Design of shear gaps for high-speed and high-load MRF brakes and clutches

D Güth¹, A Wiebe and J Maas
Ostwestfalen-Lippe University of Applied Sciences, Control Engineering and Mechatronic Systems, Liebigstraße 87, 32657 Lemgo, Germany, www.motion-ctrl.de
E-mail: dirk.gueth@hs-owl.de

Abstract. Magnetorheological fluids (MRF) are smart fluids with the particular characteristics of changing their apparent viscosity significantly under the influence of a magnetic field. This property allows the design of mechanical devices for torque transmission, such as brakes and clutches, with a continuously adjustable and smooth torque generation. Especially the use of MRF in devices for applications with the demand on high rotational speeds and high loads can offer advantages, because more dissipation energy and thermal load peaks can be compensated by the torque generating fluid volume. However, high rotational speeds can cause a centrifugation of the particles contained in the MRF especially in idle mode when no magnetic field is applied. This can yield on the one hand to labile and unpredictable behavior of the torque response and on the other hand to a higher wear of the MRF or in the worst case to a destruction of the MRF with respect to a long-term view. For ensuring reliable braking or coupling conditions, in this contribution the development of a Taylor-Couette flow with axisymmetric toroidal vortices in axial shear gaps of MRF brakes and clutches is considered. The developing flow profiles in these shear gaps are modeled and analyzed in detail and finally design rules for axial shear gaps are introduced. Measurements at high rotational speeds up to \(6000 \text{min}^{-1}\) with a test actuator based on this design prove the positive influence of the vortex flow on the homogeneity of the MRF suspension and on the consistency and predictability of the braking or coupling torque even under long-term conditions.

1. Introduction
The use of magnetorheological fluids (MRF) in rotatory actuators is currently increasing more and more due to their outstanding properties e.g. the smooth adjustable torque, the fast response time, the noiseless operation and the reduced design space of actuators compared to conventional dry friction based systems, [1]. Also the rapid development progress in the electric drive technology with fast rising requirements on the maximum braking power and maximum rotational speeds shows up the performance limits of conventional, friction-based electromagnetic brakes. The required lifetime, peak loads and the dissipation of braking energy cannot be ensured in a sufficient degree by these conventional systems. By using MRF brakes with a scalable fluid volume for braking, new technical capabilities can be opened up. With an appropriate design of the fluidic system of a MRF brake, more dissipation energy and thermal load peaks can be compensated, because of a braking fluid volume and also a better dissipation of energy can be realized, [2, 3]. Further challenges to meet are high rotational

¹ To whom any correspondence should be addressed.
speeds up to 6000min\(^{-1}\) and more which are often corresponding to the requirement of high energy brakes. Especially when running a brake at high rotational speeds in idle mode, but no magnetic field is applied, the magnetorheological fluid is exposed to different forces caused by accelerating fields such as gravity, centrifugal forces and inertial force. Due to high differences in the density of the MRF components, carrier fluid and carbonyl iron powder particles, these forces can cause a separation of the two-phase system, whereby the particles will concentrate in the direction of the acting acceleration forces, \[4\]. For the mentioned applications with high energy dissipation and high rotational speeds especially the shear gap has to be designed in an appropriate manner. Thereby, a distinction will be made mainly between radial (disk-shaped actuators) and axial (drum cylinder-shaped actuators) oriented shear gap designs. Especially for applications with high rotational speeds, axial shear gaps with a narrow fluid gap size in radial direction offer advantages considering a possible particle centrifugation caused by the acting radial accelerations, \[5\].

In this contribution the developing flow profiles for the non-magnetized case (Off-State mode) in axial shear gaps will be modeled and analyzed in detail. The idea is to take advantage of a developing Taylor-Couette flow in axial shear gaps that can support the homogeneity of MRF when operating with high rotational speeds. Beside a mathematical description of the developing fluid profiles depending on the rotational speed, also analysis are performed with an experimental test actuator for rotational speeds up to 6000min\(^{-1}\).

2. Modelling of fluid flow in cylinder actuators
In the design process of actuators based on MRF, two different states need to be considered: the Off-State mode with no applied magnetic field as well as the On-State Mode with an applied magnetic field for setting up the yield stress. For brakes and clutches, especially at high rotational speeds, it is in particular the Off-State mode when the actuator is driven in an idle state that has to be considered in detail due to the radial accelerations acting on the particles. As mentioned in the introduction, an axial shear gap design (cylinder) offers significant advantages due to the narrow gap size in radial direction.

