The novel MRF-ball-clutch design – a MRF-safety-clutch for high torque applications

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Abstract. This paper describes the development of a safety-clutch by using magnetorheological fluids (MRF) to switch the transmission torque between a motor and a generator in a bus-like vehicle. The clutch is based on a new design combining an axial MRF-actuator and a ball coupling mechanism. This so called “MRF-ball-clutch” avoids the disadvantages of traditional bell- or disc-MRF-clutch designs where the torque is transmitted by the MRF which leads to a self-heating due to the shearing forces in the fluid and a more or less significant drag torque caused by limitations of the relation between minimal and maximal transmittable torque. The safety clutch based on the new MRF-clutch design requires a minimum of power consumption and allows switching high torsional moments in a very compact, lightweight and robust design.

1. Introduction
A big potential for technical applications based on magnetorheological fluids (MRF), beside adjustable dampers, switchable engine mounts, etc., are so called smart clutches. There are two common designs of these clutches, the disc- and the bell- design (see Figure 1). Both consist of two rotatable parts, the input or drive side and the output or power take off side, with a small gap in between. This gap is filled with MRF that transmits the torsion moment from the input to the output side depending on its viscosity and its interaction with the surfaces. These concepts allow influencing the power transmission and realize an adjustable slip torque.

![Figure 1. Conventional MRF-clutches, “bell”-design (left) and “disc”-design (right).](image)

To activate the MRF a high magnetic field, generated by an electromagnet is necessary. Therefore a clutch based on these designs has relatively high power consumption and is critical for energy limited applications. Due to the shear stress applied on the fluid both designs have the disadvantage to...
lead to self-heating effects of the fluid as well as a limitation of the relation between minimal and maximal transmittable torque. Clutches based on these conventional designs are relatively big and heavy in relation to the transmittable torque.

Although the aforementioned designs are very popular, the performance of these clutches has room for improvement. Especially clutches that are designed to transmit higher torques, e.g. some hundred Nm in typical automotive applications, need to have mechanical parts with large surfaces to interact with the MRF. As the corresponding volume of the MRF is also very big, the electromagnetic system has to be really strong to provide a sufficient magnetic field. The minimal torque is, beside the question of the dimension of the clutch, mainly a result of the basic viscosity of the MRF. Caused by this basic viscosity a minimal torsional moment will always be transmitted, which turns out to be the limitation for some applications. Another disadvantage of the traditional MRF clutch designs is caused by the rotation of the mechanical parts that are in contact with the MRF. All passes to the outside have to be sealed very carefully. This is very challenging as the components of the MRF are highly abrasive and therefore bad for the durability of the seals. Caused by these disadvantages a MRF-Clutch based on these classic designs is not in technical or commercial use so far.

For safety critical applications, where a fast reacting clutch to switch the power transmission on or off completely is important and an adjustable slip torque is not needed, a new MRF-clutch-design was developed at the Fraunhofer LBF.

### 2. Principle of the MRF-ball-clutch

The new design is based on a combination of a ball safety coupling mechanism (see Figure 2) and an axial operating MRF-actuator (see Figure 3) and was named “MRF-ball-clutch”. Compared to the described common clutch designs where the torque is transmitted friction locked by the MRF, here mechanical coupling devices, realized with balls which are circularly located in countersinks on the front of two opposite placed discs, act interlocking to transmit the power. By the geometrical interaction of these balls and the two discs an applied torque produces a force in the direction of the rotational axis which increases the distance between input and output disc. If the torque exceeds a certain level the balls are no longer able to rest in their countersinks and the power transmission is stopped immediately. To adjust the maximum transmittable torque, a variable counter force is required that hinders the axial movement of the clutch discs. This force is generated by an axial operating MRF actuator, which is designed similar to a common single-tube damper. A solenoid coil generates a magnetic field in the fluid gap and by this the flow through of the MRF can influenced and the retention forced to open the clutch can be tuned. The principle of the MRF-ball-clutch is patented by the Fraunhofer LBF [1, 2].

![Figure 2. Principle of a ball clutch; locked (left) and unlocked (right) (Source: R+W Antriebselemente GmbH).](image)

![Figure 3. Principle of a MRF single tube damper.](image)
2.1. Example application torque wrench
To show the potential of the developed clutch concept an electrically adjustable torque wrench was chosen as a functional demonstrator to represent a typical application. Figure 4 shows a cross-section of the main parts. On the left side the “ball-clutch” is represented by two hardened steel discs with 90° countersinks and 6 steel balls of 8 mm. The balls are arranged on a circle with a diameter of 36 mm. On the right side the MRF actuator is realized by a low carbon steel piston with a coil of 0.5 mm copper wire and a tube housing also made of low carbon steel. The counterforce of the piston (typically 5.6 kN) is transmitted by a guided rod to the clutch side. To readjust the system, a “weak” retention spring is located at the right end of the rod.

![Figure 4. MRF torque wrench, cross section.](image)

The finally realized demonstrator structure (see Figure 5) consists of the MRF actuator, a handle bar with force sensor, a connector for a socket and an electronic unit. With the torque wrench it is possible to tighten a screw exactly with a predefined torque between 5 and 100 Nm.

