TRANSITIONAL AND SOLID STATE BEHAVIOUR OF A MAGNETORHEOLOGICAL CLUTCH

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Abstract:
Magnetorheological fluids can change their state from solid to liquid and vice versa. Hence, MRF-clutches are able to transmit torque either in a slipping or in a rigid mode. The first part of this paper presents experimental results concerning the yielding and engaging process. A criterion which denotes the demarcation between solid and liquid mode was to be derived. Experimental data for $T_{max\text{-}stat}$ and $T_{min\text{-}dyn}$ were obtained as function of the magnetic field strength and it was shown that their values do not depend on the speed of change of the applied torque. From these results, values for the static and dynamic yield stresses were computed, confirming the assumption that the static yield stress is larger than the dynamic yield stress. The second part of this paper describes the torsion response of a MRF-clutch resulting from varying torque under different magnetic fields. Investigated questions are: Can MRF in solid mode sustain a load without preceding creep? Is there a constant shear modulus? Does it depend on the magnetic field strength? Experiments showed a nonlinear behaviour and that a permanent deformation of the MRF has to be taken into account after release of a load.

Introduction

Magnetorheological clutches are distinguished by very good controllability of transmitted torque, very short reaction times and little wearout. The fundamental advantage over traditional clutches consists in their ability to process electric control information directly, i.e. without any mechanical links. Next to their practical advantages, a wealth of information concerning general properties of MRF can be obtained from experiments with MRF-clutches.

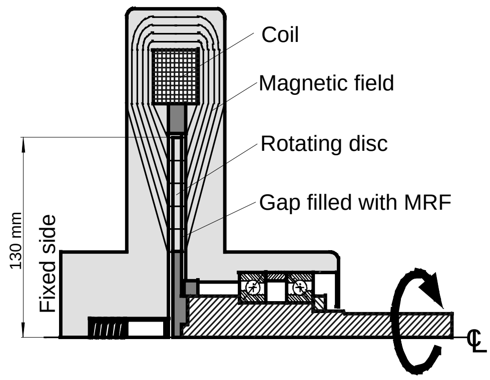

Fig. 1: *MRF-clutch used for the experiments*

Transitional Behaviour of MRF

Till today only little is known about the transitional behaviour of MRF. Nevertheless, for various application it is vital to prevent a drop of transmitted torque while transitioning from solid to slipping transmission.
The conducted experiments aim at measuring the *maximum static torque* $T_{max\text{-}stat}$ (the maximum in rigid mode transmittable torque) and the *minimum dynamic torque* $T_{min\text{-}dyn}$ (e.g. further reduction of torque below $T_{min\text{-}dyn}$ leads to engaging of the clutch). These values are to be determined as function of the magnetic flux density B within the MRF. From the measured torques the dynamic τ_{yd} and the static τ_{ys} yield stress of the MRF shall be computed.

<u>Experimental Setup</u>
The experiments where made with the MRF-clutch shown in Fig.1. The MRF 132 LD of LORD Corp. was used. The thickness of the gap filled with MRF was 1,75 mm on both sides. A controlled torque of up to 100 Nm was provided by a servo motor of Baumüller GmbH. Electric coil current and torque were controlled via PC.

The experimental setup permitted to record time, coil current, torque and torsion angle (angle the disc was distorded from zero angle position) at a rate of 50 Hz simultaniously. The torsion of the shaft as function of the torque was computed separately and subtracted from the measured torsion angle in order to get the angle just the MRF was distorded.
The magnetic flux density B within the MRF was computed by means of the FEM-program OPERA as a function of the coil current. These computations showed that B is almost independent of the radius and a mean value of B as function of the coil current can be assumed.

<u>Experimental Procedure</u>
The torque applied to the clutch by the servomotor is varying with time like the dashed line in Fig.2. The reason for choosing this function is such that the clutch shall start to rotate upon exceeding a certain absolute value of the torque ($T_{max\text{-}stat}$) and that it shall engage, e.g. stop rotation, upon falling the absolute value of the torque below $T_{min\text{-}dyn}$. This procedure was repeated several times to ensure stable condi-

tions. The rotational angle during such an experiment is also shown in Fig.2. Large slopes of the curve indicate rotation of the clutch whereas constant values show the clutch to be engaged (note 360° are 1 revolution).