However, even in these gaps a shift of the particle concentration in radial direction can occur. This can cause on the one hand undesirable effects like an insufficient or undefined behavior of the torque response when switching from idle into braking mode and on the other hand on long-term view an increased wear of the MRF. Therefore, it is necessary to take measures to ensure, even in the case of high rotational speeds, a homogeneous distribution of the particles in the MRF in the idle or Off-State mode. These measures should be based on the developing flow profiles for this type of shear gap that will be studied in detail in the following subsection. For describing the flow profiles occurring in the idle mode, the MR suspension will be treated in the Off-State mode as a continuum with the properties of a Newton fluid, while the solid phase of the suspension will not be considered as discrete particles.

2.1. Flow profiles
The fluid flow of the MRF can be considered in general by common methods of fluid dynamics that are based on the conservation laws for mass, momentum and energy. The continuity equation describes the time variation of mass in a volume element. For the stationary, rotationally symmetric case with an incompressible fluid, the continuity equation in cylindrical coordinates can be written as

\[
\frac{\partial w}{\partial r} + \frac{v}{r} + \frac{\partial w}{\partial z} = 0, \tag{1}
\]

where \(r\) is the radius position and \(v, w\) the flow velocity components in radial and axial direction respectively. The Navier-Stokes equation describes the temporal change of momentum in a volume element. With the simplified continuity equation (1) for incompressible fluids, the
Navier-Stokes equation for the azimuthal component \( \varphi \), the radial component \( r \) and the axial component \( z \) can be described for the stationary, rotationally symmetric case by

\[
\begin{align*}
&v \frac{\partial u}{\partial r} + \frac{v \cdot u}{r} + w \frac{\partial u}{\partial z} = \frac{\eta}{\rho} \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} \frac{\partial^2 u}{\partial z^2} \right) + f_\varphi, \\
&v \frac{\partial v}{\partial r} - \frac{u^2}{r} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial r} + \frac{\eta}{\rho} \left( \frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} - \frac{v}{r^2} \frac{\partial^2 v}{\partial z^2} \right) + f_r, \\
&w \frac{\partial w}{\partial r} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{\eta}{\rho} \left( \frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2} \right) + f_z,
\end{align*}
\]

where \( p \) is the pressure, \( u \) the flow velocity component in azimuthal direction, \( \rho \) the density and \( \eta \) the dynamic viscosity of the MRF. The considered volume forces \( f_\varphi, f_r \) and \( f_z \) take into account gravity, acceleration and other forces.

For low rotational speeds \( n \) or consequently low angular velocities \( \omega \), the developed flow is a steady and purely azimuthal, circular and especially laminar Couette flow, \([6]\). The resulting flow velocities can be calculated with the Navier-Stokes equations in equation (2) as a function of the radius \( r \). Therefore it is assumed that the expansion of the fluid gap in axial direction is infinite large. This simplifies the Navier-Stokes equation with \( \frac{\partial}{\partial z} = 0 \) and \( w = 0 \). Due to the laminar Couette flow, also the radial velocity component will result in \( v = 0 \) and the partial derivative \( \frac{\partial}{\partial \varphi} = 0 \) will vanish. Using these simplifications, the Navier-Stokes equation can be expressed by:

\[
0 = \eta \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} \frac{\partial^2 u}{\partial z^2} \right),
\]

\[
\rho \frac{u^2}{r} = \frac{\partial p}{\partial r},
\]

\[
\rho f_z = \frac{\partial p}{\partial z}.
\]

With the help of the first Equation for the azimuthal flow in equation (3), the velocity distribution in the radial direction can be determined. The Equation corresponds to a linear, ordinary, differential equation of second order with variable coefficients of Euler type, \([7]\). The solution results in the velocity distribution in radial direction for the laminar flow in radial shear gaps

\[
u (r) = C_1 r + \frac{C_2}{r}
\]

which is depicted in figure 1a with the coefficients

\[
C_1 = \frac{\omega_o - r_{io} \omega_i}{1 - r_{io}} \quad \text{and} \quad C_2 = \frac{r_i^2 (\omega_i - \omega_o)}{1 - r_{io}},
\]

wherein \( \omega_i \) is the angular velocity of the inner rotor, \( \omega_o \) of the outer rotor and \( r_{io} \) the radius ratio defined by

\[
r_{io} = \frac{r_i^2}{r_o^2}.
\]

