3B SCIENTIFIC® PHYSICS

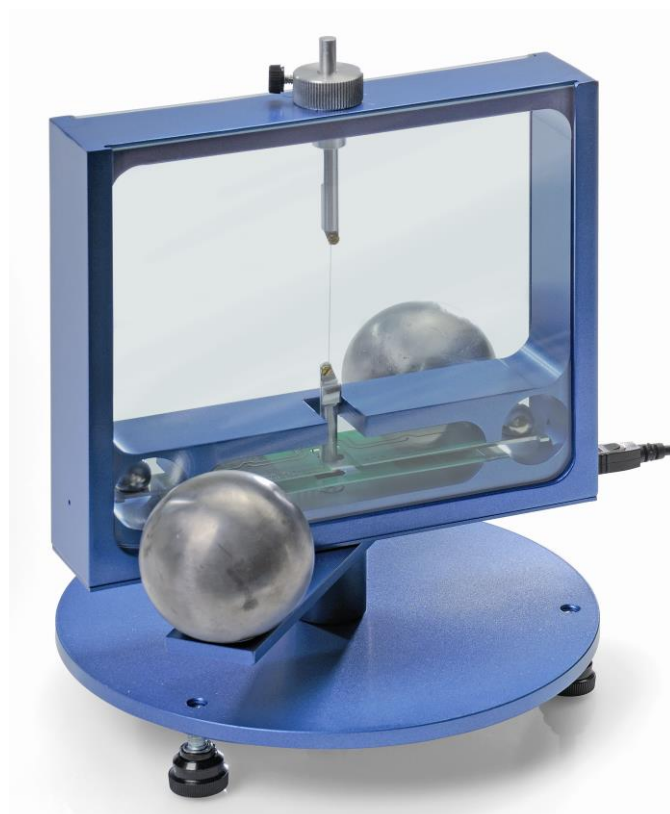...going one step further

Cavendish Torsion Balance   1003337

Operating instructions

06/18 ALF

1. Description

The Cavendish torsion balance is for demonstrating the gravitational attraction between two masses and determining the gravitational constant.

The key component of the torsion balance is a torsional pendulum, consisting of a supporting beam suspended horizontally from a thin tungsten wire and bearing two small lead spheres. The apparatus is moved from its equilibrium position by the gravitational force exerted on the two small spheres by two larger spheres. If the larger spheres are moved, the torsion balance will be drawn out of equilibrium and will oscillate around the new equilibrium

position. The motion itself can be measured using a capacitive differential sensor, which largely suppresses the noise and vibration from the signal, and displayed on a computer. To evaluate the results further, the data can be exported to a spreadsheet program. Alternatively, the movement can be demonstrated with the help of a laser pointer.