![Figure 5. Prototype of a MRF torque wrench.](image)

With the investigated demonstrator the functional capability of the developed clutch concept was approved [3]. In contrast to mechanical clutch systems, the release torque is online adjustable. The small MRF-ball-clutch is able to transmit up to 100 Nm with very low electrical power consumption.

3. High torque MRF-ball-clutch for E-mobility application
In concepts for future electric vehicles different new innovations are in discussion to solve the main problems as there is for example the relatively small cruising range of electric vehicles. Most of the concepts based on the combination of different engines, electro engines and combusting engines, which increase the complexity of the powertrain and the demand for new coupling elements / clutches.
One of the abandonings of the clutches in future electric mobility is to switch the different components of the powertrain for energy consumption or safety reasons as needed in the actual driving situation.

For a reference application named “AutoTram” [4] (see Figure 6 left) within the scope of “Fraunhofer’s System Research for Electromobility – FSEM” [5] a safety clutch has to be developed.

![Figure 6. Fraunhofer AutoTram [3] (left) and its power unit (right).](image)

The aim is to replace the passive clutch between the diesel engine and the electric generator within the power unit (see Figure 6 right) of the AutoTram by a MRF clutch. This clutch should work as safety component and should be able to decouple the two main systems even under maximum load conditions. As the power unit consists of a 180 kW V8 Diesel-engine with a maximum torque of typically 560 Nm (operating ratio of 1.2 leads to ~700 Nm) and a maximum speed of 4000 rpm, the clutch design is very challenging.

![Figure 7. CAD Model of the MRF safety clutch.](image)

Figure 7 shows a CAD model of the clutch. The design of the MRF actuator unit is similar to the design of the torque wrench actuator unit. The size, number and position of the balls are adapted to the different requirements. The clutch has a diameter of 260 mm, an overall length of 300 mm and a mass of about 15 kg. To avoid the axial displacement, generated by decoupling, the torque is transmitted over a splined shaft connection. The power consumption of the electric parts (coil) is only about 8 W. Compared to traditional active MRF and non MRF clutches these first values show a high potential of the new technology.

### 3.1. Functional tests of the MRF-ball-clutch

After setting up the MRF safety clutch, initial functional checks were made on a test rig (see Figure 8).
First results are promising: it’s possible to transmit the torque of 700 Nm and open the clutch on demand. The minimal release torque is about 200 Nm.

The measuring data of a first functional check are shown in figure 9. Torque and rotation speed are increased till 700 Nm at 2100 rpm. After a while of constant torque and rotation speed the current entry of the coil was cut off (t~75s). Consequently the clutch opens and the torque drops down.

Figure 8. Picture of the MRF safety clutch on a test rig.

Figure 9. Measuring data of the first functional tests.

3.2. Functional tests of MRF-actuator

After testing the complete MRF-ball-clutch tests with the axial MRF-actuator were performed on a tension-compression testing machine [6, 7]. The goal is that the actuator provides a retention force of 5.6 kN, equivalent to a pressure difference of 3.5 MPa. The test runs were made with different fluids provided by the Fraunhofer ISC [8].
The results are shown in figure 10. It shows the linear movement over time under a constant load or different fluids. In general the actuator is able to provide the needed force, but in the course of time there is some slow movement under load. The movement at the beginning results from settling effects of the test assembly. After that there is a more or less linear creeping that approaches a final value (see Figure 10 cycle V1 and V2). The reason for this behaviour is the separation of the MRF. The carrier fluid flows from the compression side through the particle chains in the gap to the tension side. The particles on the compression side are resting on their side. Disassembling the MRF-actuator proved that assumption, see Figure 11. But it is still possible that there are other effects like leaky sealings on the compression side.

For the MRF-ball-clutch this behavior means, that over time there is an increasing clearance in the drivetrain. This finally may lead to declutching. Even tough the measured data of the MR-fluids FSEM 5 (V4) and FSEM 7 (V5) look much better than the former ones, there may be problems with the MRF-ball-clutch in longterm operation.

The results for some long-term tests are shown in figure 12. The Fluid used in these tests (FSEM 6) is very similar to the fluids FSEM 5 and 7 that used in he former tests. The curves are showing that this fluid is also converging to a final value over time. This is depending on the load after 5 to 25
hours. Curve 4 shows that, after reaching the final value, there is no further linear movement during the duration of the test (140 hours).

4. Conclusion and outlook
The new concept of MRF based clutches using a combination of a ball safety coupling mechanism and an axial operating MRF-actuator has big advantages compared to clutches based on conventional MRF-clutch designs, which are:

- reduced thermal stress
- lower energy consumption
- reduced complexity of the construction in particular for sealing arrangements
- reduced problems of abrasion
- compact design
- reduced weight
- fast reaction time
- complete couple / decouple without any remaining drag moment

On the other side, the MRF-Ball-clutch does not allow the continuous change of power transmission (slip mode).

With respect to this promising results there seems to be a large field of applications for the described new MRF clutch concept e.g. as a safety clutch for machine tools, hand-operated power tools, in the automotive sector, etc.

Before the technology of MRF-ball-clutches can be implemented in commercial applications further investigations concerning reliability aspects, the creeping phenomena of the fluid etc. have to
be done. Therefore it is planned to build up a simple linear mrf-actuator that has no sealings on the compression side of the actuator.

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