Magnetorheological torque transmission devices with permanent magnets

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Abstract. A novel type of magnetorheological (MR) clutch whose magnetic circuit contains a combination of a permanent magnet and an electromagnet is described. Without the support of the electromagnet, the permanent magnet generates a magnetic field in the MR fluid shear gap which enables the MR clutch to transmit a torque without the supply of any electric energy. Hence, the operational states of this clutch are reversed with respect to the common MR clutches equipped with an electromagnet only. Three different MR clutches with hybrid magnetic circuits containing permanent magnet and electromagnet were designed, manufactured and tested. The three clutches differ in their number of mechanical parts which can rotate with respect to each other as well as in their size and weight and in their maximum transmittable torque. The largest MR clutch is capable to transmit torques up to nearly 800 Nm. The designs of the three novel MR clutches and the results of the mechanical tests upon variation of the coil current are presented in this paper.

1. Introduction
Magnetorheological (MR) fluids are suspensions of magnetically polarizable particles in a carrier liquid [1]. When a magnetic field is applied, the particles become magnetic dipoles and attract each other, which results in immediate stiffening of the material. This strong, fast and reversible MR effect known since its discovery by Rabinow more than six decades ago can be exploited for a large number of technical applications.

Most prominent applications of MR fluids have been found in the field of adaptive vibration damping. First automotive shock absorbers entered the market about ten years ago and the use of semi-active suspension systems has been extended to a multitude of vehicle models. Other applications of adaptive vibration damping concern driver seats in trucks and busses, seismic mitigation of buildings and the protection of cable-stayed bridges against wind excitation. A huge number of investigations have been performed on different types of MR dampers considering their design, the damping control and the MR fluids involved.

Less attention has been devoted to the use of MR fluids for controllable torque transmission so far. This lack is surprising, because variable torque transmission offers the opportunity to realize novel clutches and brakes where the torque is controlled by the magnetic field. Such clutches are capable to flexibly distribute the torque from an engine to several consumers. An example for flexible torque distribution is the control of side aggregates in a vehicle which are continuously driven by the

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combustion engine [2]. A further benefit of MR clutches is the possibility to limit the transmitted torque by the strength of the applied magnetic field. When the input torque reaches a preselected limit, the clutch slips and a higher output torque cannot be transmitted. This is especially worthwhile in applications in which safety issues have to be considered. Moreover, MR clutches bear the advantage of inherent damping in contrast to conventional clutches with hard disks.

Some work on MR clutches has already been published. The first MR clutch was reported by Rabinow who already has been aware of the strong benefit of MR fluids for controlled torque transmission [3]. A large variety of careful investigations was performed by Lampe who studied different clutch designs and basic issues of their performance [4, 5]. Kieburg et al. described a high torque clutch which was successfully tested in the powertrain of a vehicle [6]. A very small and compact MR clutch which can transmit a maximum torque of 6 Nm was developed by Kikuchi et al. [7].

The magnetic field in the MR clutch is usually generated by an electromagnet with a coil. The current in the coil determines the magnetic flux density in the MR fluid and the corresponding torque which is transmitted. This means that without any coil current the clutch works in the disengaged operational state, where only a drag torque due to the base viscosity of the MR fluid and the seal friction is transmitted. In the engaged state, the transmitted torque can only be maintained by the continuous supply of electric energy to the coil. If the clutch is primarily operated in the engaged state, this concept is energy-inefficient.

The reverse operation is possible with the use of permanent magnets in addition to the electromagnet. In such hybrid magnetic circuit with two different sources of the magnetic field the base field is generated by the permanent magnet. Correspondingly, the MR clutch can be operated in the engaged state without electric energy supply. To disengage the clutch, a counter-field is generated by the electromagnet, which weakens the field of the permanent magnet in the MR fluid gap and reduces the transmitted torque. This concept has already been demonstrated for MR dampers, in which a base damping force is generated by permanent magnets [8, 9].

Only few studies have been published regarding MR clutches with permanent magnets until now [10, 11]. Recently the feasibility of the concept of hybrid magnetic circuits for MR clutches was demonstrated [11]. The objective of this paper is to investigate the performance of MR clutches with a combination of permanent magnets and electromagnets. For this purpose, MR clutches with different designs, sizes and transmittable torques were constructed and tested.

2. MR clutch types

MR clutches are usually operated in the shear mode, where the MR fluid in a thin layer mechanically connects or disconnects the input and output shaft of the clutch. Two main designs of MR clutches are known which are designated disk-type and bell-type [4]. In the disk-type clutch, the shear gaps filled with the MR fluid are oriented perpendicular to the rotational axis of the clutch (Figure 1, left). In the bell-type MR clutch, the MR fluid gaps are oriented parallel to the rotational axis (Figure 1, right). Figure 1 also shows the magnetic field lines generated by the coil which penetrate the MR fluid in the shear gaps and attach the output to the input shaft via the stiffening of the MR fluid.