For higher rotational speeds \( n \) the relative angular velocity \( \omega \) between the inner \( \omega_i \) and the outer rotor \( \omega_o \) has to be considered. If the angular velocity of the inner rotor \( \omega_i \) is increased compared to the outer rotor \( \omega_o \) above a certain threshold, the laminar Couette flow, see figure 1b, becomes unstable and a secondary steady state characterized by axisymmetric toroidal vortices emerges as depicted in figure 1c. This behavior is also known as the Taylor-Couette flow.

The change from the Couette flow into the Taylor-Couette flow can be characterized by the Taylor number \( Ta \) that is a dimensionless quantity. The beginning of a developing Taylor vortex
Figure 1. Cross section with velocity profile of an axial shear gap (a), rotating cylinder developing the Couette flow (b) and the Taylor-Couette flow (c).

flow emerges from a threshold of $Ta = 41.3$, [8], and can be calculated for the shear gaps with a narrow height by

$$ Ta = \frac{\omega r_i h_s \rho}{\eta} \cdot \sqrt{\frac{h_s}{r_i}}. $$

wherein $\omega = \omega_i - \omega_o$ is the differential angular velocity and $h_s = r_o - r_i$ represents the shear gap height, [9]. This equation can be used for very small shear gap heights $h_s = r_o - r_i \ll r_{i,o}$. The Taylor-Couette flow can be divided into two flow regimes: the Taylor vortex flow and the turbulent Taylor vortices, [10]. Considering the developing flows in axial shear gaps of MRF actuators, it is mainly the Taylor vortex flow that will occur. The turbulent Taylor vortices regime will only be reached at very high rotational speeds or very large heights.

For shear gap sizes $h_s/r_i \leq 1$, as they will be used for MRF brakes and clutches for the announced high energy applications, the transition point can be approximated by defining a critical Reynolds number, [11],

$$ Re_{crit} = \omega_i r_i \cdot \frac{h_s \rho}{\eta} = \left(41.1 + 14.5 \cdot \frac{h_s}{r_i}\right) \cdot \sqrt{\frac{r_i + r_o}{2 \cdot h_s}}. $$

Combining equations (7) and (8), also a critical Taylor number $Ta_{crit}$ can be calculated, which represents a corrected Taylor number describing the transition point for shear gap sizes $h_s/r_i \leq 1$:

$$ Ta_{crit} = \left(41.1 + 14.5 \cdot \frac{h_s}{r_i}\right) \cdot \sqrt{\frac{r_i + r_o}{2 \cdot r_i}}. $$

Using equation (8), a critical rotational speed $n_{crit}$ can be calculated that indicates the transition point from the Couette flow to the Taylor-Couette flow for large radial fluid gaps $h_s$:

$$ n_{crit} = \left(41.1 + 14.5 \cdot \frac{h_s}{r_i}\right) \cdot \sqrt{\frac{r_i + r_o}{2 \cdot h_s}} \cdot \frac{\eta}{2 \pi \rho r_i h_s}. $$

The axisymmetric toroidal vortices of the Taylor-Couette flow induce a mixing effect in the shear gap, that can cause an inherent effect for the homogeneity of the MR fluid under the influence of centrifugal accelerations due to high rotational speeds.
When designing shear gaps for brakes and clutches for high rotational speeds, this effect should be used. As an essential criterion it has to be considered that the faster rotating boundary is always placed in the inside and the transition from Couette to Taylor-Couette flow is considered by equation (10). A further important property beside geometric aspects that is pointed out by this equation, is the temperature-dependent dynamic viscosity of the MRF. A change in the temperature will result in a change of the developing flow profile and especially in a movement of the transition point from laminar Couette flow to Taylor-Couette flow. By an increase of the temperature of the MRF and the resulting decrease of the dynamic viscosity when running in idle mode, the transition to the Taylor-Couette flow will arise at even lower rotational velocities. This behavior can be an advantage for the safe operation of brakes and clutches based on MRF.

