RLC Analysis with the MSA
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I. Introduction

RLC analysis provides information about parallel or series RLC (resistor, inductor, capacitor) combinations. These might be three explicit components, but in many cases one or two of the RLC components is parasitic. Essentially, RLC Analysis assumes that a circuit can be modeled as either a parallel or series RLC combination, and determines the component values that best fit the data for the circuit.

One basic use for RLC analysis is simply the measurement of capacitor or inductor values. It is often noted that inductor values change significantly over frequency. That can in fact be the case, but much of the apparent change results from parasitic capacitance. The supposed inductor is not in fact an isolated inductor; it is an inductor in parallel with a capacitor. RLC analysis can identify the inductive and capacitive components. This helps explain how the "inductor" will actually behave in a circuit. The same situation exists for capacitors, which have an effective series capacitance arising in part from their leads, if they have leads. Even SMT capacitors can have effective series inductance, arising in part from the height of the capacitor. If you want to fully understand how the "capacitor" will act in a circuit, you have to understand that it is not in fact a capacitor; it is a capacitor in series with an inductor.

Another prominent use for RLC analysis is the measurement of an inductor and its internal resistance, from which we can calculate the inductor Q. To do this, a high-Q capacitor is added in series or in parallel with the inductor to create resonance at or near the frequency of interest; the exact value of the capacitor need not be known. If the inductor Q is not extremely high, the Q_U of the resonant circuit will closely approximate the inductor Q. If inductor Q is high enough that the Q_U of the resonant circuit is significantly affected by the Q of the capacitor, then inductor Q_L can be calculated from circuit Q_{Res} by removing the effect of capacitor Q_C, with the formula $Q_L=Q_C*Q_{Res}/(Q_C -Q_{Res})$. This same process could be used to determine the Q of a capacitor, though getting good accuracy would depend on resonating the capacitor with an inductor whose Q is at least a significant proportion of that of the capacitor.

This document discusses RLC Analysis as performed by the MSA. One form of analysis is performed in Transmission mode, based on locating the frequency of resonance and the "3 dB points". That analysis requires minimal calibration and does not require phase information, so it can actually be performed in scalar transmission mode. RLC analysis can also be performed in Reflection mode, which requires a bit more calibration but provides higher precision and more information.

This document is divided into four parts, some of which may provide more background information than the reader cares for. It is possible to skip ahead to the section of interest. The sections are

1. This Introduction—Some background and equations. Note that the MSA does all calculations automatically, so the equations are just for reference.

2. —Determining RLC values using Transmission mode scans, based on determining resonant frequency, bandwidth and Q.

3. —Determining RCL values using Reflection mode scans. Two methods are presented, one using impedance measurements at two frequencies and the doing a continuous analysis at all frequencies based on the Slope method.

4. —Example using a parallel coil and capacitor.

Parasitic Models

As mentioned, one use of RLC Analysis is to determine parasitics in components. Figure 1 illustrates simple models of a capacitor, inductor and resistor, each with its parasitic elements.
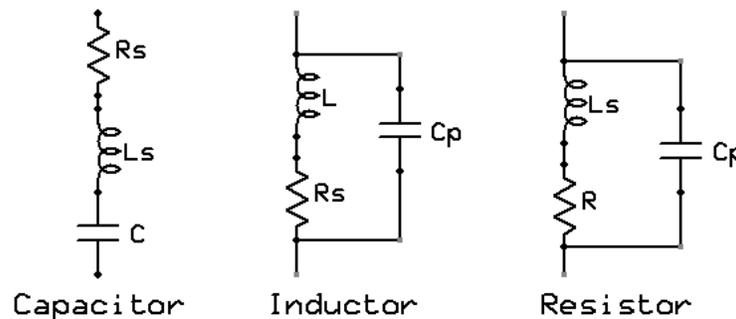

Figure 1—RLC Parasitics

The simple model of a capacitor shows series resistance and inductance along with the capacitance. A capacitor can also be modeled as having a parallel resistance, representing its dielectric loss. Typically, the losses in a capacitor are small enough that over a modest frequency range the series model is adequate.

The inductor model shows resistance in series with the inductor, and capacitance in parallel with the entire package. The series resistance of inductors can be significant, and the parallel capacitance can also be significant if the inductor has many windings, especially if they overlap. The resistor model is identical to the inductor model. The difference is that the series inductance in a resistor is typically small compared to the resistance, and the parallel capacitance is also typically small.

The important fact is that the models of all three components involve an R, L and C. In the case of the capacitor, they are all in series, and form a series RLC circuit. In the other two cases, the L and C are in parallel but the resistance is not. Nevertheless, at any given frequency, the model with a series resistance is equivalent to one with a parallel resistance, so the inductor and resistor can be analyzed at their resonant frequencies as parallel RLC circuits. Figure 2 shows the actual series and parallel RLC models we will use.
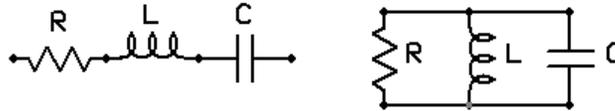
**Figure 2—Actual series and parallel models used in RLC analysis.
The user chooses which model to use.**