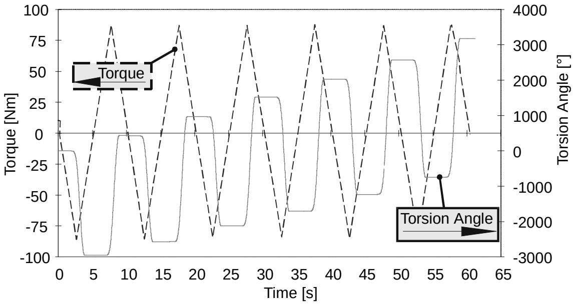

Fig. 2: *Torque and torsion angle during experiments*

Printing torque vs. torsion angle for a procedure as shown in Fig.2 gives Fig.3.

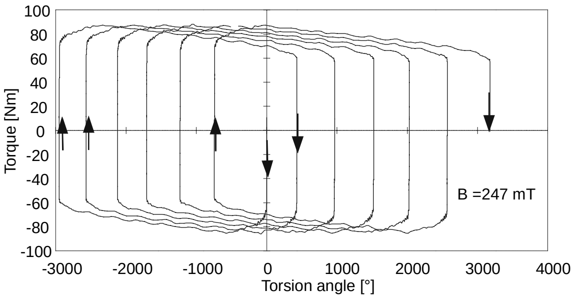

Fig. 3: *Torque vs. measured torsion angle for one experimental procedure*

Because the rotational speed of the clutch varies with time, acceleration torques have to be considered. They were computed by multiplying the known moment of inertia of the disc and the shaft with the angular acceleration obtained from central differences of torsion angle over time.

In order to proof that the frequency of the applied torque has no influence on the values obtained for $T_{max\text{-}stat}$ and $T_{min\text{-}dyn}$ a preceding experiment was made. In this experiment torque vs. torsion angle curves of the kind shown in Fig.3 were recorded for various frequencies of the applied torque. The coil current was kept constant. The single loops of the curves varied only very little, allowing to show just excerpts for transition from solid to liquid mode and vice versa. Fig.4 shows such curves of torque over torsion angle. The torsion angle were corrected such that the solid mode of the MRF is at an angle of 0° and acceleration torques were eliminated.

The good agreement of the curves for various frequencies of the torque in Fig.4 proof the frequency to have no influence on $T_{min\text{-}dyn}$ and $T_{max\text{-}stat}$.

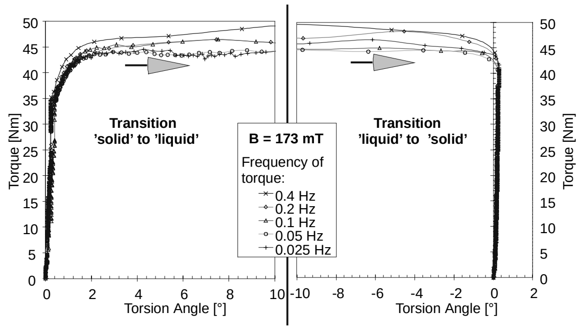

Fig. 4: *Torque vs. torsion angle*

<u>Yield Criterion</u>

In order to obtain values for $T_{min\text{-}dyn}$ and $T_{max\text{-}stat}$ a criterion for the torsion angle denoting the yielding of the MRF has to be defined. Simply spoken – at which torsion angle occur just $T_{min\text{-}dyn}$ and $T_{max\text{-}stat}$?

This derivation starts from the relation between shear angle and shear force [1], assumes solid mode, and results in an value for the angle of torsion ϕ_G for the clutch as a whole. Increasing the torsion of the clutch above ϕ_G would result in a drop of torque transmittable in solid mode, thus leading to a break of particle chains and transition to liquid mode.