2.2. Methods for verification of the development of Taylor-Couette flow

Common experiments for the investigation of the Taylor-Couette flow are based on optical methods where the investigated fluid is transparent and tracer particles for visual capturing are added. Due to the highly concentrated suspension this method is not suitable for the investigation of the Taylor-Couette flow in MRF actuators. Hence, a different method based on the measured torque in the Off-State mode is used. In case of a laminar Couette flow, the increase of torque $T$ is directly proportional to the increase of the rotational speed respectively angular velocity $\omega$ by $T \sim \omega$ following Newtonian fluid behavior, also described as the linear theory in figure 2. In the Taylor-Couette flow (Taylor vortex flow) the behavior changes due to the additional dissipation energy for developing vortices and the torque $T$ increases

![Figure 2](image-url). Torque coefficient $C_T$ of the inner cylinder as a function of the Taylor number $Ta$, [10].
by $T \sim (\omega + \sqrt{\omega})$. This regime is also described as the non-linear theory in figure 2, [12]. Using this relation, an experimental method for the verification of the development of Taylor-Couette flow is pointed out and especially the transition point can be investigated. Therefore, a dimensionless coefficient $C_T$ is introduced that represents the torque. The torque $T$ of the inner cylinder of the shear gap can be calculated under consideration of the dimensionless coefficient $C_T$ by

$$T = C_T \cdot \frac{\pi}{2} \cdot \rho \cdot \omega_i^2 \cdot r_i^3 \cdot l$$

(11)

under the assumption that the angular velocity of the outer cylinder is $\omega_o = 0$, [10]. Using equation (7), the torque coefficient $C_T$ can be calculated for narrow gaps by

$$C_T = \frac{4 \eta}{\omega_i \cdot r_i \cdot h_s \cdot \rho} = \frac{4}{Ta} \cdot \sqrt{\frac{h_s}{r_i}}.$$  

(12)

Considering the correction of the Taylor number $Ta$ expressed by equation (8), the torque coefficient $C_T$ can be calculated as a function of the Taylor number $Ta$ and the transition point and consequently the Taylor-Couette flow can be experimentally verified. Thereby it is important to avoid measuring errors for instant due to changes in the temperature of the MRF.

In the following section an experimental test actuator is introduced for analyzing the flow profiles and especially to validate the Taylor-Couette flow in axial shear gaps of MRF based brakes and clutches.

3. Experimental test actuator

For the experimental investigation, a novel test actuator with the following properties is developed:

- axial shear gap with a variable height
- rotatable inner rotor and stationary outer rotor and vice versa
- capable of high rotational speeds up to $6000\text{min}^{-1}$
- torque capacity depending on shear gap height of about $30\text{Nm}$
- rotatable independent excitation system based on one electromagnet
- volume equalization for the compensation of thermal expansion of MRF
- temperature measurement in the shear gap

A design fulfilling these requirements is shown in figure 3. The design is based on a typical axial shear gap with the specific characteristic of two shaft drives: one is for driving the inner rotor and the other for driving the outer rotor. Depending on the operation, a clamping cover has to be installed either on the left side for rotating the inner rotor, see figure 3a, or on the right side, see figure 3b, whereby the other side has to be rotated respectively. By this concept, the basic design of the test system has not to be changed, independent of the kind of operation. This is important for gaining comparable measurement results, e.g. under consideration of the sealing and the resulting friction torque. The dimensions of the shear gap are chosen with respect to the requirements mentioned before. Due to the large amount of dissipation energy generated by the operation at high rotational speeds, also the fluid volume in the shear gap has been chosen in a suitable manner. The basic criterion for dimensioning the shear gap is primarily the resulting torque that has to be achieved.

