The AR-G2 Magnetic Bearing Rheometer

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Figure 1 AR G2 rheometer

TA Instruments new rheometer, the AR-G2, was launched at the Society of Rheology meeting held in Lubbock, Texas, in February 2005. For this instrument we have introduced two features that combine to provide a low torque performance never previously obtainable on a commercial rheometer. Good low torque performance is important for the rheological characterisation of lightly structured materials such as shampoos, creams, lotions, food dressings and many others. The broader a rheometer's torque range, and the better its operation at the low torque end of the range, the more fully and accurately the rheological properties of these materials can be measured.

The AR-G2 is a combined motor and transducer (CMT) instrument. This design has traditionally been used for rheometers like the AR-G2 that operate in controlled stress in their native mode. The lower component of the measuring system is fixed, the upper component is attached to a shaft, that can rotated by a torque produced by an induction motor. The constraint on the low torque performance of such an instrument is the friction between the rotating and the stationary components. An induction motor is therefore used not only because the rapidity and stability of its response, but more specifically to minimize the friction.

But the rotating shaft has to be supported in some way, and this requires a bearing: another source of friction. Until now, all high performance commercial CMT rheometers have used air bearings, either of the jet or the diffusion type. But the limit of air bearing technology appeared to have been reached with the AR2000, and for progress to made, a new technology had to be found. Our engineers therefore turned to a magnetic bearing, which had previously been used for research instruments used only in creep [1], but would present a formidable engineering challenge to introduce onto a fully operational commercial rheometer. A solution was found in which an iron thrust plate is mounted on the rheometer shaft, which is held in position by electromagnetic actuators placed above and below the plate. The horizontal position of the rheometer shaft is sensed by a transducer mounted above the upper actuator, and the current supplied to the actuators is varied to maintain the position.

The advantages of this type of bearing over an air bearing are mainly produced by the much wider gaps above and below the thrust plate. On the AR-G2 these are around half a millimeter, for an air-bearing they would be of the order of microns. This leads not only to less friction, but also to smoother operation, allowing more accurate mapping of the slight fluctuations in the friction as the bearing rotates.

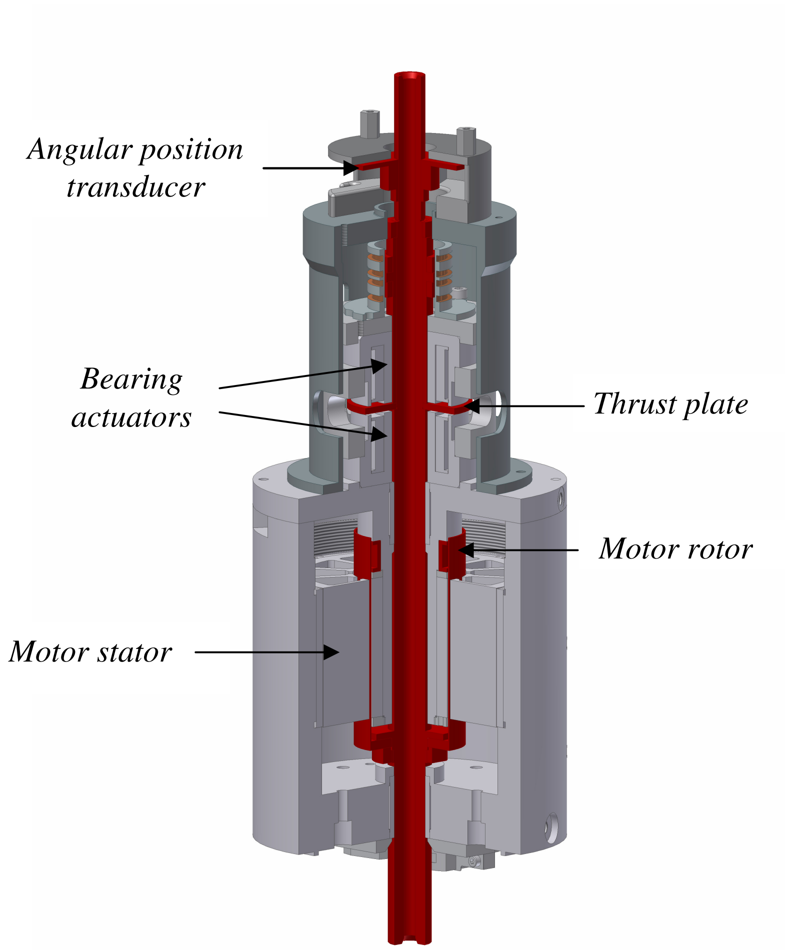

Figure 2 Cutaway of the AR-G2: rotating components are shown in red, stationary components in grey