Thanks to the short period of oscillation, between 2 and 4 minutes depending on the length of the tungsten wire, the gravitational constant can be measured within the time span of a school lesson to an accuracy better than 10%.
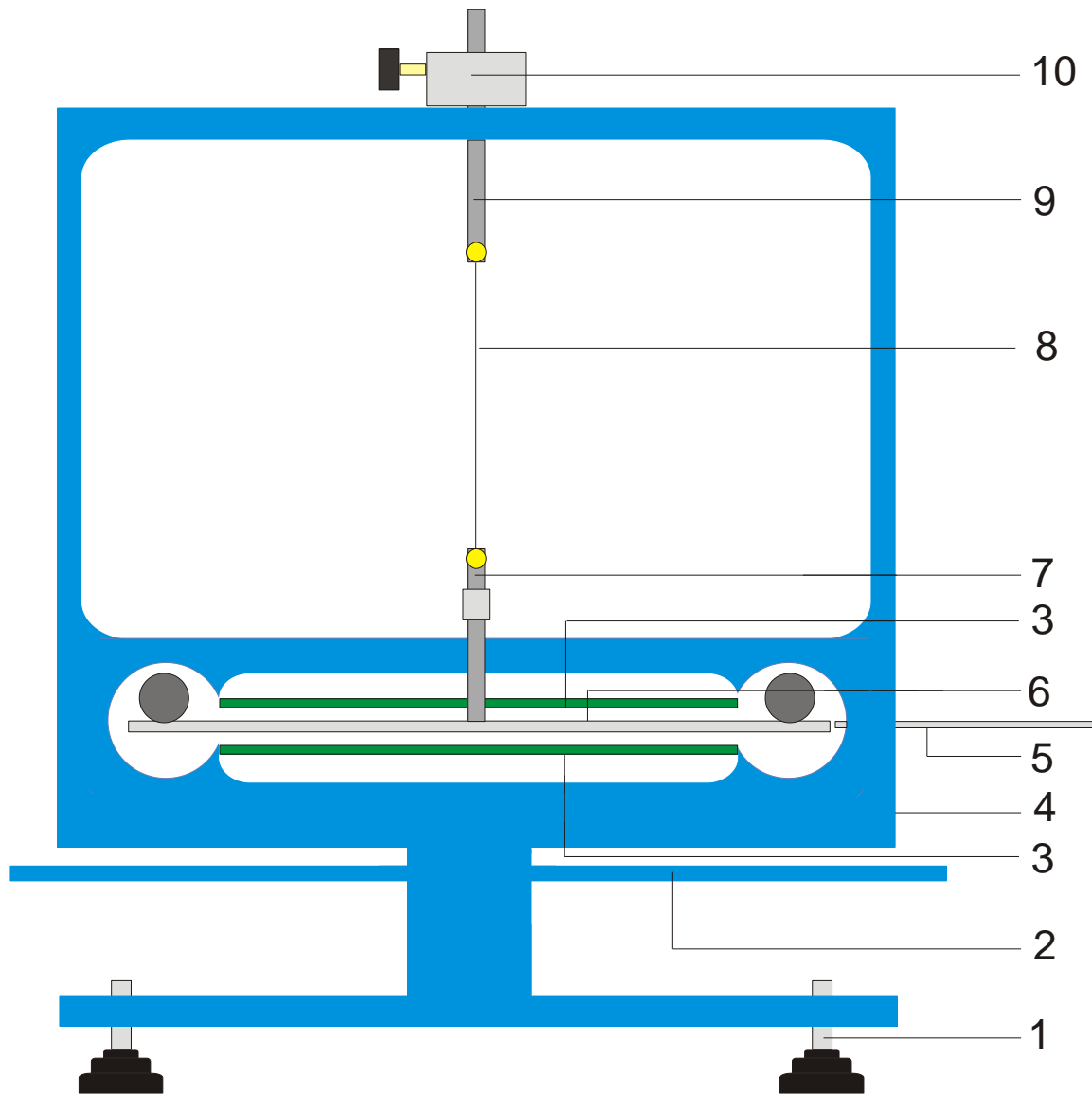
Fig. 1 Components of a Cavendish torsion balance

1 Adjustable feet, 2 Outer supporting beam for large lead spheres, 3 Capacitive differential sensor, 4 USB port, 5 Centring rod, 6 Inner supporting beam for small lead spheres, 7 Lower suspension rod with mirror, 8 Tungsten wire, 9 Upper suspension rod, 10 Rotatable mounting with protractor scale

2. Equipment supplied
1 Housing with glass plates
1 Roll of tungsten wire
1 Lower suspension rod with mirror
1 Upper suspension rod
1 Inner support beam
1 Centring rod
1 Aluminium rod with thread
2 Small lead spheres
2 Large lead spheres
1 Measurement software
1 USB lead

3. Technical data	
Mass of large spheres:	each 1 kg approx.
Mass of small spheres:	each 15 g approx.
Gravitational force:	$< 10^{-9}$ N
Torsion wire:	Tungsten, 25 μm
Period of oscillation:	2 – 4 mins
Angle resolution:	25 μrad
Sampling rate: samples/s	0.5, 1, 2, 5, 10
Dimensions:	19x18x20 cm approx.
Weight	5 kg approx.