The torque $T$ of an actuator with an axial shear gap depends on the shear stress characteristics $\tau(B, \dot{\gamma})$ of the MRF, which is a function of the magnetic flux density $B$ in the fluid gap, that is subjected to the magnetic field as well as a function of the fluid viscosity $\eta$ and the velocity gradient perpendicular to the direction of shear $\dot{\gamma}$ (shear rate). For the considered geometry of
two coaxially rotating cylinders with $\omega_i$ and $\omega_o$, the shear rate $\dot{\gamma}$ for the MRF can be described by the velocity profile $u(r)$ in equation (4) considering $u(r) = \omega \cdot r$ by

$$
\dot{\gamma} = -r \frac{d\omega}{dr} = -\frac{du(r)}{dr} + \frac{u(r)}{r} = 2r_i^2 \frac{(\omega_o - \omega_i)}{r_i^2 - r_o^2}.
$$

(13)

The flow curve describing the rheological behavior of MRF is commonly expressed by the Bingham fluid constitutive model, [13],[14],

$$
\tau(B, \dot{\gamma}) = \tau_0(|B|) \cdot \text{sgn}(\dot{\gamma}) + \eta \cdot \dot{\gamma},
$$

(14)

wherein $\tau_0(|B|)$ is the yield point depending on the magnetic flux density $B$. Due to the focused, high rotational speeds $n$ and resulting high shear rates $\dot{\gamma}$ depending on the shear gap height, see equation (13), the rheological behavior of the MRF is often not well approximated by the Bingham model, [15]. At high shear rates, most MRF show a shear thinning behavior that can be approximated more sufficient by the Herschel-Bulkley fluid constitutive model

$$
\tau(B, \dot{\gamma}) = (\tau_0(|B|) + k|\dot{\gamma}|^n) \cdot \text{sgn}(\dot{\gamma}).
$$

(15)

In this equation $n$ is the power law index and $k$ is the consistency index. The resulting torque $T$ can generally be described by

$$
T = \int \int_A \tau(B, \dot{\gamma}) \cdot dA \cdot dr,
$$

(16)

where $\tau(B, \dot{\gamma})$ is the magnetic field and shear rate depending shear stress of the MRF, $A$ is the shear surface at the radius position $r$ in the fluid gap.

The measurements are performed with the BASF fluid Basonetic 5030 that is an optimized MRF for brake and clutch applications, [16]. The shear stress characteristic $\tau(B, \dot{\gamma})$ is shown in figure 4 and the temperature dependency of the viscosity $\eta$ is depicted in figure 5. For the investigation of the transition point from Couette to Taylor-Couette flow, two different shear gap

---

Figure 3. Test actuator for experimental investigations: Half section view with a) inner rotating cylinder as well as b) outer rotating cylinder and c) a 3D model of the actuator.
4. Measurements

The test actuator based on the described design has been realized for verifying the occurrence of the Taylor-Couette flow and for investigating the influences of the Taylor-Couette flow on the torque response when applying a magnetic field. Different measurements are performed that are presented in the following subsections. Furthermore, the influences of the Taylor-Couette flow on long-term operation are investigated. The measurements with the test actuator are performed on a test bench that is equipped with an electrical drive and a torque sensor equipped with a real-time processor system for controlling and data capturing.
4.1. Steady state characteristics for torque behavior

Before investigating the occurrence and the influence of the Taylor-Couette flow, the test actuator should be characterized by typical control characteristic lines. These measurements are performed as a function of the rotational speed \( n \) for different magnetic excitations due to the applied current \( i \). The characterization is performed for a shear gap height of \( h_s = 3\text{mm} \), see figure 8, and for \( h_s = 4\text{mm} \), see figure 9. Due to a non-negligible dependency between the temperature depending dynamic viscosity \( \eta \) and the resulting braking torque, the MRF is thermically preconditioned at a temperature of \( \vartheta \approx 40^\circ\text{C} \) and the measurement is performed step by step to ensure thermal recoveries. By this measurement method thermal influences are almost eliminated. The single points of measurement are marked in the diagrams.

![Figure 8. Steady state torque characteristics for a shear gap height of \( h_s = 3\text{mm} \).](image1)

![Figure 9. Steady state torque characteristics for a shear gap height of \( h_s = 4\text{mm} \).](image2)

For the Off-State operation with the non-energized excitation system \((I = 0\text{A})\), the typical viscous behavior expressed by equation (14) with a proportional increase of the resulting torque \( T \) with respect to the rotational speed \( n \) is readily identifiable. At higher currents the measured torque \( T \) shows a decrease especially at high rotational speeds. This behavior can be explained by the shear thinning behavior of MRF at high shear rates, in this case of up to \( \dot{\gamma} \approx 10000\text{s}^{-1} \) at \( 6000\text{min}^{-1} \), [15]. The characterization shows that a usage of MRF brakes and clutches up to differential rotational speeds of \( 6000\text{min}^{-1} \) is possible. But especially the high viscous torque at high rotational speeds has to be considered with respect to the energy efficiency of an application and also to the limited life-time of the MRF, because \( T_{\text{vis}} \) rises up to about 25% of \( T_{\text{max}} \). For applications with high requirements considering efficiency and life-time further measures have to be taken into account like an intelligent fluid control, [17, 18].