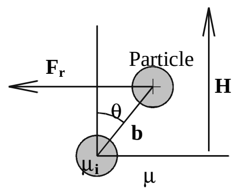

Fig. 5: *Restoring force F_r induced by magnetic field H (after [1])*

With: b - distance between particles

μ_i - internal permeability of particles

μ - permeability of suspension

[1] gives the following expression for F_r :

$$F_r = 3\mu a^2 H^2 \beta^2 f \qquad (1)$$

with: β - depending on μ and μ_i

$$f = \left(\frac{a}{b}\right)^4 \left[\left(2 f_\parallel + 2 f_\Gamma\right)\sin\theta\cos^2\theta - f_\perp \sin^3\theta\right]$$

$f_\parallel = f_\Gamma = f_\perp = 1$ (according to [1])

a – particle radius

For determining ϕ_G not the absolute value of F_r , but only its dependency on θ is of interest. This leads to:

$$F_r \sim \frac{\left(4\sin\theta\cos^2\theta - \sin^3\theta\right)}{K^4} \qquad (2)$$

with: K – length of particle chain (distance b multiplied by number of particles in a chain)

The following Fig.6 shows the relation between the shear angle θ and the torsion angle ϕ of the clutch. The torque transmitted by the MRF computes as:

$$T(\phi) = \int_{R_{inner}}^{R_{outer}} F_r(\phi, r)\,dr \qquad (3)$$

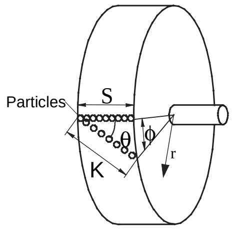

Fig. 6: *Relation between shear angle θ and the torsion angle ϕ of the clutch (only one gap filled with MRF shown)*

From Fig.6 one can find for θ and K:

$$\theta = \arctan\left(\frac{r}{S}\sin\phi\right) \quad ; \quad K^2 = S^2 + r^2 \sin^2\phi \qquad (4)$$

Introducing equations (4) and (2) into equation (3), integrating from the inner to the outer radius of the clutch, using Simpsons rule, results in Fig.7. Normalizing the maximum torque to 1 eliminates the need for knowing absolute values of F_r.

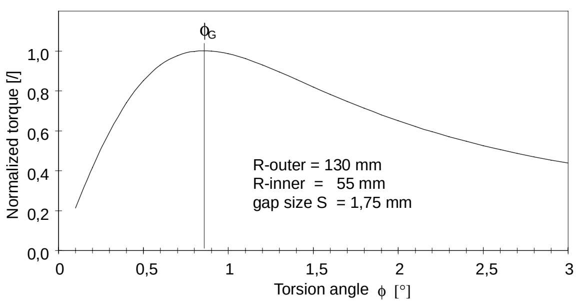

Fig. 7: *Computed normalized torque vs. torsion angle ϕ of the clutch*

Fig.7 proofes the torque transmitted in solid MRF mode to have a maximum value at a certain angle ϕ_G **.** Exceeding this angle results in a decrease of transmittable torque, hence the MRF yields and changes to liquid mode. From Fig.7 one can read:

$$\boldsymbol{\phi_G = 0.85°}$$

Experimental Results

From Fig.8, showing experimental results obtained for various magnetic flux densities, one can read $T_{min\text{-}dyn}$ and $T_{max\text{-}stat}$ (see Fig.9). These are the torques occuring at ϕ_G.

Using the equations for $T_{min\text{-}dyn}$ and $T_{max\text{-}stat}$ derived in [2], the yield stresses of the MRF can be computed from the geometry of the clutch and the torques shown in Fig.9. They are depicted in Fig.10.

Comparing Fig.9 with Fig.10, it is remarkable, that $T_{max\text{-}stat} < T_{min\text{-}dyn}$ despite $\tau_{ys} > \tau_{yd}$. This apparently controverse observation is only possible because the radial shear stress distribution in solid state (linearly increasing with radius) is different from the distribution in liquid state (constant over radius) (see [2]). This is surprising in the first view, but confirms the following observation.

During further experiments a torque was applied to the clutch by lever and weight. It was possible to apply such a load, depending on the coil current, that the clutch started to rotate in order to come to rest after a few degrees of rotation. This procedure was self repeating until the lever had rotated far enough to decrease the applied torque considerably. This phenomena of successive yielding and engaging can only be explained by $T_{max\text{-}stat}$ to be smaller than $T_{min\text{-}dyn}$, e.g. the clutch yields at $T_{max\text{-}stat}$ and because $T_{min\text{-}dyn}$ is smaller, it comes to rest again.