Q

Inductors, capacitors and circuits containing them are sometimes judged by the "quality factor" called Q. Inductors and capacitors store energy, and resistors dissipate energy. The formal definition of Q is based on the amount of energy stored compared to the energy dissipated:

$$Q = 2\pi \; \frac{Max\_Energy\_Stored}{Energy\_Dissipated\_per\_Period}$$

This is not a handy definition for actually calculating Q, but it explains the essence of Q. This definition applies to any circuit at any frequency. For calculation, it is handier to use these formulas, where X_L is the reactance of an inductor and X_C is the reactance of a capacitor:

Series RL : Q= X_L/R   Parallel RL : Q=R/ X_L

Series RC : Q= $|X_C|$ /R   Parallel RC : Q= R/ $|X_C|$

Equation 1—Q formulas for Resistance Combined with Inductance or Capacitance

For parallel or series LC circuits, at resonance the Q of the circuit is a combination of the Qs of the components:

$$1/Q_{Res} = 1/Q_L + 1/Q_C$$

Equation 2—Combining Inductor and Capacitor Q values

For unloaded RLC circuits, in this paper we treat R as including all the internal resistance, and treat that resistance as belonging to L, so the Q_U of the unloaded circuit is the same as the inductor Q from the above formulas. If the RLC circuit is connected to a source and load, and we want the Q_L (which here means loaded Q, not inductor Q) of the loaded circuit, then the R has to include the net of the internal resistance and that of the source and load. Another useful formula in the case of resonant RLC circuits is:

$$\text{Series RLC}: Q = \frac{1}{R}\sqrt{\frac{L}{C}} \qquad \text{Parallel RLC}: Q = R\sqrt{\frac{C}{L}}$$

Equation 3—Q of RLC Circuits at Resonance

II. RLC Analysis in Transmission Mode

In Transmission mode, we will send a test signal to the device under test (DUT) and measure the transmitted response. There are several ways the transmission can occur. The DUT can be in series (series fixture), or can be shunt to ground (shunt fixture). Typically, attenuators are included on each side of the DUT to make sure a precise resistance (R_0) is presented to the DUT on each side. Even if R_0 is 50 ohms, attenuators are used to improve the often not-so-good return loss of the Tx (output) and Rx (input) ports of the VNA.

Series RLC
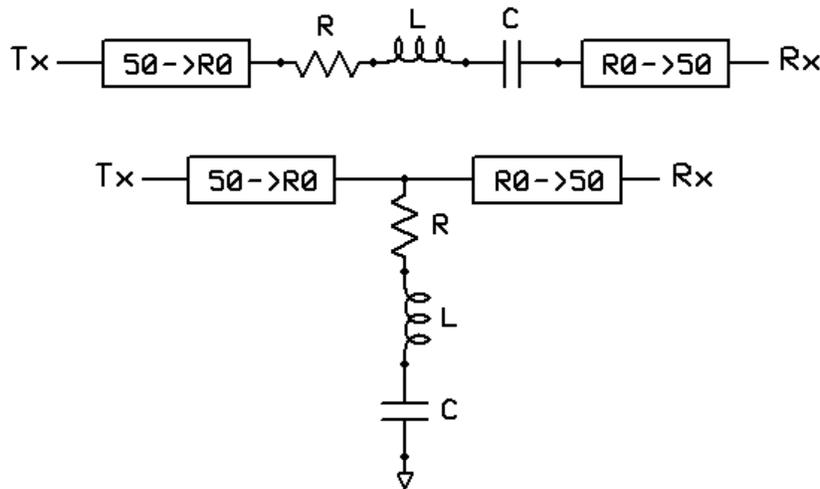Figure 3 illustrates a series RLC device in both types of fixtures.

Figure 3—Series RLC device in series (top) and shunt fixtures.
The attenuators on each side present resistance of R_0 to the device.

The series RLC device will produce low impedance at resonance, equal to its series resistance, R. This means that in a series fixture it will produce a maximum response at resonance, creating a peaked response. In a shunt fixture it will produce a minimum response at resonance, creating a notched response. Note that when the device resonates, it must push current back and forth through the R_0 resistances. This means the load on the resonant circuit is $R+2*R_0$ for the series fixture (current must be pushed through both at once) and is $R+R_0/2$ for the shunt fixture (current is pushed through one or the other; they act in parallel). The loaded Q_L of the RLC circuit, which is the reactance at resonance (Xres) of L, divided by the total resistance, is therefore:

$$Series\_Q_L = \frac{X_{res}}{R + 2 * R_0} \qquad Shunt\_Q_L = \frac{X_{res}}{R + R_0/2}$$

Equation 4—Q_L of series RLC device in series and shunt fixture

(In the introduction we used Q_L to refer to the Q of the inductor. In Equation 4 and hereafter, Q_L refers to the loaded Q of the RLC device in the fixture.) Note that a large R_0, which is often thought of as a light load on the resonant circuit, is actually a heavy load for a series RLC circuit, and produces lower Q_L.

