

The paper presents the performances of two magnetorheological clutches with different geometries. The main challenge is selecting the appropriate magnetorheological clutch for each engineering application. The second section of the paper describes the two magnetorheological clutches with different geometric configurations. Magnetorheological clutch with cylindrical geometry (MRC-CG) is detailed in the first part of section 2, followed by magnetorheological clutch with disk geometry (MRC-DG) in the second part. The third section presents the experimental setup together with the control and acquisition software. Fourth section presents the experimental data together with comparative analysis of the performances of two magnetorheological clutches with different gap geometry. The last section draws the conclusions and highlights the perspectives for further development to combine the advantages of the two geometries.

2. MAGNETORHEOLOGICAL CLUTCHES WITH TWO GEOMETRIC CONFIGURATIONS

The geometrical constrains represents one selection criterion for choosing magnetorheological clutch type. The geometric configuration of the magnetorheological clutch is defined by length L in the axial extension and outer radius R_{ext} to the radial direction, respectively. A volume is available for each magnetorheological clutch type taking into account the geometry. The disk-type magnetorheological clutch (MRC-DG) is the most common configuration due to it is easy to manufacture and leads to reasonably good results in terms of weight and compactness [10]. The geometric criterion of $L/R_{ext}<0.36$ is associated with MRC-DG. The MRC-CG corresponds to the ratio L/R_{ext} grater than 2 ($L/R_{ext}>2$). These two geometric configurations of magnetorheological clutches (MRC-CG and MRC-DG) arranged at extreme values of the L/R_{ext} ratio are examined to emphasize their advantages and limitations.

The same MRF is selected for testing both magnetorheological clutches to quantify only the influence of the gap geometry. The MRF-132DG commercial magnetorerheological fluid designed by Lord Co for use in general power dissipation control applications is selected. MRF-132DG is commonly used for engineering applications and its magnetorheological properties are available in literature [12, 27, 28].

2.1. Magnetorheological clutch with cylindrical geometry (MRC-CG)

Magnetorheological clutch with bell shaped cylindrical geometry has an important advantage because it encapsulates a double friction surfaces (Fig. 1). The MRC-CG required an axial extension large enough to encompass the cylindrical gap. The MRC-CG has an input shaft with constant speed and an output shaft with variable speed.

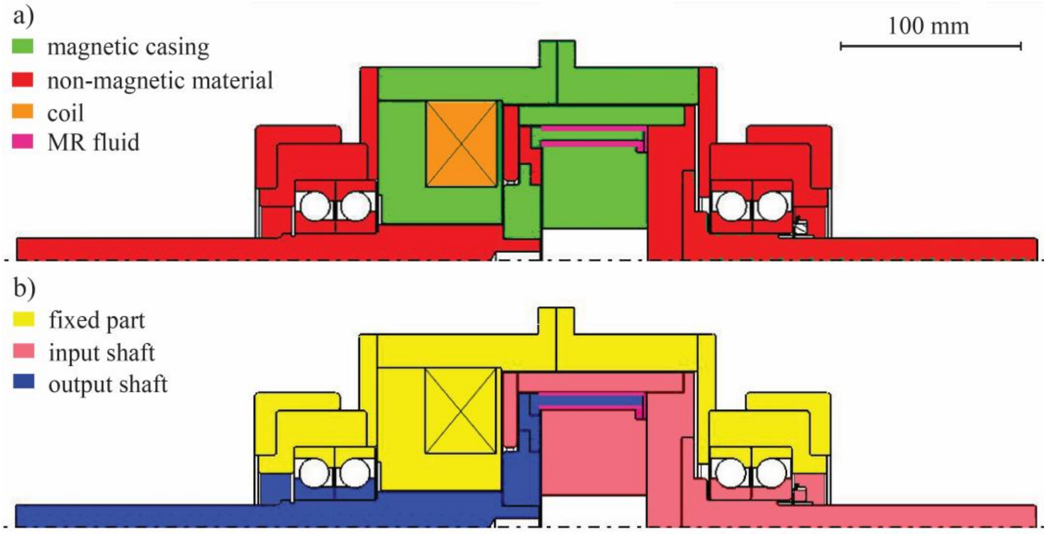

Fig. 1 – Magnetorheological clutch with cylindrical geometry (MRC-CG): a) materials selected (MRF – magenta, coil – orange, material with magnetic proprieties – green, material without magnetic proprieties – red); b) speed of the mechanical parts (input shaft with constant speed of 1000 rpm – pink, output shaft with variable speed from 500 to 1000 rpm – blue, fixed part – yelow).

