Capacitance Dilatometry in a Surface Force Apparatus

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A capacitance dilatometer attachment for the surface force apparatus has been developed in which the surface that moves under the influence of the applied force is attached to a plate of a capacitor. The method has been applied to measure the forces between mica in electrolyte and to measure dispersion forces of mica and silica in air. In this case, the retarded form of the dispersion force fits the measurements much better than the non-retarded form.

1. Introduction

In the classic surface force apparatus [1,2] the distance between the surfaces is measured by the interferometry of white light with a resolution of about 1 nm and the force is measured from the movement of one of the surfaces attached to a cantilever spring which deflects under the influence of the force. The interferometric method requires the preparation of partially silvered transparent mica sheets of uniform thickness (1-5 μm). The process of making the sheets is difficult; it has always been desirable to find a method of measuring the distance between the surfaces that is faster and more accurate.

This paper describes an attachment [3] for a conventional surface force apparatus [2] that makes use of capacitance dilatometry to obtain measurements of the distance between surfaces that is accurate, stable and linear over a long range. The separation between the surfaces can be controlled by a magnetic force transducer [4]; the displacement is obtained directly from the output of a lock-in detector by means of signal analysis.

2. The Equipment

A schematic diagram of the apparatus is shown in Fig. 1. The apparatus is contained within a stainless steel chamber to which the upper mica surface is fixed. The lower mica surface is mounted on the head at the left end of a double cantilever mechanical spring of stiffness a few hundred N/m which, at its right hand end, is rigidly connected to the chamber.

The moving plate of the capacitor is fixed to the cantilever; the fixed plate of the capacitor is attached above it to the chamber. The two capacitor plates and the cantilever are made from non-magnetic stainless steel; the plates are circular with diameter 1.5 cm and gap around 0.1 mm giving a capacitance of about 10 pF.

There are three capacitances associated with the capacitor, that between the two plates and those from each plate to earth. The former is about 10 pF, the latter are of the order of 2000 pF, arising mostly from the shielded connecting cables. The main problem in capacitance dilatometry is to measure the former accurately (to 1 part in 10^6 or more) in the presence of the latter. This problem is solved by the use of a variable ratio transformer bridge which ensures that only the capacitance between the two plates is taken account of in the measurement [5,6].

The conventional operating mode of a bridge is to balance it manually. This means that it takes many seconds to obtain a balance and this is even harder to do when the balance is changing. Faster measurements may be obtained from the output of the lock-in detector but allowance has to be made for its capacitive admittance. We have obtained the relation between the output voltage of the lock-in amplifier and the distance moved by the capacitor [3].

The separation between the surfaces is varied by means either of a piezoelectric transducer acting on the upper surface or a magnetic force transducer [4] acting on the lower one.

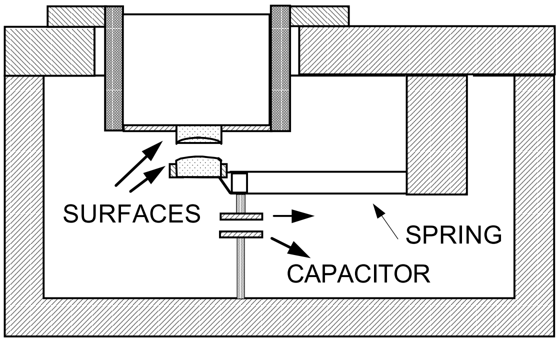

Fig. 1. Schematic diagram of surface force apparatus with capacitance stage. The lower moving surface is attached to a double cantilever spring, thereby ensuring that the surfaces remain parallel when the spring is deflected. The top plate of the capacitor is fixed to the moving cantilever head, the bottom is stationary.

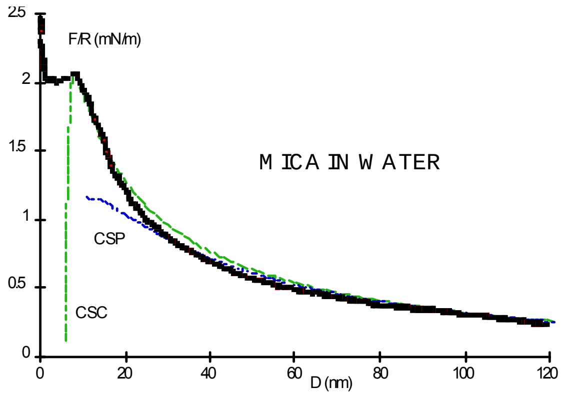

Fig. 2. Normalised force *F/R* against separation *D* between mica surfaces in pure water. *R* is the radii of curvature of the surfaces. The double layer electrostatic repulsion lies between the fits calculated for constant surface potential (CSP) and constant surface charge (CSC). It is followed by a jump into contact due to spring instability.