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Parallel RLC

Figure 4 shows a parallel RLC device in each type of fixture:
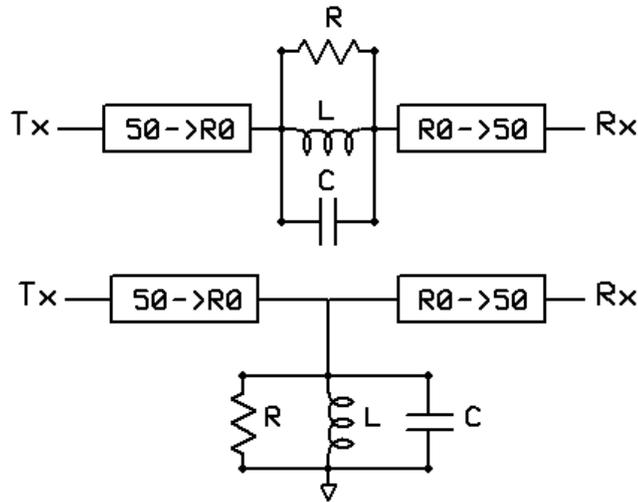

Figure 4—Parallel RLC device in series (top) and shunt fixtures.
The attenuators on each side present resistance of R_0 to the device.

The parallel RLC device will produce maximum impedance at resonance, equal to its parallel resistance, R. This means that in a series fixture it will produce a minimum response at resonance, creating a notched response. In a shunt fixture it will produce a maximum response at resonance, creating a peaked response. Note that when the device resonates, it must push current back and forth between L and C, and some of that current will be drained by R and the two R_0 resistances. This means the load on the resonant circuit is $R\|2*R_0$ (meaning R in parallel with $2*R$) for the series fixture (current can be drained from LC through either R or the two R_0 resistance, and any current through one R0 must also pass through the second) and is $R\|(R_0/2)$ for the shunt fixture (current is drained through R or through either R0; they all act in parallel). The loaded Q_L of the RLC circuit, which is the total resistance divided by the reactance at resonance (Xres) of L, is therefore:

$$Series\_Q_L = \frac{R\|(2*R_0)}{X_{res}} \qquad Shunt\_Q_L = \frac{R\|(R_0/2)}{X_{res}}$$

Equation 5—Q_L of parallel RLC device in series and shunt fixture

Determining Q_L from Bandwidth

The equations for loaded Q (Q_L) are useful because we have a simple means to determine Q_L graphically. If we locate the frequency of resonance and the two "-3 dB points", we calculate Q_L as follows:

$$Q_L = \frac{F_{res}}{BW_{3dB}}$$

Equation 6—Determining QL from resonant frequency and bandwidth between the -3 dB points

One point needs clarification. When calculating Q_L from Equation 6, we need to find the "-3 dB points". These are always the frequencies where the response falls to 3 dB below the maximum

(that is, the half-power points). For a peak response, this means they are 3 dB below the top of the peak. For a notch response, it means they are at the absolute -3 dB level. For a notch, it is tempting to look at the points that are 3 dB above the notch bottom. We will see later that these points can be utilized to calculate R, L and C, but they are not the points that determine Q_L and therefore they require a different formula.

Procedure for Determining RLC values from Q
At this point, we can determine R, L and C in the following manner, which the MSA does automatically:

1. Find the resonant frequency (F_{res}) and the bandwidth between the 3 dB points (BW_{3dB}).
2. Use Equation 6 to calculate Q_L.
3. Plug Q_L into either Equation 4 or Equation 5, to get a relationship between R and X_{res}.
4. Measure R directly at F_{res}. This is relatively easy, because the net reactance at resonance is zero (for series RLC) or infinite (for parallel RLC). (Remember, Xres is the reactance of L at resonance, not the net reactance of L and C combined.) This means that at resonance the only thing we are measuring is R. We don't even need phase information to make this measurement.
5. Use the R value from (4) to find X_{res} from the relationship in (3).
6. Calculate $L=X_{res}/2\pi F_{res}$ and $C=1/[L*(2\pi F_{res})^2]$

There is one other very important relationship that can simplify our job. The resonant frequency is the geometric mean of the two -3 dB frequencies, so long as R is significantly smaller (for series RLC) or larger (for parallel RLC) than the reactance of L or C at resonance. Typically, if the unloaded Q_u exceeds 5, this geometric mean formula is reasonably accurate.

Examples: Self-Resonant Capacitors As RLC Circuits
Consider Figure 5, which shows a scan of a 0.1 uF capacitor, which has been analyzed using RLC analysis in a shunt fixture.

Figure 5—0.1 uF capacitor, measured as 98.5 nF
The displayed Q is Q_L and equals 0.01468

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The capacitor in Figure 5 is resonating with the series inductance of its leads, plus its internal inductance. The resonant frequency is the notch at the P- marker. The upper (high frequency) -3 dB point is at marker R. The lower -3 dB point is off the left end of the graph, but can be determined as the square of the resonant frequency divided by the upper -3 dB frequency; this makes the resonant frequency the geometric mean of the two -3 dB frequencies. Using that information, RLC analysis calculates and displays various information, which has been copied and pasted into the title of Figure 5. Most importantly, the 100 nF capacitance was fairly accurately measured as 98 nF. The series inductance is 13 nH and the series resistance is 0.08 ohms. This capacitor had short leads, but it doesn't take much to create inductance of 13 nH.

