Probe Theory and Tuning

May 19, 2025

Probe Theory

The NMR probe is a send/receive antenna–in other words, a tuned LCR circuit, just like you'd find in a radio. The sample, a vial of water, sits inside an inductor coil, and this coil is connected in series to a tuning capacitor. Together with the resistance of this bit of circuit, the fixed inductance L and adjustible tuning capacitance C_t determine the frequency range over which the probe is sensitive enough to respond to the fairly small NMR signal. To get this signal to an amplifier, the impedance of this antenna has to be matched to a standard 50Ω transmission line. A second matching capacitor C_m is attached as a shunt on the input/output end to adjust the impedance accordingly. Here we shall analyze the workings of this circuit.

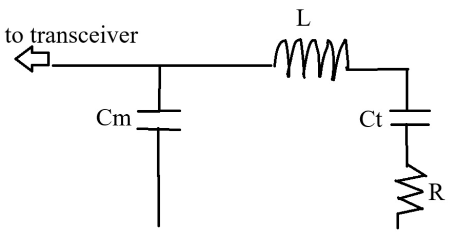

Figure 1: The probe circuit.

Consider the complex conductance of this circuit:

$$S = \frac{1}{Z} = \frac{1}{i\omega L + \frac{1}{i\omega C_t} + R} + i\omega C_m.$$

C_t determines the resonance of the LCR antenna–you adjust this for maximum response to the ω that the transmitter puts out in its pulses. You adjust C_m so that the conductance is to be pure real and equal $\frac{1}{50}$ Mho. Rationalizing the denominator, you'll find

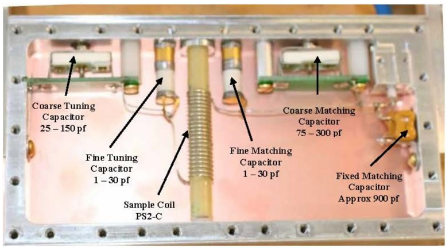

Figure 2: Inside the actual probe.

that the real part yields

$$50 = \frac{R^2 + \omega^2(L - \frac{1}{\omega^2 C_t})^2}{R}$$

or

$$C_t = \frac{1}{\omega^2 L - \omega\sqrt{50R - R^2}}$$

The vanishing imaginary part implies

$$-\omega L + \frac{1}{\omega C_t} + \omega C_m \Big[R^2 + \Big(\omega L - \frac{1}{\omega C_t}\Big)^2\Big] = 0$$

or

$$C_m = \frac{L - \frac{1}{\omega^2 C_t}}{R^2 + \Big(L - \frac{1}{\omega^2 C_t}\Big)^2},$$

and substituting for C_t yields

$$C_m = \frac{1}{\omega}\frac{\sqrt{50R - R^2}}{50R}.$$

Tuning

Of course, you don't expect to find the probe pre-matched and tuned. Suppose that the impedance is actually $50\Omega + \Delta + i\delta$. Then in principle you have to tune the two capacitances to cancel both the real and imaginary deviations from 50Ω. You can see from the expressions for the matched capacitances that these adjustments are not entirely independent of each other.

You observe the response of the NMR probe by inserting a tool–just two loops of wire on a stick–into the sample space and observing the voltage the RF induces across the loops with an oscilloscope. By Faraday's Law,

$$V = -\frac{d\Phi_B}{dt} = -A\frac{dB}{dt},$$

where A is the total area of the two loops, and B is the size of the magnetic field threading them. Here is a typical trace for a pulse with the probe circuit tuned to the RF pulse.

Note that, though the pulse coming out of the RF pulse generator is rectangular, what the loop tool (and your sample) see are a charging curve (after the RF turns on) followed by a ringdown (after the RF shuts off).

Figure 3: What the sample sees.

You tune the capacitances by using the special non-ferrous screwdriver on the adjustment screws on the top of the probe housing:

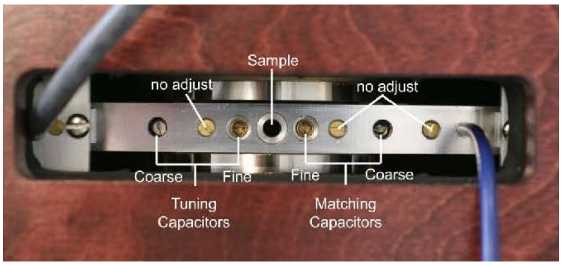

Figure 4: The adjustment screws.

Sometimes it is enough to roughly tune just the probe frequency–that is, just C_t–and let C_m go where it will. To do this, connect the loop probe to the oscilloscope. If C_t is very far away from what it ought to be (Figure 4), you will see a beat response decaying to the drive at a lower amplitude as the RF transmitter tries to drive the slightly damped circuit at a frequency which is very different from the antenna's tuning. When C_t at about the RF frequency, you will see a single-frequency exponential charging/discharging pulse (Figure 5).

On the other hand, you may find yourself needing to tune the matching capacitance as well–for example, if you want to maximize the effective RF applied to the sample. The finer process for simultaneous tuning and matching is described in the manual. The basic idea is that you are making a reflectometer which is nulled when the impedance of the probe is matched to 50Ω with zero phase. Begin by turning off both A and B pulses, and

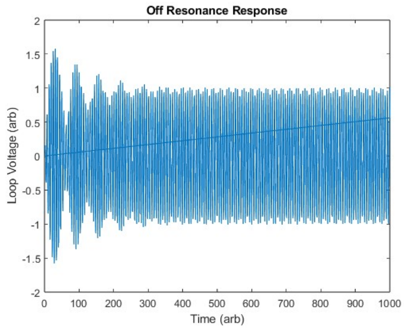

Figure 5: A simulation of probe response off-resonance. The voltage is a decaying oscillation at the natural frequency $\approx \sqrt{\frac{1}{LC_{t,u}}}$ combined with a smaller oscillation at the drive frequency of the RF generator. The result is beats, discharging to a smaller $t \to \infty$ amplitude at the off resonance drive frequency.

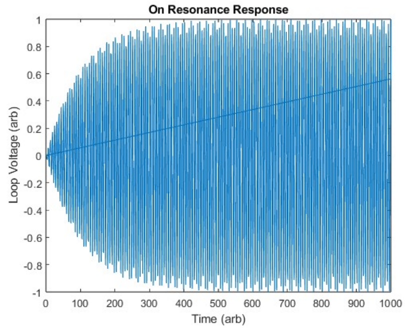

Figure 6: A simulation of on-resonance probe response. The voltage is the difference between a decaying oscillation at the (tuned) natural frequency $\approx \sqrt{\frac{1}{LC_t}}$ and a comparable amplitude oscillation at the drive frequency of the RF generator, which is now *also* at the natural frequency. There are no beats, and the amplitude is a charging exponential.

connect the CW OUT from the synthesizer module to the CW IN on the receiver and turn the CW toggle ON. Remove the BNC cable from the Pulsed Power In connector. Then grab an XY-mode capable oscilloscope, and follow the procedure on page III-20 of the Teachspin manual. The process can be tedious, but it is simple enough–you are adjusting the set screws on both tuning and matching capacitors iteratively until the reflection of the input CW from the sample probe is nulled.