A New Rheometer Platform for Extended Testing Capabilities

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ABSTRACT

A new rheometer concept based on two air bearing supported motors is introduced. The combination of two motors into one rheometer system offers increased sensitivity and new testing capabilities not possible before. Three completely different testing modes such as combined motor transducer, separate motor transducer and counter rotation are available in one single rheometer system. The aim of the paper is to describe the new technologies involved and to outline future applications

INTRODUCTION

Most technical developments are done in small but frequent steps of evolutionary improvements. However, once in a while large jumps or revolutionary steps occur. The very same is true in the case of rheometry. Big steps were the introduction of the Weisenberg Rheogoniometer in 1948[1], the invention of the air bearing supported Drag-Cup motor by Davis et al. and Plazek in 1968[2-4], the Forced Rebalance Transducer (1985)[5], and the introduction a rheometer employing an electrically commuted (EC) motor (also called brushless-DC) and a control based on Digital Signal Processors (DSPs) in 1995. In our opinion all further developments, although significant, are basically improvements of these technologies.

Now another revolutionary step is introduced. The new MCR 702 rheometer form Anton Paar is based on a new technology called TwinDrive^{TM}, in which two air bearing supported EC motors work together for unprecedented flexibility and sensitivity in rheological testing[7]. Both motors are fully functional rheometer motors, which have normal force sensors included. The motors sit opposite to each other and both motors are controlled by the same DSP controller. In one testing mode one motor acts as the drive unit while the second is programmed to stay at the starting position and acts as an extremely fast and sensitive rebalance torque transducer. Due to the fixed position the lower limits of measurable torque and normal force are significantly lower compared to the state of the art standard rheometer. But increased sensitivity is not all, the separation of drive and torque measurement has advantages in certain testing situations. In strain control the torque signal is related to the sample stress even during the drive motor adjustment time.

Moreover, since two motors are used completely new testing capabilities are available. Counter rotating of the two motors allow simultaneous microscopy at the stagnation plane while obtaining the rheological data.

The modular design allows a quick removal and mounting of the second motor, therefore enabling a simple switch from a combined to a separated motor and torque measurement and vice versa. The modular design of the MCR702 further facilitates the use of all accessories available for the standard MCR rheometer series.

BACKGROUND

The main components of a rotational rheometer are the motor with its supporting bearing system and the force measurement. Historically there are two principles used for research grade rotational drag flow rheometers[5]. In one configuration a displacement or speed (strain or strain rate) is applied to the sample by the motor and the resulting torque (stress) is measured separately by an additional force sensor. In this type of instrument, which is commonly referred to as CR (controlled strain or controlled strain rate) rheometer or separate motor transducer system the electrical current used to generate the displacement or speed of the motor is not used as a measure of the electrical torque. With the other type of instruments, often called CS (controlled stress) rheometer or combined motor transducer system, a certain electrical current is applied onto the motor assembly. The current builds up a magnetic field which produces an electrical torque resulting in a rotation of the drive shaft. In such a design there is no separate torque sensor needed, since the torque signal is directly calculated from the motor current. The movement of the motor shaft is measured by an angular displacement sensor, which in most types of CS rheometers is an optical encoder. Most CS rheometers are based on the so-called drag cup motor, which was already used in the first CS instrument, the Deer Rheometer build in 1968[2,3].

In 1995 a rheometer based on a different motor system, an electrically commuted (EC) motor, sometimes also referred to as brushless DC-motor, was introduced[6]. Since 2010 the fourth generation of rheometers employing this motor technology is now in use. From the principle of torque determination from the motor current this new rheometer resembles a classical control stress, or combined motor transducer system, but instead of a drag-cup motor it employs a fast and dynamic motor with a similar principle as it is used in a classical strain or separate motor transducer system.

Principle of the rheometer motor

For a better understanding the motor principle is described in more detail.