4.1 Safety instructions

The diode laser (1003201) meets the safety requirements for class II lasers. When used properly, experiments can be carried out using the diode laser with no risk.

- Follow the instructions in the laser's instruction manual.
- Do not look directly into the laser beam or any reflected beam.
- Do not exceed the limits for laser dazzle, i.e. none of the viewers should feel dazzled by the beam.

4.2 Note concerning where the experiment takes place

The capacitive differential sensor largely suppresses components of noise and vibration in the signal. Nevertheless, it is essential to select a bench that cannot be shaken. Serious disturbances (like the slamming of a door) cannot be suppressed and give rise to errors in the signal.

4.3 Installation of software and connection to a computer

Before the apparatus is ready to use, the software needs to be installed and the apparatus needs to be connected to the PC or notebook on which the program is running.

- Insert the CD containing the software into the CD drive of the computer.
- Open Windows Explorer and navigate to the CD drive. To start the install program, double click the file "setup.exe" and follow the instructions displayed by the install wizard.
- Connect the torsion balance to the computer via the USB cable.
- Run the program.

If the installation has been carried out correctly, a value displayed in milliradians will be shown in the top left-hand corner of the window.

A detailed description of the software can be found in Section 5.

4.4 Setting the measuring range

- Take the glass plates out of their housing.
- Screw the threaded aluminium rod into the middle of the inner support beam, then assemble the torsional balance in the housing, aligning it such that the support beam is located centrally between the two sensor boards.

- Put the glass plates back in, connect to torsion balance to the computer and run the software. Click the program's "Setup" button.
- Turn the support beam anti-clockwise by means of its mounting until it touches the glass plate.
- Click the "Adjust left border" button and confirm by clicking "OK" to define the lower limit of the measuring range.
- Now turn the beam clockwise until it touches the glass plate. This time, click the button "Adjust right border" and confirm with "OK" to set the upper limit of the range.

The design of the support beam includes lugs at the ends so that it always oscillates within the linear range of the capacitor plates.

The measurement software can pick up any measurement value between +60 and -60 mrad, although under normal circumstances the support beam will only oscillate by a few mrad during the experiment.

Figure 2 shows the dimensions of the inner support beam. The maximum angle can easily be calculated from these dimensions.

$$\alpha = \frac{(30 - 18{,}7)}{2} \div \frac{150}{2} = 75 \text{ mrad}$$
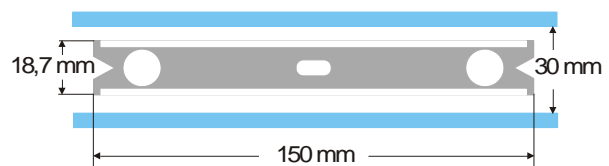

Fig. 2 Dimensions of inner support beam

4.5 Assembly of torsional pendulum

Note: Assembling the torsional pendulum is difficult. It requires a steady hand and good eyesight. The tungsten wire is very thin and can easily break, so that it needs to be treated with utmost care. In order for the wire to be seen easily, it is recommended that the torsional pendulum be assembled against a background of white paper.

- Place the torsion balance on a bench that cannot be shaken and align it horizontally.
- Screw in the lower suspension rod in the middle of the inner support beam, taking care that the surface of the mirror remains parallel to the support beam (see Fig. 3).
- Use a small screwdriver to loosen the screws attaching both suspension rods.
- Fix the upper rod to a piece of white paper using adhesive tape to stop it rolling away.
- Unroll about 8 to 10 cm of tungsten wire from its bobbin but do not cut it off yet.