Other capacitors were measured by the same means, typically with accuracy better than 2% until we reach capacitors that are low enough for parasitics in the fixture to affect accuracy. A 119 pF capacitor was measured with 4% error, and Figure 6 shows the results of measurement of a 10 pF capacitor:
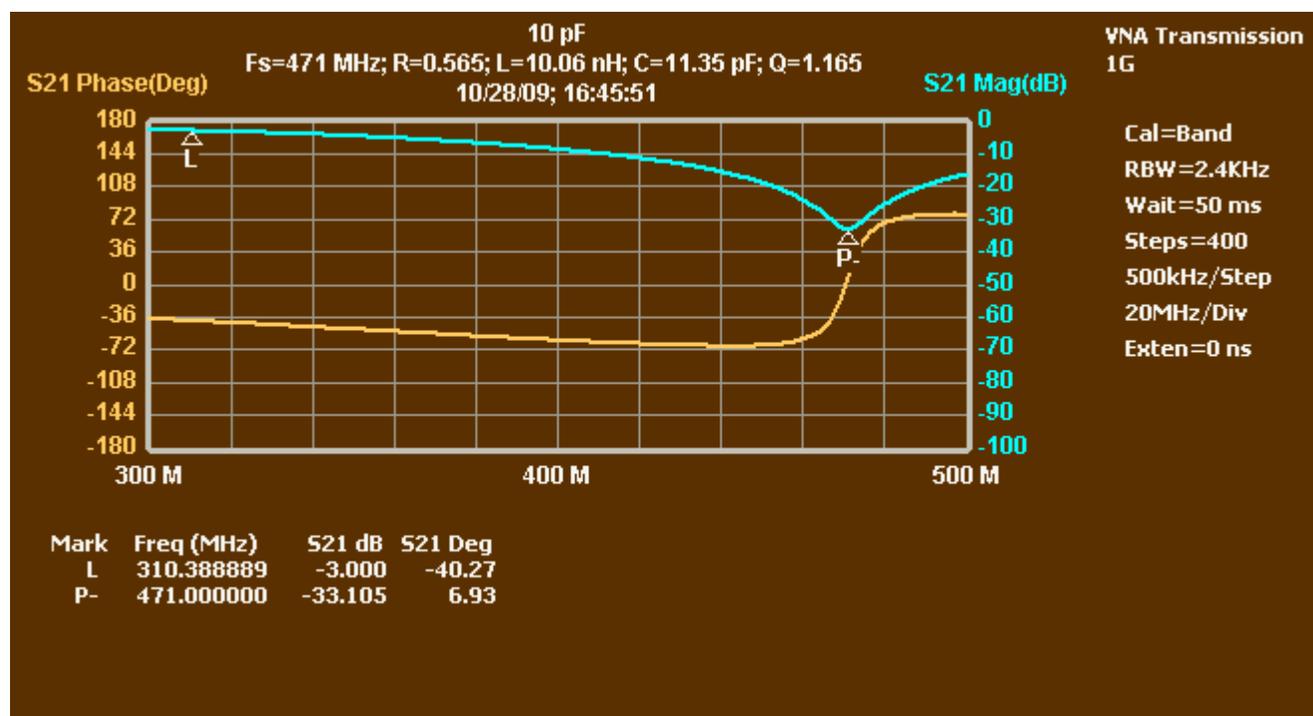

Figure 6—10 pF capacitor, measured as 11.4 pF

The measurement of Figure 6 is still quite good, considering it is made at very high frequency, and the fact that even small parasitics in the test fixture could skew the results with such a small capacitor being measured. Higher accuracy could be obtained in Reflection mode (discussed later), where OSL calibration could remove these error factors.

Use of Bottom 3 dB Points for Notch Responses
Note that in Figure 6, the L marker, which is at -3 dB, is very far from the point of resonance, and the right -3 dB point is far off the right side of the graph. It would be nice if we could use points that are 3 dB from the bottom of the notch, because they would be fairly close together. Those "bottom 3 dB points" can in fact be used, even though they are not the points that establish the 3 dB bandwidth for purposes of determining Q_L of the circuit. It turns out that for a deep notch, roughly 20 dB or more, the bandwidth between the bottom 3 dB points relates to the

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Q_U of the RLC combination. We can therefore determine Q_U and proceed in a manner somewhat similar to that described above for using Q_L.

Figure 7 shows the results of analyzing a simulated circuit with values close to those of Figure 6, and the results of RLC analysis using the bottom 3 dB points.
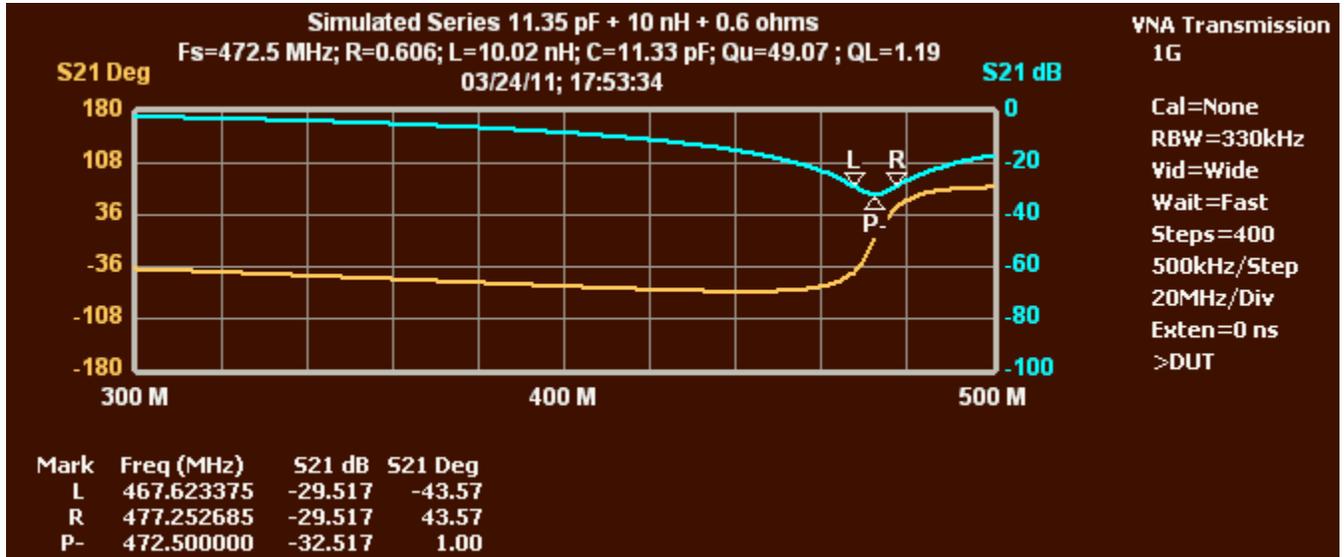