An EC-motor is a direct current (DC) motor. In the EC-motor the rotor rotates synchronously with the rotating field on the stator, thus the name synchronous motor is often used to designate servo motors of this design. In the EC-motor the current is commutated electronically and there are no brushes or other mechanical contacts to excite the motor. Therefore, an EC motor is sometimes also called brushless DC-motor. The motor is excited by special permanent magnets with a high flux density located on the rotor. The permanent magnet poles on the rotor are attracted to the rotating poles of the stator by their opposite magnetic polarity. The magnetic poles of the stator are produced by an electric current flowing through a coil system located on the stator. The flux of the current carrying windings of the coil system rotates with respect to the stator. Like the DC motor, the current carrying flux remains in position with respect to the field flux rotating with the rotor. The major difference is that the synchronous EC motor maintains position by an electrical commutation, rather than mechanical commutation.

The torque is proportional to the strength of the permanent magnetic field and to the field created by the current carrying coils. The magnetic field in the stator rotates at a speed proportional to the frequency of the applied voltage. This is called a synchronous motor since the rotor rotates at the same speed, i.e. synchronously, with the stator field. The rotor field is produced by high energy permanent magnets, each one is mounted at a fixed position on the rotor disc. Since the positions, shapes and strengths of these permanent magnets are known, also the rotor field is well-known. The EC control makes use of this knowledge of the rotor field. Therefore, it is possible to adjust the electro-magnetical torque in such a way that it is linear to the total amount of the stator current, i.e. $M \propto I_s$. In this case a change of the stator current will be followed by a change of the torque almost instantaneously. The strain or shear rate can be adjusted in a very fast way and without any overshoots. In combination with a high resolution optical encoder real strain and strain rate control is possible. It has been shown that with such a rheometer employing a single EC motor large amplitude oscillatory shear (LAOS) tests with a sinusoidal strain input can be performed[8].

In a traditional strain rheometer a similar motor concept is used. In distinction to a traditional controlled strain rheometer no separate torque transducer is needed but the electrical current of the motor, I_s, is used as a measure of the torque. Like for a CS rheometer both the pre-setting and the measuring of the corresponding properties are done from the same side of the rheometer. The described motor setup basically combines the advantage of both the traditional controlled strain rheometer with a fast motor control and the traditional controlled stress instrument with the ability to take the motor current as a measure of the torque.

Based on the EC-motor technology a new technique is now introduced which represents a large step in rheometer development and extends the capabilities of a rotational rheometer dramatically.

DESCRIPTION OF THE NEW DEVICE

The new rheometer system MCR 702 combines two powerful synchronous EC (Electrically Commutated) motor units in a modular setup: The upper EC motor in the rheometer is fixed; the lower EC motor can be extracted and integrated at will. In Fig. 1 the principle setup with the two motors is depicted. The upper motor is integrated in the rheometer head as in a standard rheometer, whereas the lower motor can be exchanged much like an accessory system of a standard rheometer.

For temperature control convection temperature devices based on electrical heating or Peltier are available (not shown in Fig. 1). A newly developed Peltier convection device combines a uniform temperature distribution with the ease of use of a Peltier based temperature control system.

Figure 1. Sketch of the rheometer system.

The new rheometer system can be operated in three different test modes, which are sketched in Fig. 2 and described in the next sections.

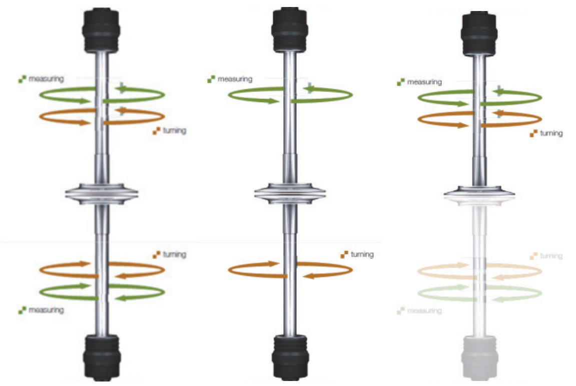

Figure 2. Schematics of the three different operation modes of the rheometer system: left – counter rotation, middle – bottom motor rotates, upper motor measures torque (SMT), right – upper motor rotates and measures (CMT).