4.2. Investigation on the transition from Couette to Taylor-Couette flow

The occurrence of vortices in the developed Taylor-Couette flow should enable a permanent mixing effect of the MRF in the axial shear gap and ensure a homogeneous particle distribution in the suspension. This effect should be verified by measurements that consider the transition from Couette to Taylor-Couette flow at the critical Taylor number \( T_{\text{a, crit}} \) using the dimensionless coefficient \( C_T \) as defined in equation (11). The measurements are performed with the introduced experimental test actuator with an inner rotating rotor and a fixed outer router. The dimension of the shear are varied in the shear gap height with \( h_s = 3\text{mm} \) and \( h_s = 4\text{mm} \). The related critical Taylor number are \( T_{\text{a, crit}} = 42.6 \) (\( h_s = 3\text{mm} \)) and \( T_{\text{a, crit}} = 43.3 \) (\( h_s = 4\text{mm} \)), see figure 6. Due to the temperature dependency of the viscosity and hence the critical rotational speed \( n_{\text{crit}} \),
see equation (10), as well as the torque coefficient $C_T$, see equation (12), the measurement values used for evaluation are captured at a MRF temperature of $\vartheta = 40^\circ$C. The corresponding critical rotational speeds are $n_{\text{crit}} \approx 580\text{min}^{-1}$ ($h_s = 3\text{mm}$) and $n_{\text{crit}} \approx 380\text{min}^{-1}$ ($h_s = 4\text{mm}$). The measurement results for the dimensionless coefficient $C_T$ as a function of the Taylor number $Ta$ are shown in figure 10 for the shear gap height of $h_s = 3\text{mm}$ and in figure 11 for the shear gap height of $h_s = 4\text{mm}$. The measured torque results are corrected by the friction torque of the sealing ring.

**Figure 10.** Transition from Couette to Taylor-Couette flow for a shear gap height of $h_s = 3\text{mm}$ at a MRF temperature of $\vartheta \approx 40^\circ$C.

**Figure 11.** Transition from Couette to Taylor-Couette flow for a shear gap height of $h_s = 4\text{mm}$ at a MRF temperature of $\vartheta \approx 40^\circ$C.
For both shear heights $h_s$ three measurements for verifying the repeatability are performed. These show a good accordance with the theoretical calculations for the linear regime of the torque coefficient $C_T$ and with the theoretical transition from Couette to Taylor-Couette flow at the corresponding critical Taylor number $Ta$. These analysis proof the occurrence of a Taylor-Couette flow in axial oriented shear gaps filled with MRF in idle mode. By further measurements the influence and the advantages on the homogeneity of the suspension MRF has to be shown. Especially the advantages on the homogeneity of MRF due to the mixing effect in idle mode needs to be validated.

\subsection*{4.3. Influences of Couette and Taylor-Couette flow on the torque behavior}

For analyzing the influences of Couette and Taylor-Couette flow on the torque behavior, both flow regimes should be considered. Therefore, the test actuator should be operated with different constant rotational speeds $n$ in idle mode with no applied magnetic field ($i = 0\,A$) and after a certain time, a current step $I$ will be applied. For ensuring the both flow regimes, the actuator is operated with a fixed inner rotor ($\omega_i = 0$) for the Couette flow (see figure 3b) and with a fixed outer rotor ($\omega_o = 0$) for the Taylor-Couette flow (see figure 3b). The analysis are performed for rotational speeds of up to $n = 4000\,\text{min}^{-1}$ and a shear gap height of $h_s = 4\,\text{mm}$.