Figure 7—Repeat of Figure 6, using simulated RLC data and the bottom 3 dB points.

Figure 7 shows similar results to Figure 6. But the points used for the analysis are now very close together. This would enable us to zoom in and get higher resolution in the area of resonance. In addition, it is possible that the R, L or C values vary somewhat over frequency (particularly R). In that case, higher accuracy is obtained if the points of analysis are clustered together in a range where their values remain constant. (In this particular case, high accuracy is simply the result of the original graph being generated by simulated data, rather than being measured. Simulated data was used simply to get a graph comparable to Figure 6.)

The RLC Dialog in Transmission Mode
When RLC Analysis is invoked (through the Functions menu) in Transmission mode, the dialog shown in Figure 8 is displayed.
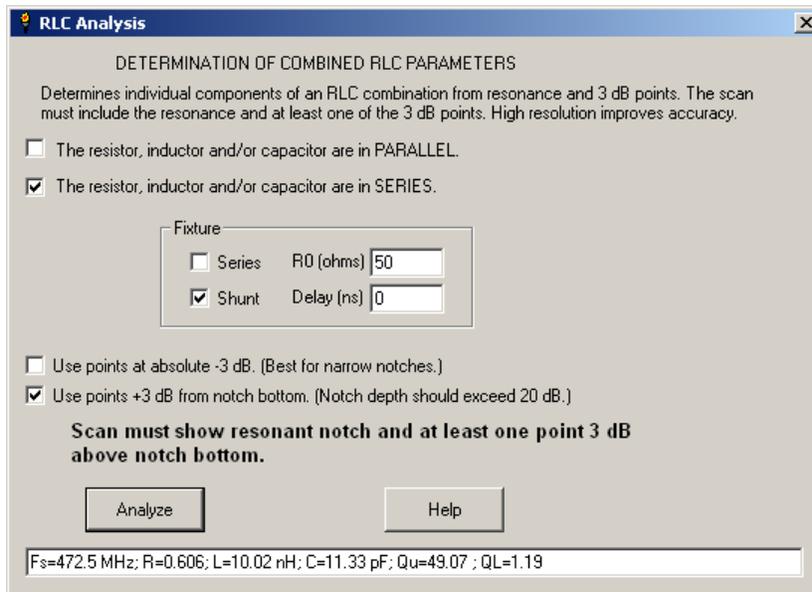
Figure 8—Dialog for RLC Analysis in Transmission Mode
The displayed results are for the data in Figure 7

This dialog allows the user to specify:

1. Whether the RLC circuit is in series or in parallel. If a single component is analyzed, an inductor would be treated as parallel RLC and a capacitor would be treated as series RLC.
2. What type of fixture is used. The fixture is in essence two attenuators with the RLC device sandwiched in between, either in series from one to the other (Series fixture) or shunt to ground between the attenuators (Shunt fixture).
3. R_0 of the fixture, which is the resistance seen by the RLC device on each side.
4. If a shunt fixture, the one-way delay of the connector linking the RLC device to the connection point with the two attenuators. For an SMA connector, with the DUT attached to the back of a mating connector, 0.125 ns may work.
5. For a notch response, which set of 3 dB points to use. Use of the top points makes the most sense for narrow notches that may not be very deep. The bottom points are better for deep notches. Either approach can be used for narrow, deep notches.

When the Analyze button is clicked, the analysis is performed and the results are displayed in the text box at the bottom. It can be selected and copied, the dialog can be closed, and the copied data can be pasted into the title section of the graph.

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III. RLC Analysis in Reflection Mode

A similar analysis can be done in Reflection mode, but a couple of refinements can be made. First, we will have phase information and so will be able to measure complex impedance at any point. (The magic of the resonant frequency in Transmission mode is that we can assume the impedance to be a pure resistance. No need to do so in Reflection mode.) Second, we can make use of OSL calibration to remove the effects of parasitics in our test fixture. We can still put our RLC devices in either series or shunt fixtures. Or, we can attach them, grounded, to a reflection bridge.