The move from air to magnetic technology greatly reduced the friction from the bearing itself, but to make full use of this improvement, it was also necessary to make changes to the motor, to reduce the friction due to that component of the rheometer. To do this, the gap between the stationary and the rotating component was increased. This is not as simple a solution as it might sound, since on the AR2000 for example, the optimal gap is used at which the temperature of the motor, which becomes warmer during its operation, does not effect the current to torque ratio. At the wider gap used on the AR-G2, this is no longer the case, and the temperature of the rotor has to be known. A way of measuring this was developed that is the subject of U.S. patent 6,798,099.

It was important that the improvements in the low torque performance produced by the changes to the motor and bearing should not have been achieved at the expense of performance elsewhere, in particular by reducing the instrument stiffness or substantially increasing the inertia. But it turns out that the magnetic bearing is stiffer in the axial direction than an air bearing, and the lateral stiffness was maintained by retaining the radial air bearings used on the AR2000, that do not contribute significantly to the friction.

To show the AR-G2 performance in steady shear, the viscosity of decane was measured at 20°C, at which it has an accepted value of 0.92 mPa.s [2], using a 40 mm diameter 2° cone and plate measuring system. Decane was used rather than water because it is less susceptible to surface effects. The results are shown below. Reasonable measurements can be made at torques as low as 0.01 µN.m. But note that the error associated with the measurement is always much lower than the reported torque. For example the error associated with the twelve data points showing the lowest torque, in which some scatter appears, was never more than 2.2 nN.m, and was usually around 1 nN.m. These errors were back calculated from the angular velocity, assuming the value for the viscosity of decane quoted above.

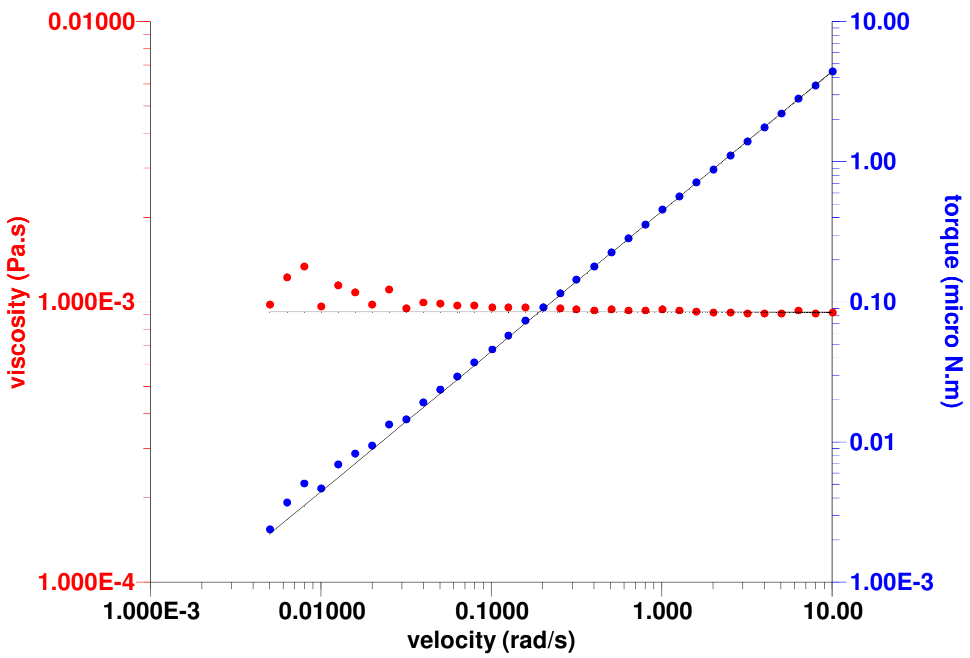

Figure 3 Decane measured in steady shear:
the continuous lines indicate a value of 0.92 mPa.s

The AR-G2 performance in oscillation is shown by a Newtonian oil of viscosity 5.537 Pa.s. Two data sets are shown, one for which torque (stress) control was used, the other for which direct displacement (strain) control was used. In both cases, reasonable measurements could be made to torques as low as 3 nN.m. As in the case of the decane data, the torque error associated with the data was much lower than the reported torque.