COUNTER-ROTATION MODE

In the counter-rotation test mode the MCR 702 employs both EC motors as drive units as well as torque transducers. The motors are set to rotate in opposite directions, with parallel rotation as a further option. The preset speed is divided and shared by the two motors. This mode is an invaluable option for microscopy applications, in which the observation of sample particles and structures is sometimes difficult if the sample is sheared and therefore "rushing past" the microscope.

In the counter-rotation mode rotational tests can be performed with the motors moving in opposite directions. This results in a fixed stagnation plane in the measured sample, which is therefore easier to investigate microscopically. Users can also move the level of this stagnation plane by adjusting the two motors' individual rotational speeds, while still maintain the same differential speed between the two motors.

Regarding speed, the counter-rotation mode simply "doubles the score". Since the maximum speed difference of the two motors is twice as high as the speed of a single EC motor, the maximum speed difference is doubled – up to 6000 rpm.

To determine the required rheological parameters, the speed is calculated from the difference between the two motors' individual speeds, while the torque of the upper motors is recorded.

An additional application of this mode is extensional rheological testing, in which samples such as polymer melts are measured using counter-rotating drums. Since the torque is measured directly by the air-bearing-supported motor unit without any interference from additional mechanical bearings, data towards the lowest torques are obtained.

SMT MODE

In the separate-motor-transducer (SMT) mode, both motors are employed, but in a synchronized fashion. One motor is kept at a fixed position and operated solely as a torque transducer, while the other exclusively functions as a drive unit. In this way, the MCR 702 is turned into an enhanced separate-motor-transducer rheometer for rotational and oscillatory tests at a wide measuring range down to extremely low torques and normal forces.

Due to the EC motor's fast response times, the separation of the motors' capabilities gives the option of collecting sample torque data even during the acceleration process in transient testing conditions.

The SMT mode also offers increased sensitivity and new possibilities regarding normal force measurement: The normal force can be measured in two directions, opening up a variety of new applications. Most importantly, now two motors deliver two independent sets of raw data: torque, deflection angle, normal force providing more information on the sample and the rheological tests. Since both motors are run by the same controller electronics, the motors are not controlled independently but in a synchronized fashion. The transducer and the drive unit - identical systems - are in constant communication and always immediately adapt to one another.

CMT MODE

In the combined-motor-transducer (CMT) test mode the lower motor is removed and the upper EC motor is used as a single drive unit and torque transducer. In the CMT or single motor mode, the motor measures and controls the required parameters at the same time. The option of either controlling the shear rate or the shear stress opens up the wide array of applications covered by single-motor MCR rheometers.

When operating in the CMT mode a large variety of different temperature control systems or application-specific accessories can be used.

EXAMPLE MEASUREMENTS

In order to show the improved sensitivity in the SMT mode some examples measurements in this mode are presented.

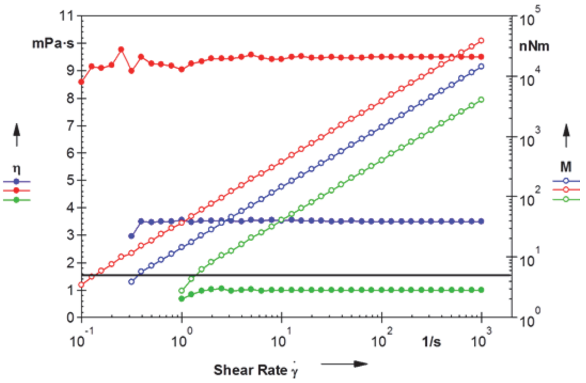

Figure 3. Viscosity and torque curves from three different liquids with low viscosities (Water, mineral oil and silicone oil). Black line indicates the 5nNm torque level.

Fig. 3 shows viscosity and torque as a function of shear rate for three different liquids with viscosities of 0.94mPas (water at 23°C), 3.5mPas (mineral oil at 25°C), and 9.5mPas (silicon oil at 25°C), respectively. The measurement geometry was a 25mm cone with a 1° cone angle. A closer inspection reveals that measurements down to torques values as low as 5nNm are possible while staying well within a 5% error band.