Higher precision is possible in Reflection mode than in Transmission mode, as long as we understand the limitations of our test fixtures. Shunt fixtures are optimal for measuring impedances below $R_0/2$, where R_0 is the impedance presented by the fixture on each side of the DUT. Series fixtures are optimal for impedances above $2*R_0$. The reflection bridge is optimal for mid-range frequencies, perhaps $R_0/10$ to R_0*10. Most commonly, R_0 is 50 ohms, but we can easily build fixtures with other R_0 values—for the series and shunt fixtures that is simply a matter of changing the attenuators on each end of the fixture.

Repeat of a Self-Resonant Capacitor in Reflection Mode
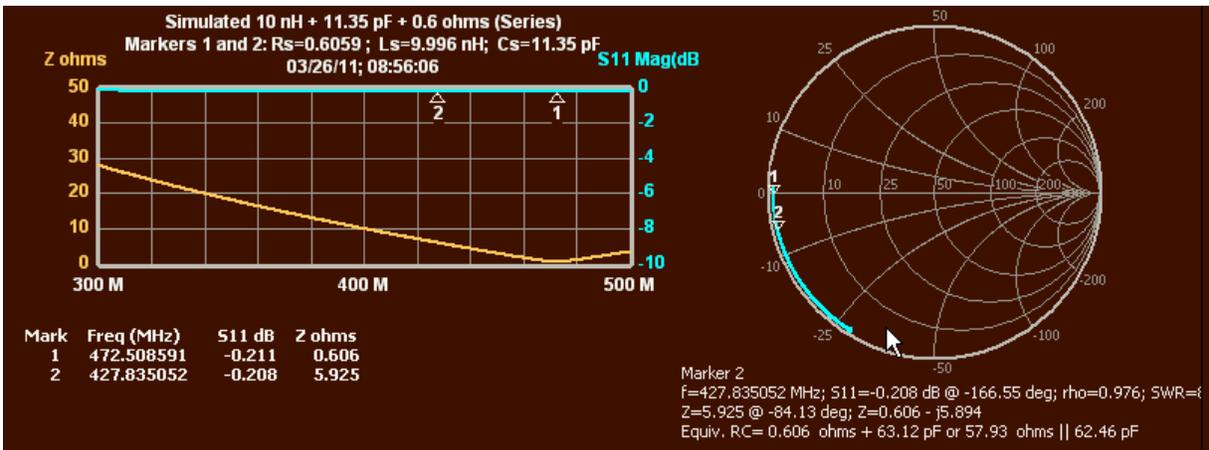Figure 9 shows the same circuit we last analyzed, but this time in Reflection mode.

Figure 9—Same circuit as Figures 6 and 7, in Reflection Mode
RLC values in second line of title were copied from analysis results.

The left axis shows impedance magnitude, rather than the usual phase. It shows that, while the magnitude of S11 barely changes, the magnitude of the impedance changes significantly, and bottoms out at resonance. The Smith chart in Figure 9 shows that the two marked points differ primarily in their angles, with point 1 having near-zero reactance and point 2 having -5.89 ohms of reactance.

The RLC values shown in the second line of the title in Figure 9 are very close to the values being simulated, as one would expect. In actual operation, there would be measurement errors, and it is important to use a fixture that minimizes those errors. Measurement of these low impedance values would best be done with a shunt fixture. A 50-ohm shunt fixture would be fine, though if there was a need to maintain a relatively high output level, a fixture with lower R_0 could be used. A 50-ohm reflection bridge would do a decent job of measuring the overall

magnitude of a 6 ohm impedance, but might not do well at accurately identifying the small 0.6 ohm resistive component.

Parallel RLC Circuits with Low and High Q
So far we have focused on series RLC circuits. Figure 10 shows Reflection mode RLC Analysis of a parallel RLC circuit. Actually, it is simulated data for a parallel LC circuit with the inductor having Q of 10 (meaning the inductor has significant series resistance), and the capacitor with very high Q. This makes it not truly a parallel RLC circuit, but we will model it as such and see how it turns out.
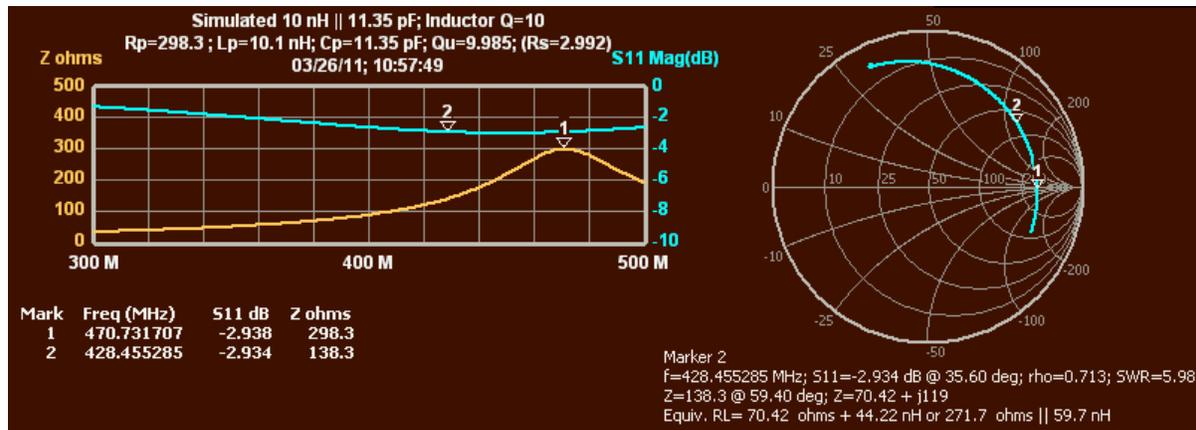

