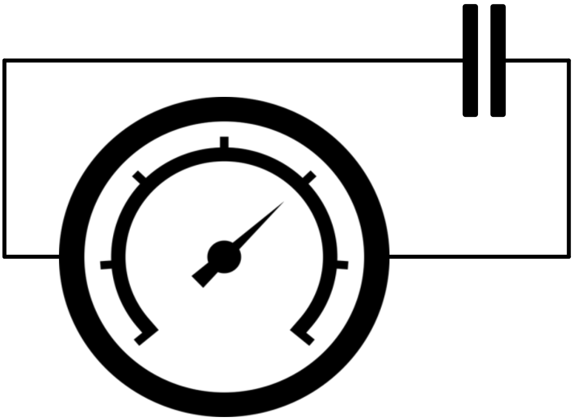

AP003: MEASURING CAPACITANCE

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.

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. 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 at the feedthrough.

Operating Environment

The capacitors in the Razorbill Instruments cells are not sealed, and can be sensitive to the environmental conditions. In general, dry air, helium gas, nitrogen gas and vacuum have very similar dielectric constants, so changing between them affects the reading by at most 0.06 %.

Liquids however have much larger dielectric constants. If liquids condense on the plates, or are adsorbed in large quantities, then they will substantially affect the measurements. Water in particular has a much larger dielectric constant than steam or ice, so inadequate pumping before cooling a cryostat can result in a distinctive peak in capacitance around 290 K as the water vapour condenses then freezes. 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 wiring 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. Cable resistance is generally not a problem, and resistive coaxes are often used in cryostats to limit heat load.

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.

For use with Lakeshore SC and SS cable, Razorbill Instruments normally chooses Molex 73415-2261 male connectors, which work well, and Molex 73415-341x female connectors, which require a short piece of 26 AWG PTFE tube over the dielectric to make them reliable.

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 1-10 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.

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. The sensors in Razorbill cells are designed with slightly better shielding on the "low" plate, which should be connected to the "low" input on the bridge for best results. Swapping cables will provide slightly worse signal to noise, but sometimes allows the experiment to continue by moving a fault from the sensitive low line to the less sensitive high line.

For capacitance bridges, Razorbill Instruments would usually recommend an Andeen-Hagerling model 2550A or similar. Older manual bridges such as the General Radio 1616 or 1621 are also suitable.

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 example to measure a 100 mΩ sample on the end of 5 Ω cables. 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. So Kelvin contacts are not required, and it is fine to connect the “force” and “sense” 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 very low cost alternative for cases where the length of coaxial cable inside the cryostat is sufficiently short.