- Fix the end of the wire to the paper next to the upper suspension rod using a strip of adhesive tape. Now wrap the wire around the fixing screw and screw it in till it is tight, taking care to ensure the wire does not get kinked. As far as possible, the wire should run between the central axes of the two suspension rods (see Fig. 3).
- Now place the lower suspension rod on the paper about 4 to 5 cm below the upper rod. Wrap the wire around the fixing screw so that it is slightly under tension and screw it in tight.
- Now you can cut the wire off the roll.
- Carefully suspend the torsional balance from a stand by its upper suspension rod and check that it is aligned horizontally.
- To align the support beam for the torsional pendulum horizontally, take it back off the stand and carefully lay it on the bench. Undo the screw for the lower suspension rod, hold the rod still with your hand and move the beam as needed. Tighten up the screw again and check the alignment once more.

- Once it is correctly aligned, carefully place the torsion pendulum in its housing, setting the support beam on top of the lower, green sensor board, with the upper suspension rod passing through the hole drilled in the top of the housing.
- Adjust the height using the adjustment screw so that the support beam can swing freely between the sensor boards. The screw must be screwed against the flat side of the suspension rod.
- If the pendulum cannot swing freely, repeat the above procedure for positioning the suspension system on the support beam. Further correction can be made using the adjustable feet.
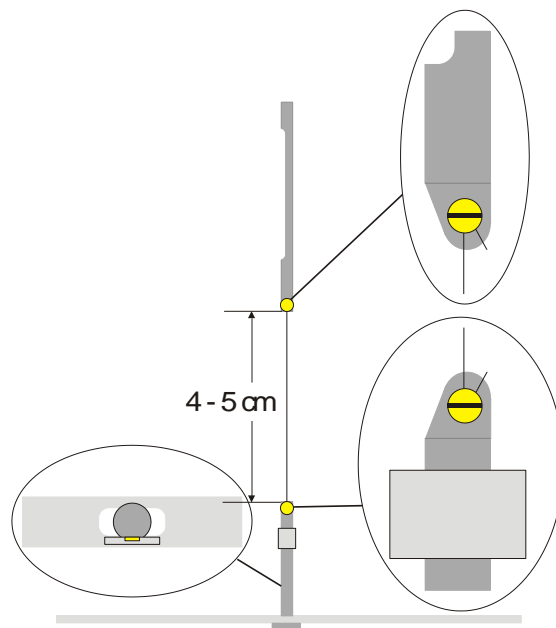- Place the small lead spheres on the inner support beam and insert the glass plates.

Fig. 3 Schematic diagram of torsional pendulum (the detail on the left shows a view from above of the support beam with the lower suspension rod)

4.6 Setting the zero point

To set the zero point, it is recommended that the following laser be used as a laser pointer:

Diode laser, red 650 nm   1003201

- Place the torsion balance on a bench that cannot be shaken about 2 to 3 m from a flat wall and connect it to a computer (see Fig. 5).
- Set up the laser so that the beam is at the same level as the mirror on the lower suspension rod.

- Observe the laser pointer on the wall.
- Wait till the vibration of the torsional pendulum has died down.
- Turn the support beam in a series of steps of small angles by means of the upper suspension rod until it comes into contact with the glass plates. A 45° graduated scale is attached to the housing around the suspension rod for your assistance (see Fig. 4).
- Observe the movement of the light pointer and mark the maximum extent of the

oscillation to the left and right on a piece of paper fastened to the wall.

- Determine the centre position between the marks for the two extremes and mark that on the wall, too.
- Turn the suspension rod until the support beam is in this central position and wait for the pendulum to stop vibrating in that position.

Alternatively, the support beam can be fixed in this central position using the centring rod.

- Set this position as the zero position in the software.
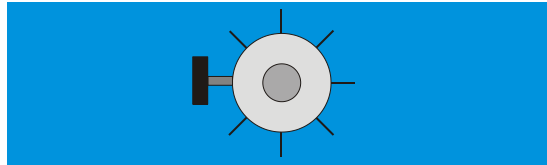- Keep the set-up of the apparatus like this for the course of the experiments.