Figure 10—10 nH parallel to 11.35 pF, Inductor Q=10

The analysis is performed from the measured impedances at two points marked by the user, typically in the area of resonance. The analysis results pasted into the second line of the titles show R_P =298, L_P=0.1 nH and C_P=11.35 pF. Note that in parentheses is shown R_S=2.992. This is the resistance in series with the inductor that would provide the same Q_U value as the parallel resistance (298) in the RLC model. This lets us analyze the circuit as a parallel RLC circuit even though we know the model does not quite fit, and derive the R_S value that fits the real world circuit. This conversion of R_P into equivalent R_S works as long as $1/Q^2$ is small, so it is a good approximation unless Q is very poor. Note the small error in the determined L value (10.1 nH vs. 10 nH). That error is due to the use of a parallel RLC model that does not quite fit the actual simulated circuit. For Q_U of 10 or better, this error is small and the parallel RLC model works well. There is also some error due to the fact that the simulated data uses a fixed inductor Q of 10, meaning that the R_S value actually increases with frequency and is not constant as assumed in the RLC model. But the error from that source is small if the marker frequencies are not too far apart.

The impedances at the markers in Figure 10 are in the range that could be well-measured with a 50-ohm reflection bridge. But if the inductor had a Q value much higher than 10, the impedances would become much larger and it would be more accurate to use a series fixture. Figure 11 shows another parallel LC combination, but with inductor Q of 200:
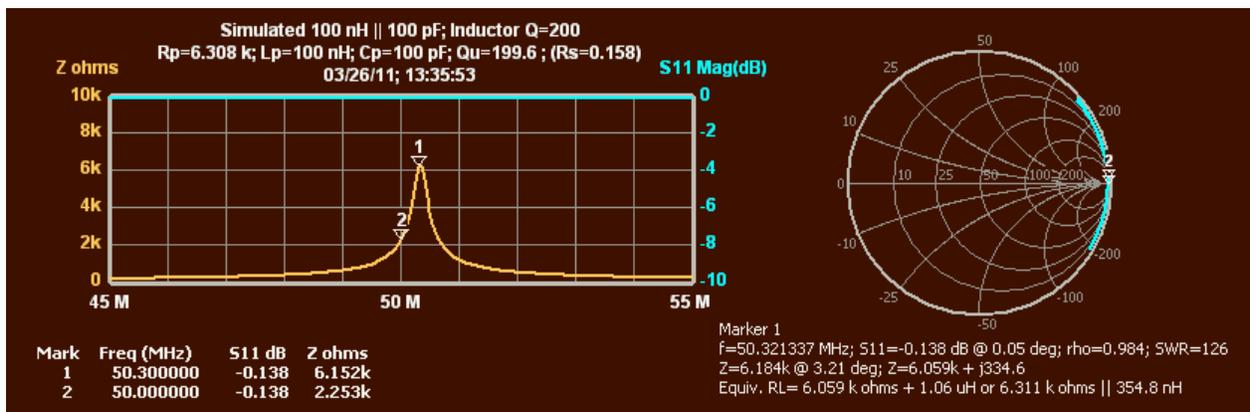
Figure 11—100 nH || 100 pF with Inductor Q=200
Larger component values were used to be more realistic with high Q.

Mathematically, the simulated values were perfectly recreated. (The tiny error in Q_U is due to the fact that the capacitor did not have infinite Q, though it was 100,000.) The inductor has reactance of 31.6 ohms at 50.3 MHz, so the specified Q of 200 indicates series resistance of 0.158 ohms, as the analysis found. This means the ultimate accuracy depends only on the accuracy of S_{11} measurements at the marker points. The impedances involved in Figure 11 would require a series fixture for accurate measurement.

Why the Series Fixture is Better for High Impedances
There is a simple way to visualize why the series fixture will be better at measuring high impedances. Starting with the graph in Figure 11, we can use Functions→Generate S21 to create a graph showing the S_{21} values that are produced by the impedances shown in the graph, in either a shunt or series fixture. Figure 12 shows the result of doing so for each fixture type.
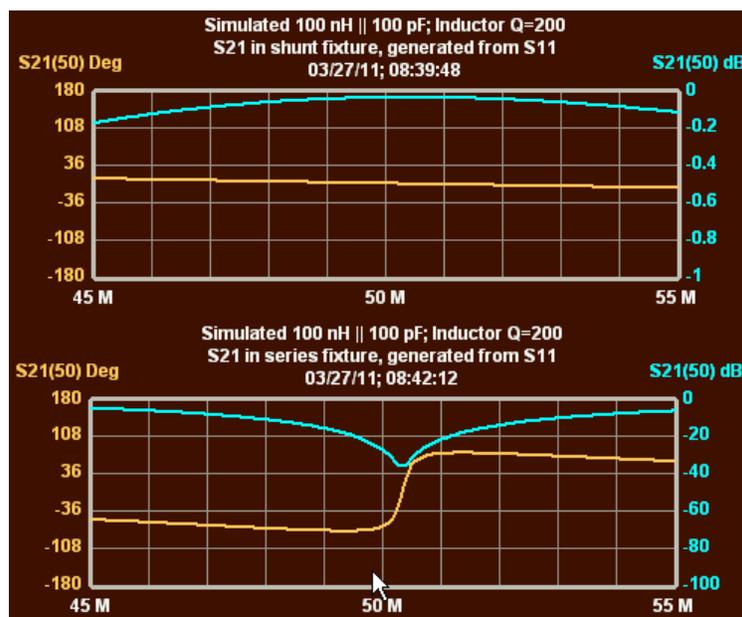

