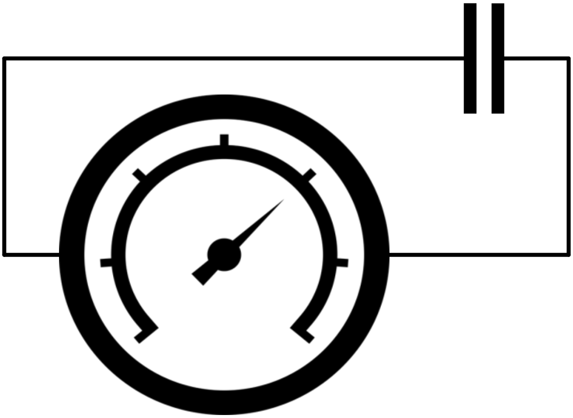
AP003: Measuring Capacitance



Razorbill Instruments stress and strain cells use parallel plate capacitive sensors. In strain cells, the capacitor measures the displacement applied to the sample, and in stress cells it measures the force applied. This application note describes the sensors, how they should be connected, and cabling requirements. It also discusses some different options for measuring the capacitance.

Most users will use the recommended capacitance bridge: the Keysight Technologies E4980AL-032, so will not have to consider the other options for measuring capacitance.

Sensor description

The sensor in the cell is a parallel plate capacitor with guards on both plates, and is isolated from the body of the cell. There are two coaxial cables coming from the sensor, one from each plate. The plate is connected to the core of the coax, and the shield of the coax is connected to the guard around that plate.

This arrangement was chosen to minimise the interference coupling into the sensor from the cryostat or user measurement and the noise coupling back from the sensor to the measurement. For best results, the body of the cell should be connected to the cryostat, which should be grounded (which is also advisable in most systems from a safety point of view). The guards and coax shields should be grounded by being connected to the instrument measuring the capacitance. Ideally, they should not be connected to ground anywhere else, as this would create a ground loop. In particular, they should not be connected to the cryostat.

Operating environment

The capacitors in the Razorbill Instruments cells are not sealed and can be sensitive to the environmental conditions. Depending on the age of the cell (and thus the exact model of capacitor installed), the capacitors may be very sensitive to atmospheric humidity. Refer to AP006 for more information about this and about accuracy in general.

Liquid nitrogen or oxygen condensing in the capacitor is also problematic and carries the added risk of damaging the capacitor through rapid expansion as the cell is warmed up.

Cables and components

The following constraints apply when choosing components to install for capacitance measurement in the cryostat.

Cables

Coaxial cables are required. Usually, coaxial cables are chosen when high frequencies are used, to prevent radiation, and to precisely control the impedance. In this case however, with cable lengths typically below 10m and frequencies well below 1MHz, impedance matching is not important. Instead, coax cables are needed to provide shielding and accurately control the capacitance between various components of the system.

This means that when selecting a coaxial cable, the key feature is good shielding, with a high level of braid or foil coverage. For installation in a cryostat, heat conduction down the cable is also a concern, see AP004 for more information on that subject. Vacuum compatibility is also important, and cables with foamed dielectrics are often unsuitable. Insulation materials must also be compatible with the low temperatures expected.

It is often appealing to choose a resistive cable to limit thermal conductivity. Depending on the bridge or meter used, the resistance of the cable does have a small negative impact on the measurement. Resistance in the core slightly increases noise with most measurement instruments. Resistance in the braid makes it less effective as a shield, so can make the measurement sensitive to interference from other circuits in the cryostat. On balance, the resistive cables are usually worth it unless the cryostat has lots of surplus cooling power.

For use inside the cryostat Razorbill Instruments normally chooses Lakeshore Type SC or SS, depending on thermal conductivity constraints. For outside the cryostat, any typical lab BNC or SMA cable is fine.

Connectors

As with the cables, there are no concerns about impedance, so connectors can be chosen to match cable diameter, and for convenience. For connections inside the cryostat, especially when using 1 mm diameter coax, Razorbill Instruments normally uses MMCX connectors. Male connectors are generally easy to obtain, but female connectors can be harder to find. Cells are provided with female connectors attached and twice as many male connectors are supplied in the box with each.

For use with Lakeshore SC and SS cable, Razorbill Instruments normally chooses Huber+Suhner 11MMCX-50-1-2/111 and 21MMCX-50-1-2/1110E, though we have also used Molex and Cinch parts in the past.