Fig. 4 Mounting of torsional pendulum with scale as viewed from above
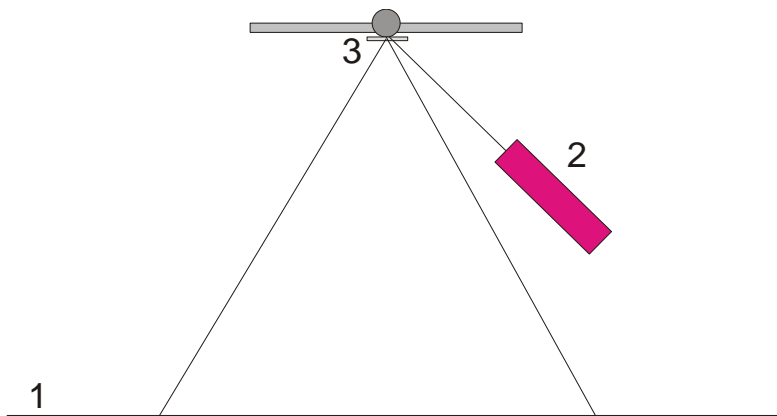

Fig. 5 Set-up of laser pointer for determining zero position (1 wall, 2 laser, 3 mirror)

4.7 Experimental procedure

- Place the large lead spheres on the outer support beam at position 1 (see Fig. 6) and wait till the vibration has settled down (by observing the laser pointer). Calibrate the zero point if necessary.
- Move the outer beam to position 2 and start the measurements.

- When the small spheres have almost reached their equilibrium point, move the outer beam to position 3.
- Once the small spheres have almost reached their new equilibrium position, then stop the measurement.
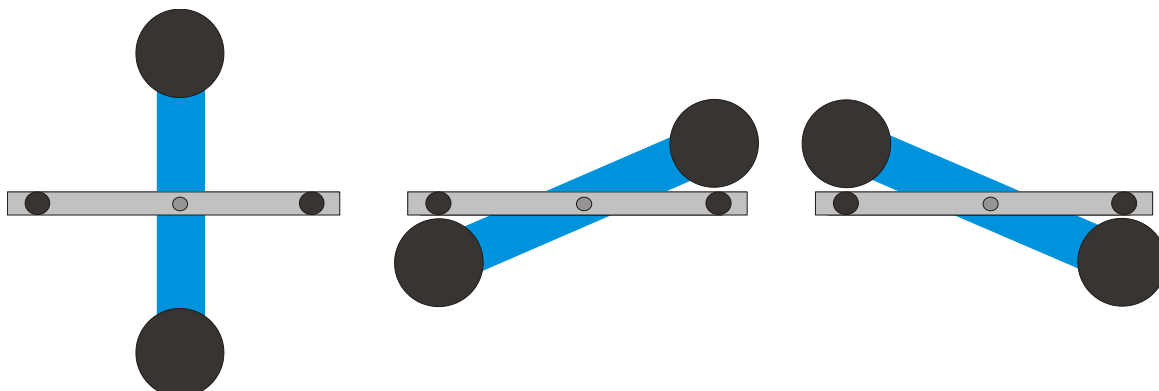- Save the plot of the measurements.

Fig. 6 Positions of outer support beam (as seen from above) Left: Position 1, Centre: Position 2, Right: Position 3

4.8 Evaluation

4.8.1 Determining the point of equilibrium

- The equilibrium position α_1 can be calculated from the first five maximum deflections after the initial movement to position 2 by means of the following equation:

$$\alpha_1 = \frac{1}{2} \cdot \left(\frac{\alpha^{(1)} + \alpha^{(3)} + \alpha^{(5)}}{3} + \frac{\alpha^{(2)} + \alpha^{(4)}}{2} \right)$$

- Use the cursor to mark the maxima and minima of the curve and read off the values in the "Data" field on the information bar (see Fig. 7).

Alternatively, the values can be taken from a spreadsheet prepared using Microsoft Excel if the results have been saved in this format beforehand.

- Work out the new equilibrium position α_2 after moving the beam to position 3 in a similar way.