Two types of materials (magnetic and non-magnetic) are selected in the design phase, Fig. 1a. The magnetic circuit is made of magnetizable iron (green in Fig. 1a). The magnetic circuit is arranged on the fixed side (yellow in Fig. 1b) to be connected to the power supply and on the rotating part. The driving part is the input shaft and the inner casing at a constant speed (pink in Fig. 1b). The variable speed part is built using two pieces: the output shaft and the bell shape (blue in Fig. 1b).

Both length and radius have been selected to achieve the design torque. A special attention in the design stage of the MRC-CG is paid to the magnetic circuit. The magnetic circuit is designed to guide the magnetic field to 1 mm gap with the MRF (Fig. 2a). The coil generates magnetic flux in correlation with the current through it. A copper wire of ϕ 0.35 mm with 2000 turns has been used to manufacture the coil. A maximum power of 8W has been measured for a current of 0.25A through the coil. The two-dimensional axi-symmetric model [29] corresponding to the MRC-CG geometry has been considered for numerical analysis of the magnetic field using FEMM V4.2 software. The magnetic flux density along the gap length is plotted in Fig. 2b (see the red arrow in Fig. 2a) for three current values of 0.078A, 0.156A and maximum 0.25A, respectively. The starting point of the arrow marks the zero position of the gap length (closed to the coil), while its tip indicates the position of the gap end located at 60 mm. The magnetic flux density at maximum current value varies along the gap from 0.42T close to the coil to 0.27T at the other end located away from the coil. This distribution confirms the fact that the combination of magnetic – non magnetic materials used in the MRC-CG design directs a quasi uniform magnetic flux density along the gap.