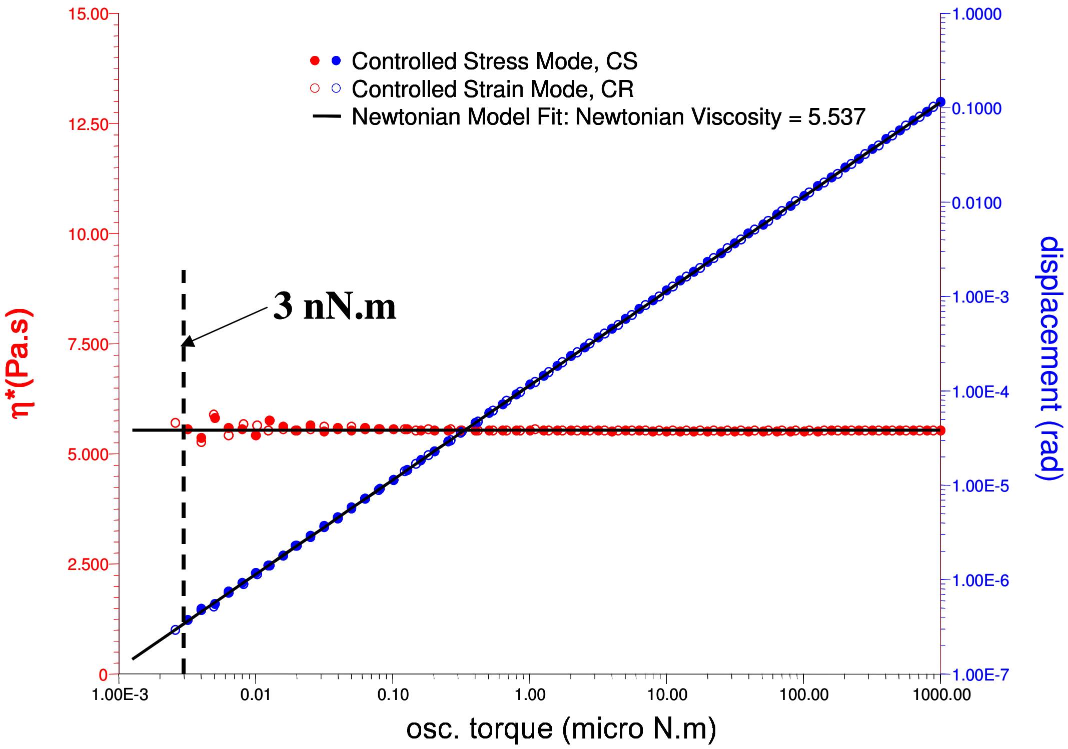

Figure 4 Newtonian oil of viscosity 5.537 Pa.s measured in oscillation under controlled torque and controlled displacement

Standard oils and other ideal materials are useful for demonstrating the performance of a rheometer, but other than that they would not normally be of interest to the practical rheologist. A more relevant sample is a fruit flavoured salad dressing, stabilized by xanthan. A 40 mm parallel plate at a gap of 1000 µm was used to perform a frequency sweep on this sample at 20°C, under direct strain control at 1 mrad.

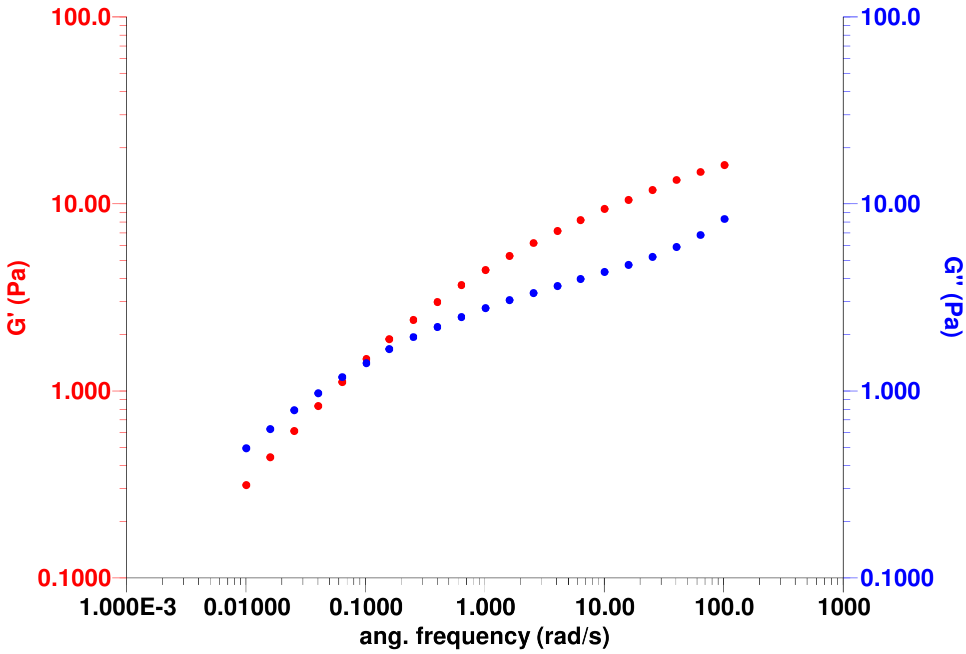

Figure 5 Fruit flavoured salad dressing measured under a directly controlled displacement of 1 mrad