The measurement results for the Couette flow are shown in figure 12 and for the Taylor-Couette flow in figure 13. When operating the test actuator with the Couette flow, a significant overshoot can be identified for the rotational speeds larger than $n = 2000\,\text{min}^{-1}$. Also the stationary value is reached for some measurements only after 10 seconds. It is assumed that the slow decrease of torque behavior can be explained by the shearing of the MRF under the influence of a magnetic field which causes magnetic forces acting on the particle and finally the resulting chain formation of particles also results in a homogenization. When utilizing the Taylor-Couette flow with its resulting mixing effect, the torque response shows no overshoot and the stationary torque is immediately reached.

Considering the measurement results the advantages of the Taylor Couette flow can be identified by a more constant and homogenous torque response as predicted by the Bingham model. For ensuring these conditions when applying a sudden current excitation, a homogeneous distribution of particles in the suspension MRF is required.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{torque_couette.png}
\caption{Torque behavior when applying a current step for Couette flow ($\omega_i = 0$).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{torque_taylor.png}
\caption{Torque behavior when applying a current step for Taylor Couette flow ($\omega_o = 0$).}
\end{figure}
4.4. Influences of Couette and Taylor-Couette flow on long-term measurements

The advanced behavior on the torque response using the Taylor-Couette flow should also be analyzed by a long-term run of the experimental test actuator. Therefore an appropriated test cycle is defined as shown in figure 14 with different phases of braking and idle mode. The shear gap height chosen for the measurement is \( h_s = 4\text{mm} \). The cycle starts with an On-State measurement with an applied current \( I \) at a low rotational speed \( n_{stat} = 10\text{min}^{-1} \). The resulting torque is defined as \( T_{stat} \). Subsequently follows an On-State measurement with high rotational speeds \( n_{dyn} \) that are varied between rotational speeds from \( n_{dyn} = 1500\text{min}^{-1} \) to \( n_{dyn} = 4000\text{min}^{-1} \). The resulting torque is defined as \( T_{dyn} \). At the end of the test cycle an idle phase with a constant rotational speed of \( n_{idle} = 1000\text{min}^{-1} \) is investigated over a time period of 10s. The measured torque during this phase is defined as \( T_{idle} \). The time durations for measuring \( T_{stat} \), \( T_{dyn} \) and \( T_{idle} \) are varied for each cycle.

The measurement results are shown in figure 15 for a long-term run with 2000 test cycles for both flow regimes. Therein the three different phases characterized by the torque \( T_{dyn} \), \( T_{stat} \) and \( T_{idle} \) are presented. For the analysis only stationary torques are evaluated, where acceleration or deceleration phases are not considered. The results for the torque \( T_{dyn} \) show a relative constant behavior over all measurement cycles for both flow regimes cases. The significant difference between the results are the variation in torque that is distinctive for the Couette flow. These large variations in the measured torque with peaks up to 5Nm depend on the rotational speed \( n_{dyn} \). With an increase of the rotational speed \( n_{dyn} \), a decrease of the torque \( T_{dyn} \) can be identified. When utilizing the Taylor-Couette flow, the decrement in torque is significant lower. Considering the On-State measurements with the low rotational speed \( n_{stat} = 10\text{s} \), the resulting torque \( T_{stat} \) shows a more stable behavior for the Taylor-Couette flow. The measurement results for the torque \( T_{idle} \) at a constant rotational speed \( n_{idle} = 1000\text{min}^{-1} \) show a very stable behavior over all measurement cycles for the Taylor-Couette flow. Regarding the torque behavior for the Couette flow, the torque \( T_{idle} \) shows a significant decrease in torque after approximately 1000 measurement cycles that can be an indicator for a potential and nonreversible particle centrifugation. A further indicator for this assumption is pointed out by the measurements of the torque \( T_{dyn} \) for the Couette flow that is decreasing more compared to the torque \( T_{dyn} \) for the Taylor-Couette flow.

The performed mechanical work during these 2000 cycles for each flow regime can be

![Figure 14. Definition of a test cycle for long-term measurements.](image-url)
summarized to a total value of 16.2MJ. The total volume of MRF in the shear gap for these measurements was 80ml. Considering a limited Lifetime Dissipated Energy (LDE) of 2.7MJ/ml, [19], the complete test cycle represents a lifetime for the MRF of about 7%.