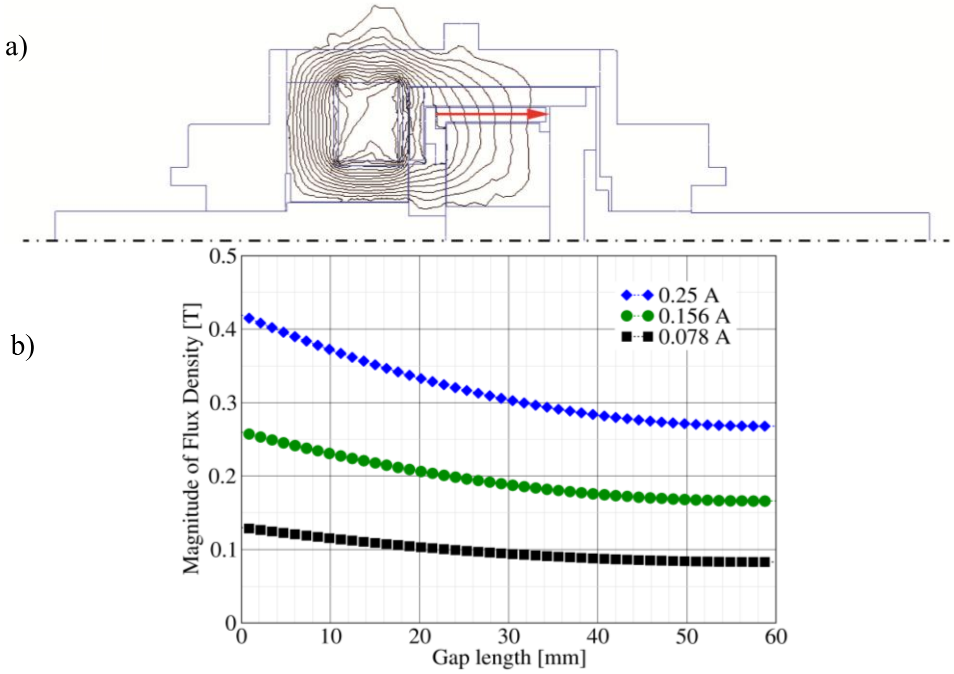

Fig. 2 – Numerically computed distribution of the magnetic field: a) two-dimensional axi-symmetric meridian cross-section of MRC-CG at a current value of 0.156A; b) along to the gap length for three current values of 0.078A, 0.156A and 0.25A.

2.2. Magnetorheological clutch with disk geometry (MRC-DG)

The magnetorheological clutch with disk geometry (MRC-DG) is extended in the radial direction, Fig. 3. The magnetic and non-magnetic materials are selected in the design phase (Fig. 3a). The magnetic circuit is made of magnetizable iron (green in Fig. 3a). The magnetic circuit (coil and outer casing) is mounted on the fixed part (yellow in Fig. 3b). The MRC-DG has a constant speed input shaft and an output shaft with variable speed. The driving part is the shaft and inner casing at a constant speed (pink in Fig. 3b). The variable speed part includes the disk and the output shaft (blue in Fig. 3b).

The disk radius and the gap of 1 mm were selected to achieve the design torque for MRC-DG. The MRC-DG is designed to lead the magnetic flux to the gap (Fig. 4a). The coil consists of a copper wire of ϕ 0.5 mm with 2900 turns. The maximum power of 6.7W obtained with the current of 0.219A through the coil wires is determined. The magnetic field generated by the coil is driven by the magnetic circuit yoke in the gap with the MRF. The magnetic field distribution into the gap of the clutch has been numerically computed using two-dimensional axi-symmetric model [29] for three current values of 0.065A, 0.13A and maximum 0.219A, respectively. The starting point of the arrow marks the zero position of the gap at maximum radius closed to the coil, while its tip indicates the position of the gap length at the minimum radius (Fig. 4a). The magnetic flux density distribution along the gap length with MRF experiences a decreasing from 0.4T close to the coil and a value of 0.05T in the proximity of the shaft at smaller radius at maximum current value of 0.219A (Fig. 4b). A significant variation of the magnetic flux density is obtained along the gap length based on the numerical analysis.

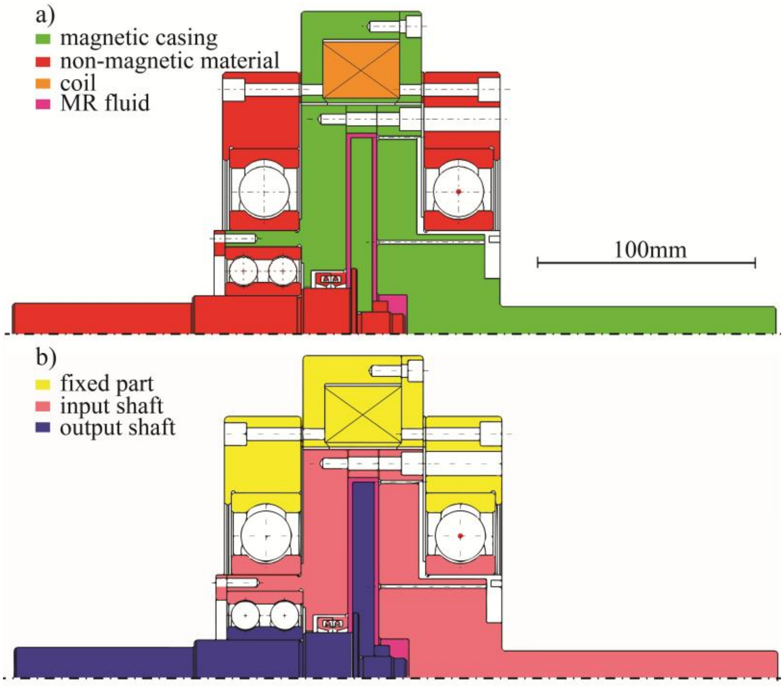

Fig. 3 – Magnetorheological cluch with disk geometry (MRC-DG): a) materials selected (MRF – magenta, coil – orange, material with magnetic proprieties – green, material without magnetic proprieties – red); b) speed of the mechanical parts (input shaft with constant speed of 1000 rpm – red, output shaft with variable speed from 500 to 1000 rpm – blue, fixed part – yelow).

