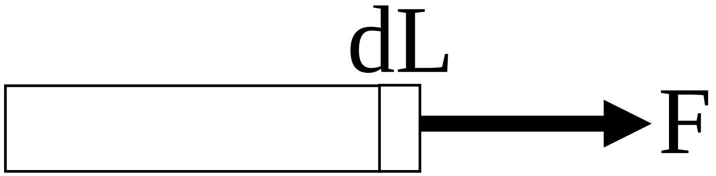
AP007: Force or Displacement?



This application note describes the feedback sensors in Razorbill Instruments stress and strain cells. Some cells measure displacement, some measure force, and some measure both. In general, both is best, and if only one can be used then force is usually superior to displacement. But this is not the case for every experiment.

This note describes in detail exactly what each type of sensor measures and how that relates to the properties of the sample. See also AP006 for more detail on the accuracy and repeatability of the sensors themselves.

The sample and the cell

In order to understand the pros and cons of each type of sensor, it is first necessary to understand how they work. Figure 1 shows a simplified drawing of the key parts of a UC200 cell, which contains both force and displacement sensors. The FCxxx series cells are very similar except that the displacement sensing capacitor is missing. The CSxxx series cells are also similar, except that the force capacitor, force block and force spring are missing. Instead, the sample and displacement capacitor are joined directly to the fixed end.

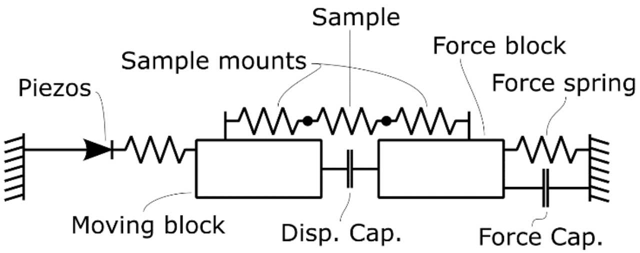


Figure 1: *Simplified functional diagram of a UC200*

In this diagram, the piezoelectric actuator arrangement has been simplified, and the compliances of the actuators and the surrounding titanium have been combined into a single spring. Similarly the flexures which guide the moving block are omitted as they don't affect the measured force or displacement.

When the moving block moves, the displacement capacitor measures the movement between the two sample mounts. The force applied to the sample makes the force block move and compresses the force spring. This movement is measured by the force capacitor.

The displacement measurement

The displacement measured by the displacement sensor is the movement between the moving block and the force block (or fixed end in a CSxxx cell). It is important to understand that this is not exactly the same as the length change in the sample. Ideally, the spring constant of the sample mounts would be much larger than the spring constant of the sample, and then the sample would extend by the displacement measured by the sensor. In reality, even for soft samples, the epoxy will deform, and for stiff samples there may be some deformation of the sample plates too. Figure 2 shows a finite element analysis of a sample under tension, showing how the epoxy deforms. One can estimate the impact this has when converting from displacement to strain, but it is difficult to do this accurately, even with finite element analysis, as the exact dimensions of the epoxy layers are not usually known and the elastic modulus of the epoxy can vary significantly with temperature.

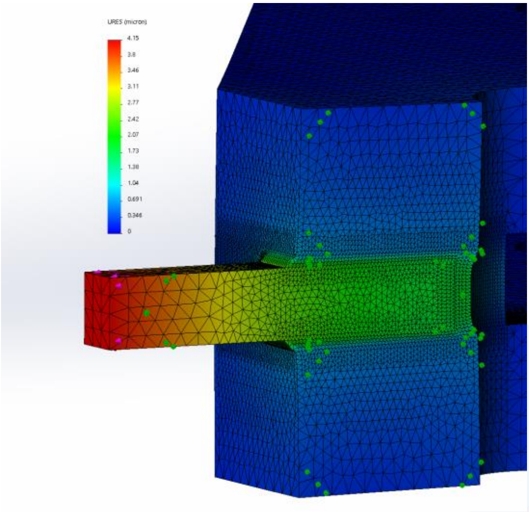


Figure 2: *Simulation of 20N force applied to a 0.2x0.3mm sample with 25um epoxy above and below, showing significant epoxy deformation.*

An additional caveat with displacement measurement is thermal expansion. All Razorbill Instruments stress/strain cells are thermally compensated so that temperature changes produce little or no movement from the piezoelectric actuators, but they still expand and contract due to the thermal expansion of the titanium they are made from. The sample will also exhibit thermal expansion, and for many samples the detailed thermal expansion is not known. One can use the displacement sensor to control the length of the sample, but if the unstrained length of the sample is not known, then we do not know when the sample is in an unstrained state.