Disk-type and bell-type clutches have different advantages and disadvantages. The disk-type clutch can be made more compact with a large number of parallel disks and corresponding shear gaps, which leads to a large transmittable torque. However, at high rotational speeds the torque is more prone to particle separation due to the centrifugal forces acting on the heavy iron particles in the MR fluid. In contrast, in bell-type MR clutches, the particles can move only over the small distance of the thin MR fluid gap.
Figure 1. Disk-type MR clutch (left) and bell-type MR clutch (right), each with input shaft and output shaft, the magnetic circuit made from magnetisable material and the magnetic field lines penetrating the MR fluid.

3. MR clutches with hybrid magnetic circuit

In the following, three MR clutches equipped with a hybrid magnetic circuit containing a permanent magnet and an electromagnet are introduced. All three clutches were designed in the bell-type configuration. Their designs especially differ in their number of mechanical parts which can rotate with respect to each other. In the simplest design, the clutch consists only of the input and the output part. In this case, the electromagnet is not stationary in the clutch operation with rotating input and output shaft. Hence, the coil has to be electrically connected by sliding contacts. Other differences between the three presented MR clutches concern their size and weight as well as their maximum transmittable torque.

3.1. Two-part MR clutch

Figure 2. Scheme of the two-part MR clutch with permanent magnet and electromagnet.

The first MR clutch with permanent magnet and electromagnet consists of two parts which are mechanically connected to the input shaft and the output shaft, respectively. Figure 2 exhibits the schematic design as well as the outer dimensions of the clutch. The coil is connected to the input shaft, whereas the other magnetic source, the permanent magnet, is attached to the output shaft. The torque
is transmitted by the MR fluid in the two concentric gaps which are oriented parallel to the rotational axis according to the bell-type design. In order to distinguish between the two parts of the clutch in Figure 2, the input part is shown in gray and the output part in blue. The magnetic circuit which guides the magnetic flux through the MR fluid gaps is indicated by darker gray and blue colors.

It becomes apparent that the two magnetic sources generate magnetic fields in different magnetic sub-circuits. However, the magnetic fields superpose in the MR fluid gaps and can weaken and strengthen each other. Without current in the coil, only the permanent magnet generates a magnetic field in the MR fluid. This operational mode is schematically shown in Figure 3, left. Here, the MR fluid in the gaps stiffens without any supply of electric energy and a corresponding torque can be transmitted by the clutch. Figure 3, middle, visualizes the operational state, in which a current applied to the coil causes a magnetic field which counteracts the field of the permanent magnet. As a consequence, the two fields weaken each other and the MR fluid re-liquefies. This means that the engaged and disengaged states of the clutch are reversed with respect to the known MR clutches with an electromagnet only.

Finally, in the third operational mode in Figure 3, right, the magnetic field of the electromagnet strengthens that of the permanent magnet. Such an enhanced magnetic field causes an even higher yield stress in the MR fluid than in the operational mode with the permanent magnet only. This should lead to a higher torque transmission of the clutch.

![Figure 3. Magnetic field lines in the two-part MR clutch in three different operational modes: Magnetic field generated only by the permanent magnet (left), negative superposition or weakening of the fields (middle) and positive superposition or strengthening of the fields (right).](image)

In order to quantify the magnetic field, FEM simulations of the magnetic flux density in the MR fluid gap were performed. The results are shown in Figure 4. In the operational mode with the permanent magnet only, the magnetic flux density in the MR fluid gap amounts to 450 mT. Decreasing the magnetic field strength by a counter-field caused by a coil current of -7.5 A results in a magnetic flux density of less than 50 mT. When the polarity of the coil current is reversed to +7.5 A, the two magnetic fields strengthen each other and the total magnetic flux density is enhanced to 830 mT. This demonstrates that the magnetic flux density can be varied in a very broad range and a medium flux density is generated by the permanent magnet without electric energy supply.
Figure 4. Magnetic flux density in the MR fluid gap for the three operational modes corresponding to coil currents of -7.5 A, 0 A and +7.5 A, received from FEM simulations. The position in the MR fluid gap refers to a line along the gap shown in the right figure.

The described MR clutch with the hybrid magnetic circuit containing permanent magnet and electromagnet was designed in more detail, manufactured and tested. Figure 5 exhibits the design model of the MR clutch and the assembled demonstrator. In both pictures, the electromagnet is integrated in the bottom part and the permanent magnet in the top part of the clutch. The mass of the MR clutch is 11 kg and it can be operated at rotational speeds up to 2000 rpm.

Figure 5. Design model of the two-part MR clutch (left) and demonstrator model (right).