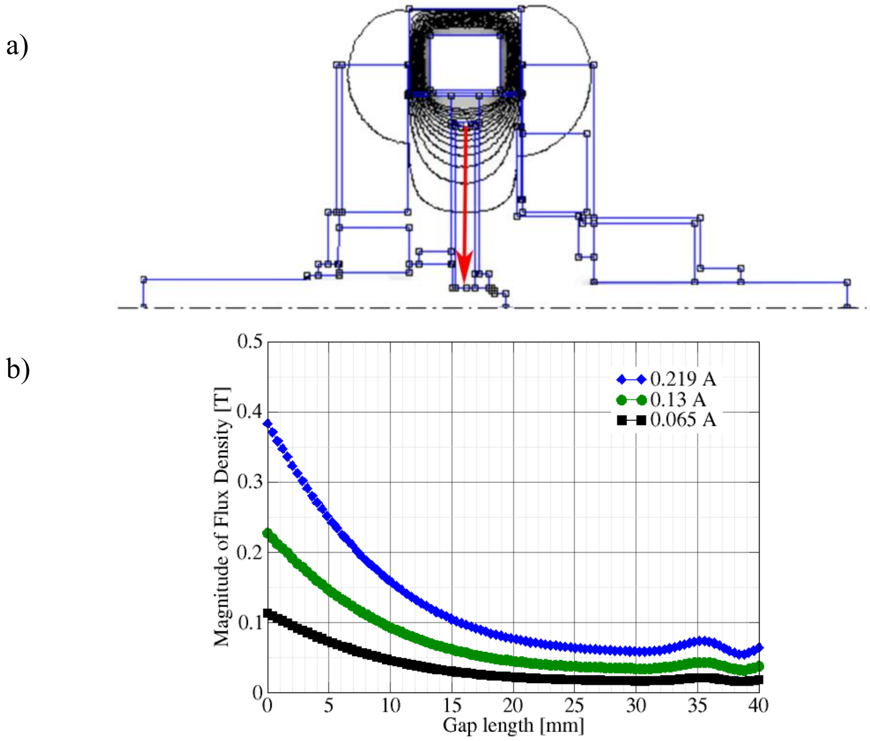

Fig. 4 – Numerically computed distribution of the magnetic field: a) two-dimensional axi-symmetric meridian cross-section of MRC-DG at a current value of 0.13A; b) along to the gap length for three current values of 0.065A, 0.13A and 0.219A.

3. TEST RIG FOR EVALUATING THE PERFORMANCE OF MAGNETORHEOLOGICAL CLUTCHES

An in line test rig is developed to measure the performance of the magnetorgeological devices. The test rig consists in two variable speed drive motors (pos. 1 and pos. 4), torque transducer (pos. 2), magnetorheological clutch (MRC) (pos. 3), speed (pos. 5) and temperature (pos. 6) sensors, DC source (pos. 7), the control (pos. 8) and data acquisition (pos. 9) systems (Fig. 5). The electric motor (pos. 1) is controlled by a frequency converter to maintain the input shaft of MRC (pos. 3) at a constant speed.