4.8.2 Determination of gravitational constant G

m = Mass of small speheres

r = Distance of spheres from axis of rotation

M = Mass of large spheres

M_B = Mass of inner support beam

L_B = Length of inner support beam

W_B = Width of inner support beam

b = Distance between large and small spheres

T = Period of oscillation

k = Angular constant

$\Delta\alpha$ = Difference between equilibrium points $\alpha1 - \alpha2$

The moment of inertia of the torsional pendulum J_{tot} is given by the sum of the moments of inertia of the small spheres J and of the inner beam J_B.

$$J = 2 \cdot m \cdot r^2$$

$$J_B = \frac{1}{12} \cdot M_B \cdot \left(L_B^2 + W_B^2 \right)$$

$$J_{tot} = J + J_B$$

$$\tau = k \cdot \Delta\alpha$$

$$k = \left(\frac{2\pi}{T} \right)^2 \cdot J_{tot}$$

$$\tau = G \cdot 2 \frac{m \cdot M \cdot r}{b^2} \cdot \left(1 - \left(\frac{b}{\sqrt{b^2 + 4r^2}} \right)^3 \right)$$

By substituting the values and rearranging the equation as appropriate, the required value G can be derived.
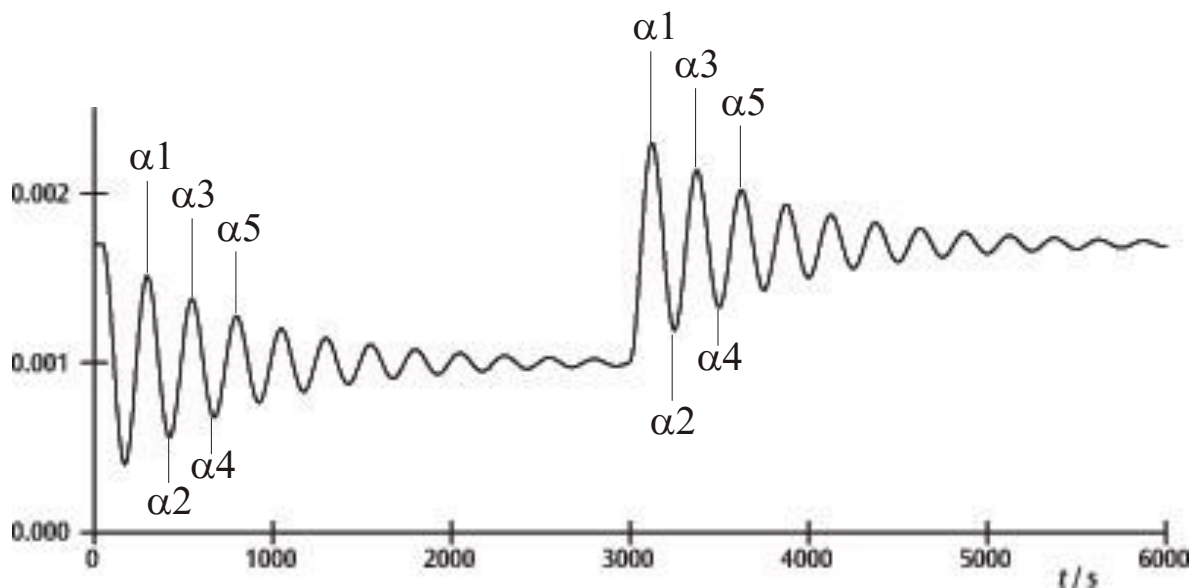