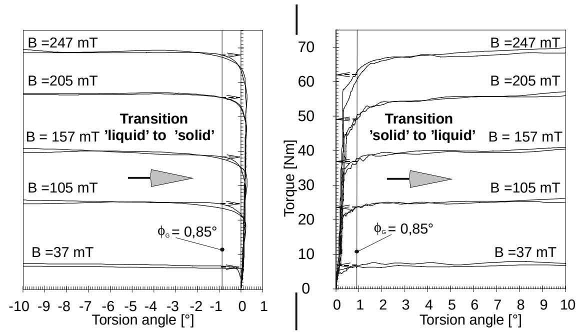

Fig. 8: *Torque vs. torsion angle for transition from 'solid' to 'liquid' and vice versa*

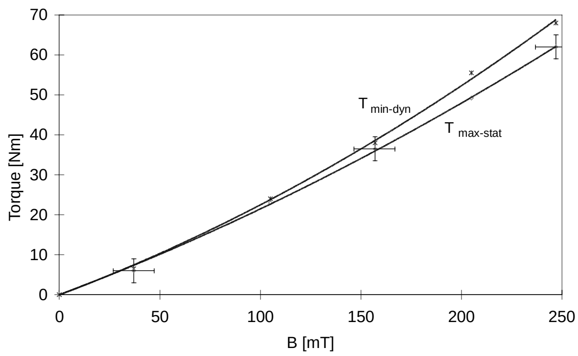

Fig. 9: *Maximum static torque $T_{max\text{-}stat}$ and minimum dynamic torque $T_{min\text{-}dyn}$ vs. magnetic flux density*

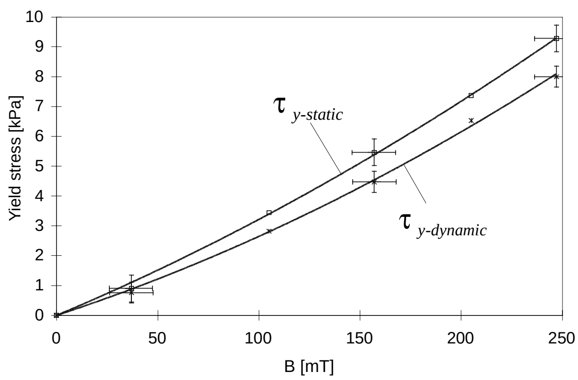

Fig. 10: *Static and dynamic yield stresses of the MRF 132 LD vs. magnetic flux density*

Using the data obtained for τ_{ys} and τ_{yd} (Fig.10) and the torque equations in [2], it is now possible to design a clutch with zero torque jump while transitioning between solid an liquid mode.

Torsion Response of a MRF-Clutch

This part of the paper is dealing with the solid mode of MRF. Experiments were made also with the clutch shown in Fig.1, but now the applied torque did not exceed the magnitude necessary to make the clutch yielding, e.g. the MRF was all the time in solid mode. The first question to be answered was: Can MRF in solid mode sustain a load without preceding creep? Therefore a constant torque was applied to the clutch over a period of 48 hours, keeping the coil current constant. The torsion angle was recorded during this period of time and results showed no measurable creep.

For the next experiment, a sinusoidal torque as shown in the inner picture in Fig.11 was applied to the clutch.

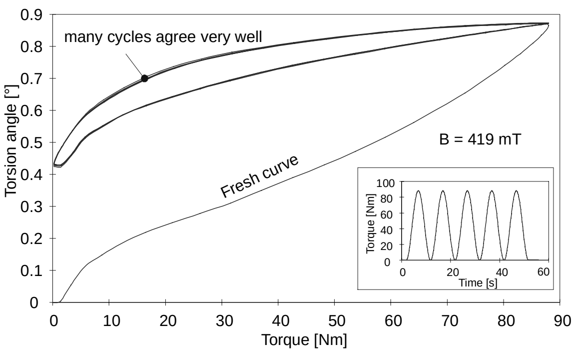

Fig. 11: *Torsion angle vs. torque for sinusoidal torque of constant amplitude*

From the curve shown in Fig.11, for other magnetic flux densities analog curves were obtained, the following conclusions have to be drawn:

1. The maximum torsion angle caused by a time varying torque as well as the remanence torsion angle remaining after reducing the torque to zero depends only on the magnitude of the maximum torque.