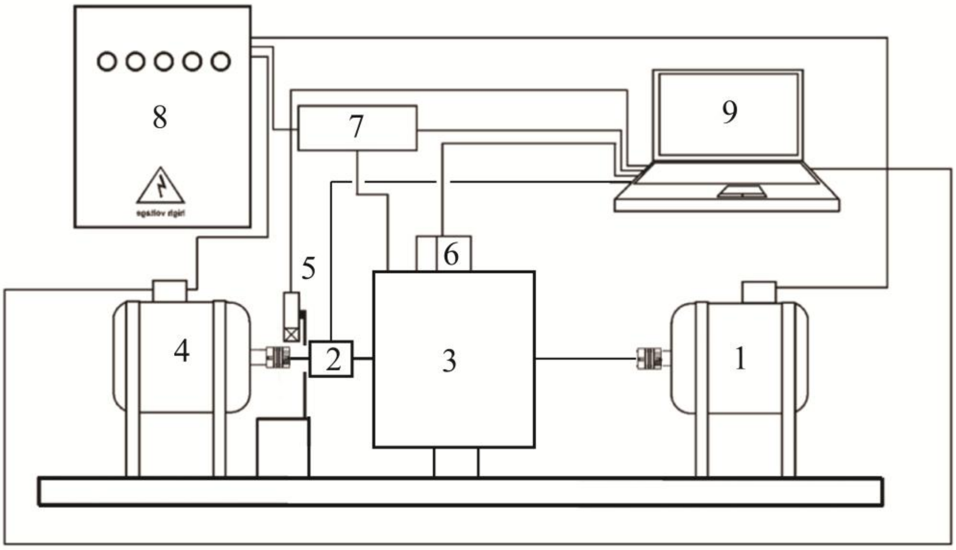

Fig. 5 – Sketch of the test rig with main components given in Table 1.

The control system (pos. 8) sets the variable load to the electric motor (pos. 4) using a frequency converter. The electric motor (pos. 4) is connected with the output shaft of the MRC (pos. 3) through the torque transducer (pos. 2). The data acquisition system (pos. 9) records the following data: the torque at the output shaft, the speed of the output shaft, both current and voltage applied to the coil of the magnetorheological clutch and both inner and outer temperature of the magnetorheological clutch, respectively. The temperatures are measured on the external surface of the magnetorheological clutch while the inner point is located close to MRF. The maximum inner temperature up to 45°C is measured while up to 30°C is recorded on the MRC-CG casing.

The main characteristics and technical data for the test rig are presented in Table 1.

Table 1

Main characteristics of the magnetorheological clutch test rig

Pos.	Component	Main characteristics
1	High speed electrical motor (drive motor)	Maximum speed 2 910 rpm Maximum power 3 kW, IP 55
2	Torque transducer	Speed range 0–9 000 rpm, Torque range 0–20 Nm
3	Magnetorheological clutch	MRC-DG weight ≈ 45 kg MRC-CG weight ≈ 60 kg
4	High speed electrical motor (driven motor used as load)	Maximum speed 2 880 rpm Maximum power 4 kW, IP 55
5	Optical speed sensor	Speed range 0–10 000 rpm, Accuracy ±0.5%
6	Temperature sensors	2 temperature sensors: close to MRF (0–200 °C), on external surface (0–100 °C)
7	Programmable DC source	Voltage range 0–32 V, Current range 0–10 A
8/9	Control/acquisition system	10 Hz acquisition frequency Maintain a constant speed independently by torque variation

4. INVESTIGATION THE PERFORMANCES OF MAGNETORHEOLOGICAL CLUTCHES

Both magnetorheological clutch types were installed successively on the test rig to determine the performances at same operating conditions (Fig. 6).