For the evaluation of the performance of the MR clutch, it was filled with a MR fluid which contains 35 vol.% carbonyl iron particles in silicone oil and was developed in the same laboratory. The clutch was mounted in a self-made test-rig which is shown in Figure 6. In these experiments, the torque at different coil currents was measured in the braking mode. This means that the output shaft of
the clutch was fixed like in a brake. The input shaft was driven by an electric servomotor at low speed and the braking torque was measured with a torque sensor between the motor and the clutch.

Figure 7 shows the results of the torque measurements in comparison with calculated data. For the calculations, a simple model for the resulting shear force was used, which includes the shear stress of the MR fluid depending on the magnetic flux density in the MR fluid gap. The measurements and the calculations were conducted at various coil currents between -7.5 A and +7.5 A. The comparison in Figure 7 shows that the experimental torques are lower than the calculated data. However, the general dependence of the torque on the coil current is in rough agreement with the predicted behavior. Without coil current (0 A), a medium torque of 17 Nm can be transmitted by the clutch without electric energy supply. When a counter-field is generated in the MR fluid gap by a coil current of -7.5 A, the transmitted torque is diminished to 1-2 Nm. With a reversed coil current of +7.5 A, an enhanced transmitted torque of 34 Nm was achieved.

![Figure 6. Experimental test setup for torque measurements with the two-part MR clutch integrated.](image)

![Figure 7. Measured and calculated torque of the two-part MR clutch in dependence on the coil current.](image)

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Figure 7. Measured and calculated torque of the two-part MR clutch in dependence on the coil current.

The results demonstrate that the broad variability of the magnetic flux density in the MR fluid gap by the variation of the coil current corresponds to a wide range of torque transmission. Without any coil current and electric energy supply, a medium torque is transmitted by the clutch.

3.2. MR clutch with stationary electromagnet

The second MR clutch with permanent magnet and electromagnet consists totally of four parts which can rotate with respect to each other. Figure 8 exhibits the schematic design of this more sophisticated clutch. The input shaft (blue in Figure 8) is coupled to the part with the permanent magnet. The torque is transmitted to the output shaft (red in Figure 8) via the MR fluid in the axially oriented concentric gaps. In contrast to the two-part MR clutch, the housing of this clutch is stationary and allows a tight attachment to the environment. Finally, the fourth part of the clutch containing the coil is apart from the other three parts. It can be mechanically connected to the housing, which avoids the necessity of sliding electrical contacts. However, the relative motion of the coil with respect to the magnetic circuit in the output part of the clutch could cause disturbing eddy currents. In order to eliminate such eddy currents, alternatively the coil part can be coupled to the output shaft. For this purpose, a commutator ring is attached to the output shaft (Figure 8).
Figure 8. Scheme of the MR clutch with stationary electromagnet consisting of four separate parts: Input shaft, output shaft, coil part and housing.

Figure 9 exhibits the three working modes of the MR clutch in correspondence with the two-part clutch. Again, without any coil current, a magnetic field is generated by the permanent magnet, which causes a torque transmission without energy supply. The magnetic field of the permanent magnet in the MR fluid gaps can be decreased or increased by the electromagnet, depending on the polarity of the coil current.

Figure 9. Magnetic field lines in the MR clutch with stationary electromagnet in three different operational modes. Magnetic field generated only by the permanent magnet (left), negative superposition or weakening of the fields (middle) and positive superposition or strengthening of the fields (right).

In Figure 10, maps of the calculated magnetic flux density in the MR fluid clutch received from FEM simulations are revealed. The red ellipses indicate the region of the MR fluid gaps. When only the permanent magnet generates the magnetic field in the gaps, a medium flux density is achieved (Figure 10, left). With the counter-field generated by the electromagnet, the magnetic flux density in the MR fluid gaps nearly vanishes (Figure 10, middle). Finally, a positive superposition of both magnetic sources leads to a very high magnetic flux density in the MR fluid gaps (Figure 10, right).
Figure 10. Top: Maps of the magnetic flux density in the MR clutch with stationary electromagnet in three different operational modes (top): Magnetic field generated only by the permanent magnet (left), negative superposition or weakening of the fields (middle) and positive superposition or strengthening of the fields (right). Bottom: Corresponding scheme of the MR clutch. The red ellipses indicate the region of the MR fluid gaps.

Figure 11. Demonstrator model of the MR clutch with stationary electromagnet.

Figure 12. Measured torque of the MR clutch with stationary electromagnet in dependence on the coil current.