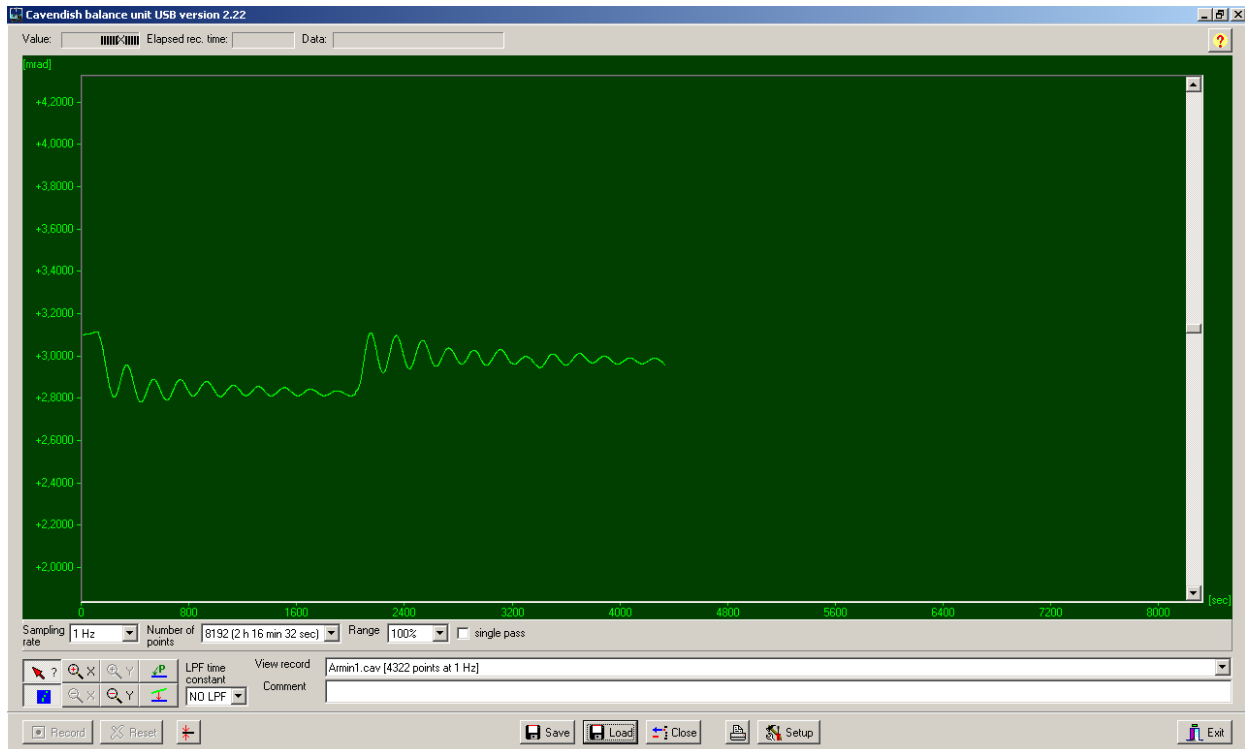Fig. 7 Determination of equilibrium points

Fig. 8 Example of measured curve

5. Software description

5.1 Information bar

The information bar at the top of the window contains three fields. The "Value" field displays the value currently being measured by the torsional balance. The "Elapsed Time" field displays the time from the start of the measurement and the "Data" field shows the data at any point in the trace where the cursor is located.

5.2 "View Record" bar

The "View Record" bar is located on the right beneath the trace window. The following information is displayed there: the sampling rate, the measuring mode, "Single pass" (for one-off measurements) or "Continuous" (for long-term measurements) and whether the measurement is being made in real time or is from a data record that has been loaded into the program.

5.3 Comment bar

The comment bar is located directly beneath the "View Record" bar. It allows comments regarding the experiments to be entered.

5.4 Tool bar

The tool bar is on the left under the trace window and allows for the selection of parameters for the acquisition of measurements. 5 separate sampling rates can be selected from the "Sampling Rate" field. The "Number of Points" field offers 7 "data breadths" from 512 to 32768 points and allows 19 hours of data or more to be recorded. The "Range" field offers the choice of 6 different ways to scale the y-axis. When the "Single Pass" option is selected, recording of data stops after a single pass. Otherwise the data is acquired on a continuous basis.

Underneath the tool bar on the left there are 8 buttons in 2 rows. The top left of these is the "Examine Data" button. Selecting this button causes an angle to be displayed in the information bar along with the time. If the cursor disappears, clicking this button can make it visible again.