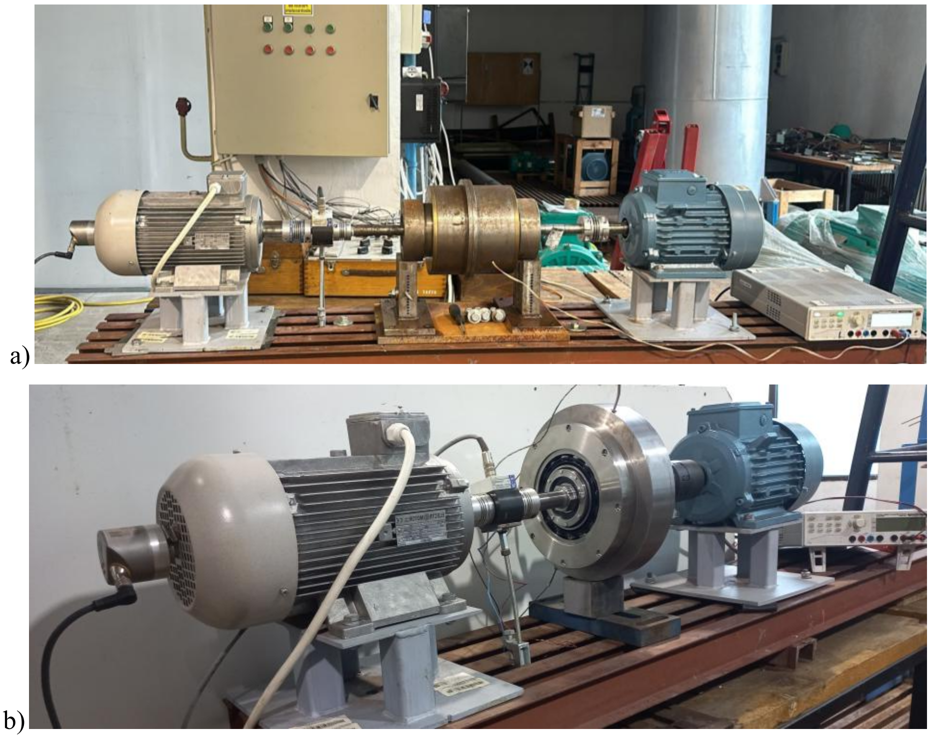

Fig. 6 – Magnetorheological clutches installed on the test rig for measuring their performances: a) MRC-CG; b) MRC-DG.

The speed of the electric drive motor connected to the input shaft was set at 1000 rpm. The variable speed of the driven electric motor used as a load is selected using the control software platform. The speed difference between the shafts from 50 rpm to 500 rpm in 50 rpm increments was successively selected during each experimental campaign. The torque measured for three current values is plotted in Fig. 7 for both geometric configurations of magnetorheological clutches. The control platform is designed to protect the torque transducer against failure by imposing a maximum threshold value. The measurement campaign is automatically stopped if the torque exceeds the maximum threshold value. Then, the campaign resumes after the problem has been fixed.

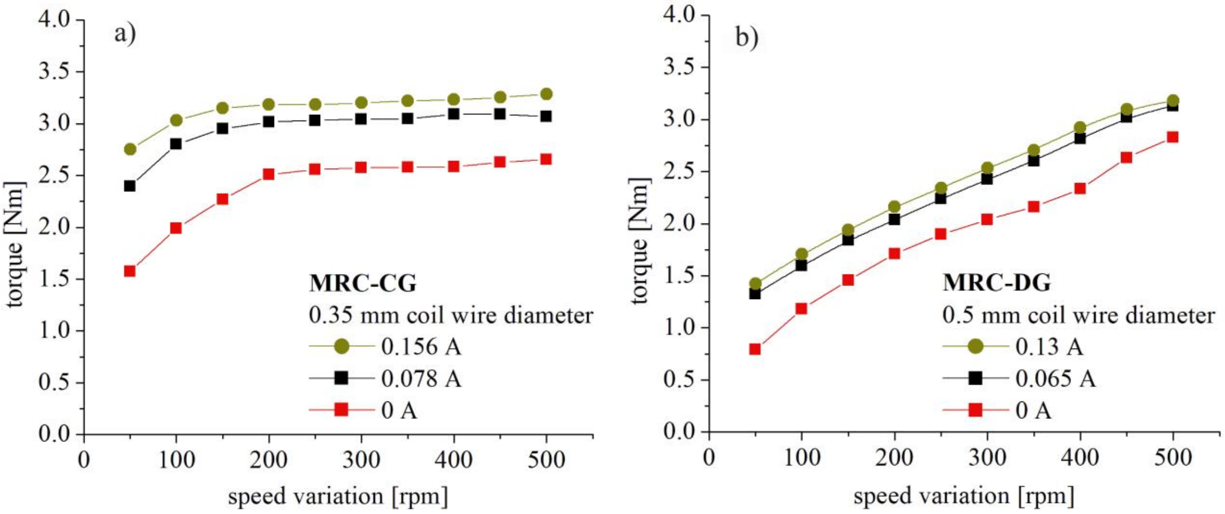

Fig. 7 – Torque measured for each magnetorheological clutch type in terms of speed variation between the shafts at three current values:a) MRC-CG; b) MRC-DG.