2. Because on one hand the fresh curve is nonlinear and on the other hand always a remanence torsion exists, MRF in solid mode can not assumed to be linear elastic bodies.

In order to permit a quantitative statement about the deformation of the clutch, a sinusoidal torque with varying amplitude was applied to the clutch. Fig.12 shows the result for such a procedure. It has to be interpreted in such a way that the torsion angle went trough the loops in sequence of the numbers '1' to '6'. In Fig.13 and 14 the maximum torsion angle (points 'B' in Fig.12) and the remanence torsion angle (points 'A' in Fig.12) are drawn against the maximum torque reached before reducing the torque. From Fig.13 and Fig.14 one has to conclude that the remanence torsion angle as well as the maximum torsion angle increase stronger than linearly with getting closer to the yielding torque $T_{max\text{-}stat}$. For in relation to $T_{max\text{-}stat}$ small torques the remanence and the maximum torsion angle become independent of the magnetic flux density.

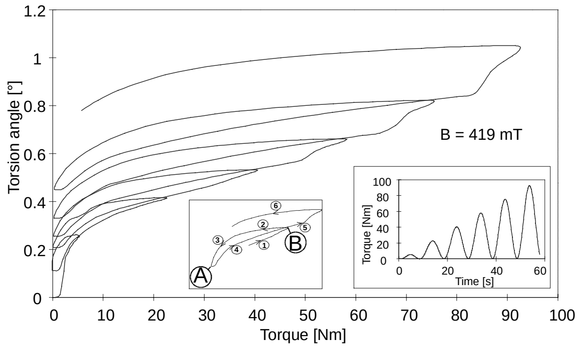

Fig. 12: *Torsion angle vs. torque for sinusoidal torque of increasing amplitude*

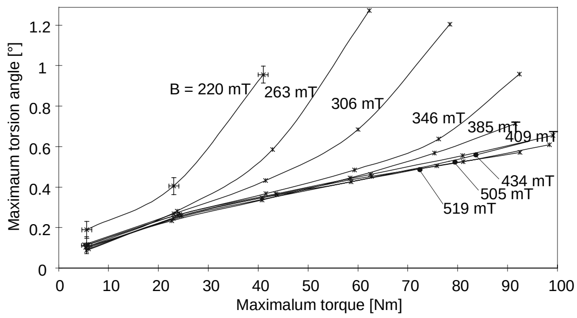

Fig. 13: *Maximum torsion angle vs. maximum torque (according to point 'B' in Fig.12)*

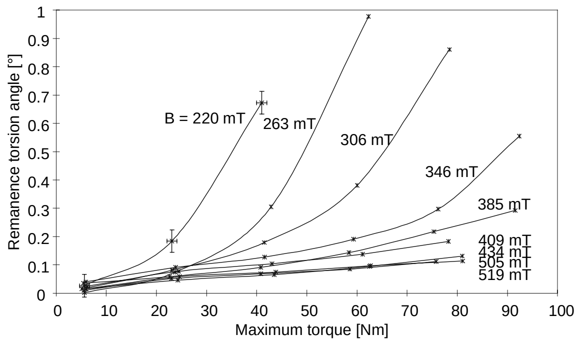

Fig. 14: *Remanence torsion angle vs. maximum torque (according to point 'A' in Fig.12)*

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[2] Lampe, D., MRF-Clutch- Design Considerations and Performance, ACTUATOR 98, Bremen, 1998

[3] Großmann, K.; Grundmann, R.; Neundorf, H., Intelligente Funktionsmodule der Maschinentechnik, Schlussbericht zum Landesinnovationskolleg 1995 bis 1998, Schriftenreihe des Lehrstuhls für Werkzeugmaschinen der Technischen Universität Dresden, 1999