Both the x and y axes can be magnified using the positive zoom button and by clicking with the left mouse button in an active window. Clicking the negative zoom button and the active window allows the original magnification to be restored. The maximum zoom setting displays 512 points in the time shown multiplied by about 1.5 mrad.

Selecting the "Connect Data" button allows a line to be drawn linking individual measured points.

To the right, one above the other, are the two buttons "Select Points" and "Apply Corrections". "Select Points" allows 1, 2 or 3 points on the trace to be selected in order define an offset, a linear

function or a quadratic curve. These can then be used to correct any drift in a long-term measurement. Changes in humidity have proved to be the main cause of any such drift. In order to select points, click the "Select Points" button and click on the trace window and choose P1 from the pop-up menu. Then you can choose the first point for the drift correction. This procedure is then repeated to select the points P2 and P3.

In order to carry out a correction, click the "Apply Corrections" button. If the correction is unsatisfactory, there are two methods for modifying it. The first involves deactivating "Apply Corrections" by clicking the button again, then the points can be chosen again and the full procedure is then repeated. The second way to modify the correction is to change the function coefficients directly. To do this, click on the trace window and choose "Set coef." from the pop-up menu. New values for A, B and C can then be entered. Click "OK" to confirm these and click on the trace window again. Then click "Manual Coefficients OFF" in order to start the "Manual Coefficients On" function and to view the correction with the modified values. The coefficients can be changed as often as necessary until the correction is satisfactory.

5.5 Low-pass filters

The "LPF Time Constant" button allows users to select from 12 different low-pass filters or turn them all off. This function is only required in some unusual circumstances. All experiments should be started with the "No LPF" option selected. If the movement of the inner support beam differs significantly from simple turning movements, a function to suppress matching periods causes such movement not to be recorded. If this is not the case, use of a low-pass filter may help.

5.6 "Reset" button

Once a set of measurements has been made successfully, the acquisition parameters for the measurements, such as sampling rate, number of points, measuring mode, etc. can then be reset. Clicking the "Reset" button activates the function.

5.7 "Record" button

Clicking the "Record" starts recording of measurements. The button then becomes a "Stop" button with which the measurements can be brought to a halt manually. Once a set of measurements is finished, either automatically or manually, a notification is shown, asking of the data acquired should be saved.

5.8 "Save" and "Load"

Clicking the "Save" button causes data to be saved. The standard format is *.cav. Two other formats (*.txt and *.xls) are available to allow for further analysis of data in a spreadsheet.

The "Load" button allows previously saved data to be loaded into the program.

After acquiring data for 2 minutes, the program will save a file called temp.cav. The measurements are saved in this temporary file to stop data being lost in the event of a power failure, for example. The data can then be restored up to the point where the temp file was last saved before the power cut. Every time a new set of measurements is started, this file is overwritten.

5.9 Print

Clicking the "Print" button allows the data to be printed out. In addition to the trace itself, the sampling rate, the number of points and the filename are all shown on the print-out. Comments from the comment field can be added to the print-out if the relevant option is selected.

5.10 "Setup" button

This button allows the min. and max. limits for the torsion balance's measuring range to be defined.

"Y minimum" and "Y maximum" define the overall range for the torsion balance. Changing these values allows the read-outs from the balance to be modified. The buttons "Adjust left border" and "Adjust right border" set the display such that the upper (adjust right border) or lower (adjust left border) edges of the trace window is matched to the position of the support beam.

5.11 Calibration of zero point

The button directly to the right of the "Reset" button determines the zero point for the support beam. The zero point of the beam's oscillation will be set to the point at which the button is clicked. To determine the centre point, the support beam is set in the centre under the sensor plates and temporarily fixed there using the centring rod. The button is then pressed. The geometric centre of the sensor boards is thus defined as the zero point and movement away from this axis on either side is then displayed in milliradians (mrad).

5.12 "Exit" button

Clicking the "Exit" button closes the program.