The torque measured for the MRC-CG shows a fairly uniform distribution around 2.5 Nm with the speed variation between the shafts when no magnetic field is applied (Fig. 7a). The maximum torque value of 3.2 Nm is reached at the current value of 0.156A while the distribution becomes more uniform with the speed variation between the shafts. The maximum torque value leads to a torque density of 0.33 kNm/m^3 for MRC-CG. Torque control for the MRC-CG comes from the MRF response due to the power variation applied to the coil. A rather limited contribution to the MRC-CG torque control is distinguished due to the speed variation between the shafts for the cylindrical gap geometry.

The torque distribution for the MRC-DG reveals a monotonous increase from 0.75 Nm at a speed difference between the shafts of 50 rpm to 2.75 Nm at 500 rpm when no magnetic field is applied (Fig. 7b). The maximum torque value around 3.17 Nm at a speed difference between the shafts of 500 rpm is measured for a current value of 0.13A obtaining a torque density of 0.7 kNm/m^3 for MRC-DG. The MRC-DG covers a wide range of torque control due to both gap geometry and the speed variation between the shafts, while the contribution due to the MRF's response to the power variation applied to the coil is quite limited.

Obviously, a significant difference in the torque distribution between the two magnetorheological clutches is noted in Fig. 7. The MRC-DG highlights a significantly wider range of torque control with the variation of speed between the shafts than the MRC-CG. The maximum torque value is practically the same for both magnetorheological clutches. However, the maximum torque value for the MRC-DG is reached at a speed difference between the shafts of 500 rpm, while for the MRC-CG is reached for a speed range from 200 rpm to 500 rpm. In addition, MRC-DG exhibits approximately twice the torque density of MRC-CG. These results demonstrate that the MRC-DG provides a wider torque control range than the MRC-CG with a more compact solution.

5. CONCLUSIONS

In this study, two magnetorheological clutches with different geometric configurations (cylindrical denoted MRC-CG and disk labeled MRC-DG) were designed and tested with the same commercial MRF to determine the influence of the geometric configuration on their performances. Practically the same maximum torque value was measured for both magnetorheological clutches. However, a significant difference in torque variation between the two magnetorheological clutches with different geometries is determined in the speed range from 50 rpm to 500 rpm between the output and input shafts. A linear torque distribution with speed variation between the shafts is measured for the MRC-DG, while a quasi-constant torque distribution is obtained for the MRC-CG in the same speed range. Based on the highlighted results, it can be concluded that the MRC-DG provides a wider variation in the output shaft mechanical power in relation to the input shaft than the MRC-CG. Therefore, MRC-DG is the first choice in selection for engineering applications.

Both magnetorheological clutches were designed with the coil installed on the fixed side to be connected directly to the DC source. As a result, the input/output shafts rotate while the casing is fixed. The mechanical solutions were designed with ball bearings between the fixed and rotating parts. The technical-economic criterion (e.g. torque density) in the choice of magnetorheological clutches for engineering applications is the selection of the most compact one. The MRC-DG torque density value of 0.7 kNm/m^3 is more than twice the MRC-CG value of 0.33 kNm/m^3. In conclusion, the MRC-DG is the feasible solution for the engineering application because it is more compact than the MRC-CG. The combination of the two fundamental geometries (cylinder and disk) leads to magnetorheological clutches with T-type or multi-disk geometries that incorporate the advantages of both better covering the requirements for some engineering applications.

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