In Fig. 4 oscillatory frequency sweeps at a strain of 100% are depicted for water and two low viscous mineral oils. All three measurements were performed at a temperature of 25°C by using a 50mm diameter cone with a cone angle of 0.5°. A small cone angle was selected in order to limit the effects of fluid inertia at higher frequencies.

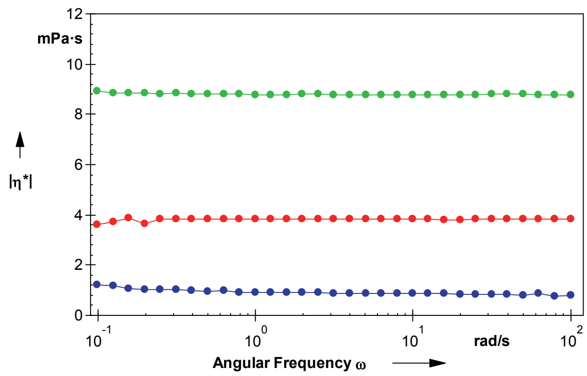

Figure 4. Frequency sweeps for water and two low viscous mineral oils at 25°C.

As can be seen from Fig. 4 measurements over four decades in frequency and up to an angular frequency of 100rad/s are possible even for the water sample.

As an example for the normal force performance a silicon oil sample with a high viscosity of 1000Pas has been measured using a 50mm diameter cone with a 2° cone angle. Fig. 5 shows the viscosity and the normal force as a function of shear rate for five different measurements under the same conditions. A good reproducibility can be observed even at small normal forces.

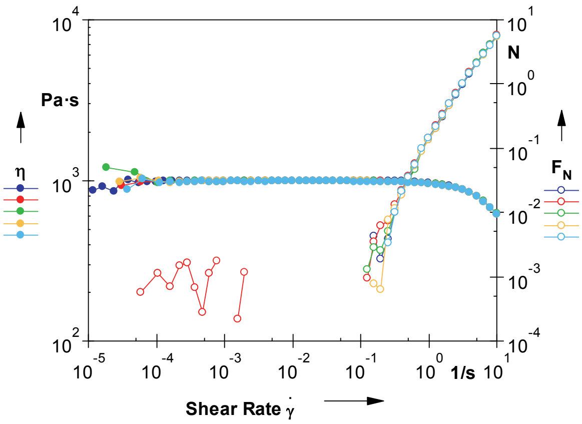

Figure 5. Viscosity and normal force for a high viscous silicon oil. Data form five individual measurements are plotted.

In Fig. 6 the first normal stress difference and the first normal stress coefficient for the same measurements as in Fig. 5 are depicted. Both properties can be measured reproducible from relatively small shear rates.

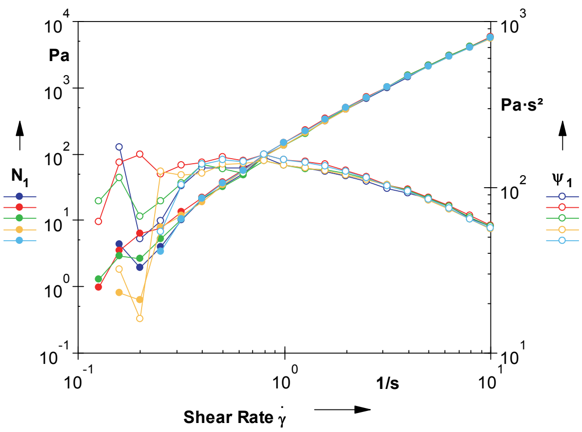

Figure 6. First normal stress difference and the first normal stress coefficient for a high viscous silicon oil. Data form five individual measurements are plotted.

CONCLUSIONS

A new rheometer concept with two fully functional EC-motors sitting opposite to each other is introduced. Beside higher sensitivity with respect to torque and normal force completely new testing capabilities such as counter-rotation testing becomes available. In addition the rheometer can be operated as separate motor transducer (SMT) as well as a combined motor transducer (CMT) system. All combined the new rheometer system will with any doubt be recognized as one of the few big revolutionary steps forward in the history of rotational rheometry.

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