These measurements compare the influence of the Couette flow and the Taylor-Couette flow and demonstrate advantages considering the consistency and the prediction of the resulting torques when using the mixing effect of the Taylor vortex flow. The measurements also indicates that MRF brakes even for high rotational speeds are realizable with a good performance on long-term view. By considering the limitations like a remaining viscous torque and the torque-speed characteristic shown in figure 8 and figure 9, MRF brakes and clutches can be used for certain applications with requirements like long lifetime, peak loads and a high braking power accompanied by high maximal rotational speeds.

5. Conclusions
In this contribution the different flow profiles in axial shear gaps are modelled in detail. Especially the development of Taylor vortices in axial shear gaps was described and the transition from a simple Couette flow to a Taylor-Couette flow considered. The occurrence of a Taylor-Couette flow should ensure a homogenous particle distribution in the MRF at high rotational speeds by using the mixing effect of the Taylor vortices. A homogenous particle distribution is required for a constant and predictable torque behavior when applying a magnetic field. For proving the transition between these both flow regimes when the rotational speed is increased over a certain threshold, a measurement method based on a dimensionless torque coefficient as a function of the Taylor number was introduced. This transition was investigated by using an experimental test actuator with a variable height of the axial shear gap whose design was based on the theoretical consideration of the development of Taylor vertices. Different measurements
are performed with the test actuator that are showing

- the steady state characteristic for torque behavior at high rotational speeds for different shear gap heights,
- the proof of the development of Taylor-Couette flow using the dimensionless torque coefficient for different shear gap heights,
- the advantages of Taylor-Couette flow when operating in idle mode and switching in the On-State mode for setting up a desired and predictable torque and finally
- long-term measurements pointing out the advantage of the Taylor-Couette flow.

Considering the Taylor-Couette flow in the design process of MRF actuators for high energy applications with high rotational speeds, a homogenous suspension with a constant torque behavior also in the long term view can be ensured.

Acknowledgment

This contribution is accomplished within the project HLD-Fluidbrake, funded by the Federal Ministry of Education and Research (BMBF) of Germany under grant number 1713X09.

References

[1] Maas J, Guth D and Wiehe A 2011 Mrf-actuator concepts for hmi and industrial applications SPIE Smart Structures/NDE vol 7977 p 797714
[2] Smith A L, Holzheimer J C, Ulicny C and Kennedy L C 2007 JIMSS 18 1131–1136
[3] Wiehe A, Noack V and Maas J 2009 J. of Phys.: Conf. Series 149 012084
[4] Guth D, Wiehe A and Maas J 2010 Modeling approach for the particle behavior in mr fluids between moving surfaces Proc. of 12th Int. Conf. Electro-rheological Fluids and Magnetorheological Suspensions (Singapore: World Scientific) pp 457–463
[5] Neelakantan V A and Washington G N 2005 JIMSS 16 703–711
[6] Constantinescu V 1995 Laminar Viscous Flow
[7] Bronstein I N, Semendjajew K A and Musiol G 2007 Handbook of Mathematics
[8] Taylor G 1923 Philosophical Transactions of the Royal Society of London, Series A 223 289–343
[9] Kirchgässner K 1961 ZAMP 12 14–30
[10] Schlichting H 1982 Grenzschicht-Theorie
[11] Wieghardt K 1974 Theoretische Strömungslehre vol 2
[12] Stuart J T 1958 J. of Fluid Mechanics 4 1–21
[13] Bingham E C 1922 Fluidity And Plasticity
[14] Phillips R 1969 Engineering Applications of Fluids with a Variable Yield Stress Ph.D. thesis The University of California at Berkeley
[15] Lee U, Kim D, Hur N and Jeon D 1999 JIMSS 10 701–707
[16] BASF SE 2009 Magnetorheological Fluid Basonetic® 5030 - Optimum torque transmission for clutch-type applications BASF SE www.basonetic.com
[17] Guth D and Maas J 2012 SPIE Digital Library/Proceedings 8341 834121
[18] Guth D, Schamoni M and Maas J 2012 Modeling approach for a fluid movement induced by magnetic forces for viscous loss reduction of mrf brakes and clutches ASME Conf. Proc. pp SMASIS2012–8135
[19] Wiehe A, Kieburg C and Maas J 2012 Temperature induced effects on the durability of MR fluids Proc. of the 13th International Conference Electrorheological Fluids and Magnetorheological Suspensions - in press