Together, these two things form a gain and offset error in converting from displacement to strain. While the strain calculated this way is much more accurate than the strain one might estimate when using a simpler technique (such as gluing samples directly to an actuator), a higher level of accuracy is desirable.

The force measurement

The force measurement is independent of the stiffness of the sample mounts. Because the sample mounts, sample, and force spring are all in series with each other, they all experience the same force. One can then convert the measured force to a sample stress using only the cross sectional area of the sample, which is relatively easy to measure.

The force sensor is also better for identifying the zero-strain point at low temperature, because no matter how much the sample may have expanded or contracted on temperature changes, zero force means zero stress and zero strain.

There are still limitations on the accuracy of the force sensor though. The spring constant of the force spring is somewhat temperature dependent, and if not corrected for this will introduce a gain error of around 10% at 4K when converting from capacitance to force. The correction is described in AP006, and on the calibration curve for cells built after spring 2023.

The dominant errors in the zero point offset are drift (mostly due to humidity), temperature repeatability, and hysteresis after applying large forces. The former can be reduced or eliminated with longer pumping times before cooling the cell, and in general repeatability of less than 1% can be achieved with care.

Other considerations

The sections above describe how force should generally be considered the more accurate metric of the stress/strain in the sample, but there are a number of other considerations which come up when choosing which to use.

Displacement naturally measures strain, where force measures sample stress. In most cases, stress and strain are closely related, and either one can be converted to the other using the elastic modulus. For some experiments or materials, there may be reasons to prefer one to the other to make for easier interpretation of the data.

Availability of appropriate stress/strain cells can also be a factor. The range of devices offered by Razorbill Instruments does not often include two equivalent cells one with a force sensor and the other with a displacement sensor. Requirements for certain cell size, travel, cost etc. can drive cell choice and thus sensor choice. Of particular note here is the availability of force sensors: at present ranges of between ±50N and ±200N are available. For very soft samples, the force sensors may not have the resolution to obtain a useful measurement.

Measuring both

At the time of writing, there is one cell available which can measure both the force and displacement at the same time, the UC200. The UC200 comes with a suitable multiplexer so that both sensors can be measured with a single capacitance bridge. In addition to the obvious advantage of being able to choose either sensor during the experiment or data analysis, there are several other significant benefits.

When the cell is operating correctly and the sample is intact and deforming elastically, the force and displacement will be proportional to each other.

If the sample begins to deform plastically, then the displacement will continue rising, but the force will level off. Checking that this is not happening can help confirm the sample is intact and undamaged, but experiments where the sample is plastically deformed intentionally are also possible.

Some forms of plastic deformation, such as progressive failure of the epoxy holding the sample, also have distinctive forms on a force/displacement curve which may let them be identified before they reach the point where they end the experiment.

If the sample breaks or pulls out of the epoxy, this will be obvious as the force snaps back to zero. Knowing this has happened can save time in debugging or trying to measure a broken sample.

While absolute measurements of the elastic modulus will remain difficult due to geometric uncertainties and the specific limitations of the sensors discussed above, significant changes in elastic modulus will be detectable. This is particularly relevant for materials with a structural transition.

Can I use voltage instead?

This is a question we get asked quite a lot: Can I use the voltage I'm applying to the stacks to estimate sample strain, instead of measuring the capacitor? The answer, unfortunately, is usually no. The stress/strain applied to the sample is not that directly related to the voltage for several reasons:

- The magnitude of the stress/strain depends on the relative stiffness of all the springs shown in figure 1. Including the one shown as part of the piezo (which is related to the cell spring constant in the datasheet of the cell).
- The stroke of the piezo actuators is very temperature dependent.
- At any given temperature the extension of the piezo actuators is quite hysteretic. The stress applied at 100V and rising is different from the stress at 100V and falling. The magnitude of this effect is quite temperature dependent.
- The extension hysteresis is also complicated by temperature. The extension obtained by going from 300K to 100K, then applying 100V is different from that obtained by applying the voltage then changing the temperature.

So in order to obtain accurate data, relying on voltage to indicate stress/strain is not recommended. It can be useful for diagnostics though: for example if the experiment starts out OK, but after a while applying a voltage no longer produces a force, then the sample is probably broken.