3. Experimental Results: Mica in Water

A droplet of pure water was injected between the two mica surfaces and the force measured as a function of separation *D* between them [3]. The adhesive pull-off force in water was 1.2 mN. The area of contact in air between the surfaces was circular with radius 48 μm. The results obtained are shown in Fig. 2. It can be seen that at large distances there is an electric double layer repulsion, a jump into contact at 8.2 nm due to spring instability followed by a hard core repulsion. The data are in agreement with those obtained by Pashley [8], except for one feature. The data of Pashley show a jump into contact at 3 nm. The reason for this difference is that the method of measuring displacement with FECO used by Pashley [8] and all others only measures the separation from the point of instability to contact, whereas the method used here measures both that and the distance that the surfaces move when they distort from their initial shape under the forces of adhesion [3, 9].

The electric double layer force was calculated with the non-linear Poisson Boltzmann equation with a surface potential of 150 mV and a Debye length of 140 nm; the van der Waals attraction was given by a non-retarded interaction with a Hamaker constant of 2.2×10^{-20} J. The theoretical curves were displaced outwards from contact by a distance of 5 nm to allow for that part of the jump due to distortion of the surfaces.

The size of the jump is obtained from JKR theory [9] which predicts an adhesive jump of 5.4 nm. Adding this to Pashley's [8] value of the jump of 3 nm gives a total jump of 8.4 nm, in reasonable agreement with our measured value of 8.2 nm. This was the first time that the full physical jump has been directly measured in any surface force experiment.

4. Experimental Results: Dispersion Forces in the Retarded Regime.

Dispersion, or van der Waals forces, one of the fundamental forces of nature, are responsible for the structure and function of many molecular and biological systems. Few direct measurements of dispersion forces between surfaces in air have been made to date because of the smallness of the forces involved. Because of this difficulty the only direct measurement in the retarded regime has been those made on mica some thirty years ago [1].

In Fig. 3 are shown measurements of the dispersion force of mica in air against separation [7]. When the surfaces are separated, down to the point of inward jump, about 20 nm from contact, they retain their undistorted shape. However, when they snap into contact, as in the left hand side, they squash together, and distort in the way described by JKR theory [8]. Accordingly, because the axial contact deformation on contact cannot be obtained directly, the origin of the *D* coordinate is not apparent from the bare experimental data and has to be deduced from analysis of it. The criterion to be met is that any fit satisfies, on theoretical grounds, both the appropriate form of the dispersion force and also the contact displacement expected from JKR theory.

The limiting form of the van der Waals interaction is, in the retarded regime, $F = -(2\pi/3)BR/D^3$, where *B* is a constant. The data are fitted to this retarded limiting form, adjusting both *B* and the origin of *D*. The best fit to the retarded form is shown as the continuous line in Fig. 3. It is seen that *F* scales as $1/D^3$ with $B = 0.93\times10^{-28}$ and a surface distortion of 14.2 nm. The non-retarded form of the dispersion force is given by the dashed line. It is clear that the retarded form gives the better fit. Using JKR theory [7,9] the measured contact area and the contact distortion of 14.2 nm we obtain an average bulk modulus of $K = 3.6\times10^{10}$ J/m^3 for the mica glue silica assembly, close to the mica value.

The first ever measurements of the dispersion force of silica in the retarded regime have also been made [10]. The dispersion force has been found to be 42% that of mica.

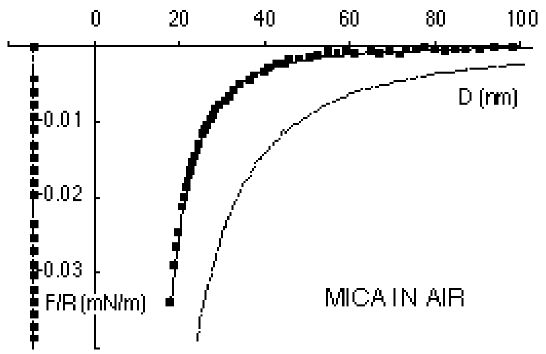

Fig. 3. Normalised force *F/R* against separation *D* between mica surfaces in air. A jump into contact occurs below 20 nm because of spring Instability. The continuous line is the retarded fit, the dashed line the non-retarded fit.

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