This data presented above for this sample are after correction has been made for the system inertia. The uncorrected data are shown for comparison below. At low angular frequencies, the response is dominated by the sample contribution. As the angular frequency increases, so does the contribution from the inertia. At the point at which the inertia and the sample elasticity exactly balance, the resonant frequency, the torque passes through a minimum and the uncorrected phase angle through 90°. At higher frequencies, the contribution from the inertia is greater than that of the sample, and an increasing large correction has to be made. These data therefore show that the increase in torque resolution is important not just in the low torque, low frequency region, but right across the range of frequencies used. At the resonant frequency the torque is low, and at higher frequencies food resolution is required to enable efficient subtraction of the inertial contribution. They also show the importance of low inertia to a CMT rheometer. For the AR-G2 this is about 18.5 μN.m.s^2. As the inertia increases, so the resonant frequency moves to lower frequencies, and the highest frequency at which the torque can be resolved is reduced.

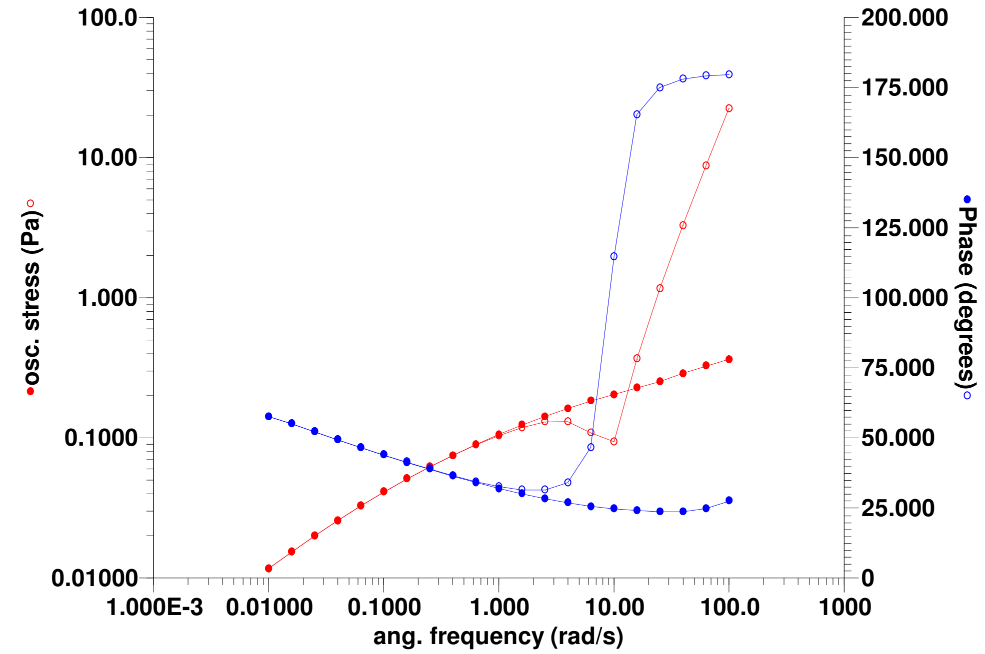

Figure 6 Corrected (solid symbols) and uncorrected (open symbols) stress and phase angle for fruit flavoured salad dressing. The continuous lines are included to guide the eye. The actual torque minimum would occur at the resonant frequency of around 8 rad s^{-1}.

The data shown above demonstrate the performance of the AR-G2 in both steady shear and oscillation, and that usable torques of the order of nN.m can be achieved with the magnetic bearing and wide gap induction motor technology introduced onto that instrument. The improvements have been made without compromising on the rheoemeter's mechanical stiffness or its inertia.

REFERENCES

1. D. Plazek, *Journal of Polymer Science A-2*, **6**, 621-638 (1968)
2. Handbook of Chemistry and Physics 69th edition, CRC Press, 1988-1989.

KEYWORD

CMT rheometer, performance, torque resolution, magnetic bearing