Feedthroughs

For best results, isolated feedthroughs are required, i.e. the coax braid is not connected to the metal of the cryostat. Most generally available vacuum feedthroughs are not isolated. There are several possible solutions:

- For complete KF or CF flanges, some manufacturers do offer isolated or “floating” feedthroughs, though often at extra cost.
- For systems without particularly high vacuum requirements, it may be possible to make a flange from an insulating material such as PEEK.
- Insulating spacers with O-rings can be inserted between standard vacuum feedthroughs and the flange.
- For KF vacuum systems, it is possible to use plastic clamps and plastic centring rings to isolate a metal flange from the rest of the cryostat.

If it is not practical to obtain an isolated feedthrough, or if re-using existing non-isolated feedthroughs, there will probably be some increase in noise on the capacitance measurement. The best grounding arrangement in this case will depend on the other noise sources in and around the lab, so some experimentation will be required.

Measurement instrument

At the time of writing, Razorbill Instruments does not offer a capacitance measurement instrument, so this is a key part of the measurement system which must be obtained elsewhere. There are several different techniques for measuring capacitance, and several instruments on the market which implement each one.

The sensors in Razorbill Instruments cells tend to have small capacitances, around 0.5-10 pF depending on the model, which limits the techniques available. The capacitance measurement mode on basic multimeters, for example, cannot measure down to these levels.

Razorbill Instruments would usually recommend a Keysight Technologies E4980AL-032 LCR meter. For increased precision (and larger budgets) an Andeen-Hagerling model 2550A or similar capacitance bridge would be an excellent choice. Older manual bridges such as the General Radio 1616 or 1621 are also suitable.

Capacitance bridges

Capacitance bridges are the most specialised instruments and generally the most accurate and repeatable way to measure small capacitances. They are also usually the most expensive option.

Details of the designs vary, but the general scheme is that the capacitor to be measured forms a half or full bridge with one or more reference impedances. Usually reference capacitors and resistors. The top and bottom of the bridge are excited with AC signals of opposite polarity, and either the reference capacitor or the excitation are tuned until the centre of the bridge is at zero volts. At this point the ratio of the excitation voltages matches the ratio of the impedance of the reference to the impedance of the capacitor under test, and the capacitance can be calculated.

From the user's point of view, one of the key properties of this type of bridge is that the two connections to the capacitor are quite different. The excited one is usually marked "high" and is actually quite insensitive to noise or parasitics, whereas the one being measured is much more sensitive. If there is a fault such as poor shielding or a partial short on the low cable, swapping cables will sometimes allow the experiment to continue by moving a fault to the less sensitive high line.

Impedance meters

Also called LCR meters, these are more general instruments and also usually cheaper than capacitance bridges, but still good enough for most measurements.

LCR meters work by applying an AC signal to the impedance to be measured, and measuring the voltage, current and phase shift. Most LCR meters are designed to measure a very large range of impedances from large (like the sensors in the cells) to very small, and as such can be connected to the sample in several different ways. They typically have four BNC terminals which can be used as kelvin contacts.

Kelvin contacts are essential where the impedance of the cables is not negligible compared to the impedance to be measured. For the capacitance measurement, the impedance of the capacitor at 100 kHz will be equivalent to 1-10 MΩ whereas the cable will be a few ohms at most, and real where the impedance of the capacitor is imaginary. Kelvin contacts are not required, and it is fine to connect the current and potential cables together with a BNC tee right at the meter.

Razorbill Instruments normally recommends the Keysight E4980AL LCR meter as the first choice for use with our products. A wide range of LCR meters are available from different suppliers, and many are capable of making measurements of the right general scale, but vary considerably in the accuracy they achieve at such small capacitances, so take care when selecting an instrument of this type.

ΔΣ capacitance converters

Delta-Sigma capacitance-to-digital converters are a type of integrated circuit capable of making highly stable and accurate capacitance measurements. Some, such as the AD7745, offer the potential to measure the sensors in the Razorbill cells at a very low cost, however, there are several hurdles to using them effectively:

- The IC is not suitable for use in the cryostat, but also cannot work with long cables to the sensor.
- As with any IC there would be much more set-up time than for a bench top instrument.

They might however provide a reasonable low-cost alternative for cases where the length of coaxial cable inside the cryostat is sufficiently short.