Like the two-part clutch, the MR clutch with stationary electromagnet was also designed, constructed and tested. Figure 11 depicts the demonstrator model of the clutch. For the investigations on the same experimental test-rig as before, a MR fluid with 35 vol.% iron particles in silicone oil was prepared and filled into the MR clutch. The measurements were conducted similar to those on the two-part clutch. The results in terms of the transmitted torque in dependence on the coil current are
depicted in Figure 12. Without coil current, a medium torque of 30 Nm is transmitted. Depending on the polarity of the coil current, the torque can be decreased or increased up to 55 Nm. However, the decrease of the torque by the counter-field is not as strong as expected. The source of the relatively high minimum torque has been identified in details of the MR fluid gap design. This will be an issue of further improvements of the MR clutch.

3.3. MR clutch with high torque transmission

The third MR clutch with permanent magnet and electromagnet was designed to transmit very high torques. The motivation for this clutch arose from the development of a hybrid vehicle for public transport, whose combustion engine should be variably connected by this MR clutch to the electric generator in the vehicle. Figure 13 exhibits the schematic design as well as the outer dimensions of the new MR clutch. The diameter of the clutch amounts to 350 mm and the length without outer shafts is 304 mm. The permanent magnet with a diameter of about 200 mm was assembled from a large number of small NdFeB magnets in order to avoid the effort of manufacturing a permanent magnet of this size in one piece.

The high-torque clutch was designed in more detail, manufactured and assembled. In order to achieve exceptionally high torques, a MR fluid with 50 vol.% iron particles in silicone oil which reaches a shear stress of 70 kPa at 700 mT magnetic flux density was selected for the clutch and manufactured. The demonstrator model of the clutch is represented in Figure 14. It was integrated in the experimental test setup for torque measurements and its performance was evaluated.

Figure 13. Scheme of the MR clutch with high torque transmission and outer dimensions in mm.

Figure 14. Demonstrator model of the MR clutch with high torque transmission (left) and integrated in the experimental test setup for torque measurements (right).
The results of the torque measurements upon variation of the coil current are shown in Figure 15. Starting from the operational mode without electric energy supply, the torque of 180 Nm can be enhanced by the positive superposition of the magnetic fields of permanent magnet and electromagnet up to nearly 800 Nm. However, the decrease of the transmitted torque by the counter-field of the electromagnet with negative currents down to 120 Nm should be improved by further modifications in the magnetic circuit design in order to extend the range of variability of the transmitted torque.

Figure 16 shows the temporal change of the torque transmitted by the MR clutch upon a stepwise increase of the coil current. The measured torque follows the steps of the current immediately, but requires some seconds to reach the final value. With a coil current of 4.2 A, a maximum torque of 730 Nm is achieved.

This high torque would be sufficient for the application in the hybrid vehicle, but it would be even better to accomplish this torque with the use of the permanent magnet only, i.e. without the supply of electric energy. Further work on this high-torque MR clutch shall be focussed on the design of a magnetic circuit, which should generate a stronger magnetic field by the permanent magnet only. Another future goal is the decrease of the minimum transmitted torque which is achieved with the counter-field of the electromagnet by a mutual cancelation of the fields of the two magnetic sources in the MR fluid gaps.

4. Conclusions

Three novel types of MR clutches, each equipped with a hybrid magnetic circuit containing a permanent magnet as well as an electromagnet and designed in the bell-type configuration were described in this paper. The clutch designs especially differ in their number of mechanical parts which can rotate with respect to each other as well as in their size and weight and their maximum transmittable torque.

The most simply designed MR clutch has only two parts which can rotate with respect to each other. Another four-part MR clutch with hybrid magnetic circuit has a stationary housing and allows the mechanical attachment of the electromagnet to this housing in order to avoid any sliding electric contacts. Finally, the third MR clutch with permanent magnet and electromagnet was designed to be operated in a hybrid vehicle for public transport. This clutch is capable to transmit high torques up to nearly 800 Nm.
With all three MR clutch designs, it could be successfully proven, that it is possible to operate the MR clutch in three different modes depending on the coil current in the electromagnet. Without any electric energy supply to the coil, the clutch transmits a medium torque due to the corresponding state of stiffening of the MR fluid. On one hand, when a coil current with negative polarity is applied, the corresponding counter-field in the MR fluid gap weakens that of the permanent magnet and the transmitted torque of the clutch is decreased. On the other hand, with a positive coil current, the fields of both magnetic sources strengthen each other in the MR fluid gaps, which results in an enhancement of the transmittable torque. Hence, a broad range of the transmitted torque which is controlled by the coil current can be achieved with this novel MR clutch principle.

The exploitation of hybrid magnetic circuits offers the possibility to reverse the operational states of MR clutches. If the clutch is engaged in the usual operational state, this engagement can be maintained without any supply of electric energy. Only for a short disengagement of the clutch, electric energy in terms of the coil current has to be supplied. Hence, in such operation the novel MR clutch works very energy-efficient, which offers far-reaching perspectives for a multitude of applications in the automotive sector and in mechanical engineering.

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