Figure 12—S21 Values in Series (top) and Shunt Fixtures

When we use a series or shunt fixture in reflection mode, the MSA is actually measuring the S_{21} of the fixture, and then computing S_{11}. The top half of Figure 12 shows what the MSA is measuring in a shunt fixture. Blue is magnitude, orange is phase. It can be seen that in the area

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around 50 MHz, where the impedance in Figure 11 makes a dramatic move, S_{21} magnitude is almost constant, and the phase changes slowly. This means that small changes in S_{21}, which could result from measurement errors, translate into huge changes in impedance. The bottom half of Figure 12 shows S_{21} in a series fixture. In the area near 50 MHz where impedance makes a big move, S_{21} magnitude and phase also make big moves. Errors in measuring S_{21} therefore translate into relatively small errors in the calculated impedance.

The Reflection Mode RLC Dialog
Figure 13 shows the dialog window that opens when Functions→RLC Dialog is invoked in Reflection mode.
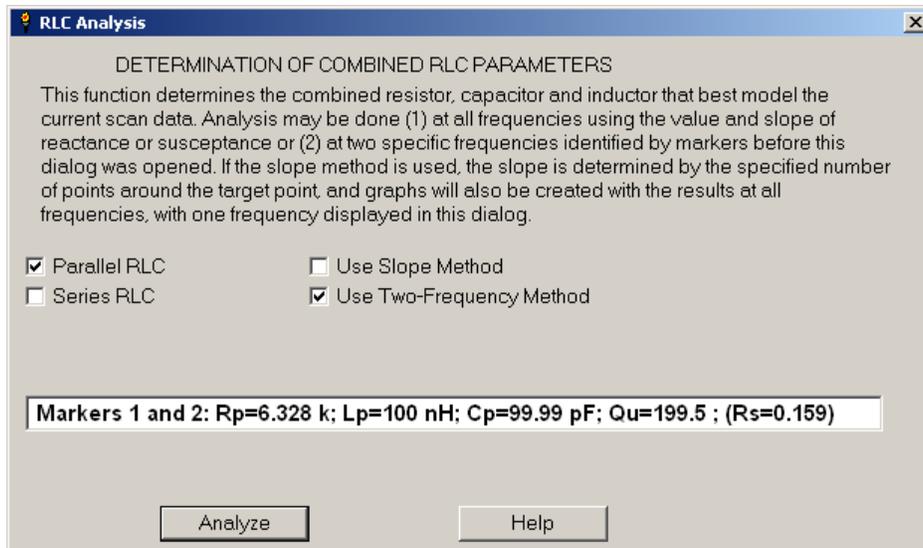

Figure 13—The Dialog for RLC Analysis in Reflection Mode

For the analyses we have been discussing, the user marks two points to be used for the analysis (with any markers), opens the dialog, indicates whether the series or parallel RLC model is to be used, and clicks Analyze. The results are displayed in the text box, from which they can be copied and pasted into the graph title. There is an alternative method that may be used, which will calculate all the values for all frequencies and create graphs to show the results.

The alternative method is invoked by selecting "Use Slope Method", which causes the dialog to look like this:
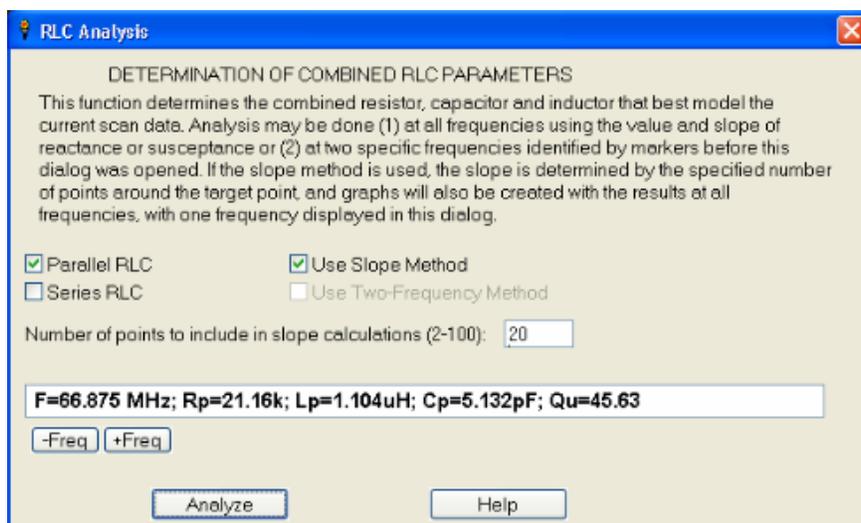
Figure 14—Dialog when Slope Method is Selected
(This and Figure 13 were also produced with different versions of Windows)

The slope method analyzes each frequency using the impedance value and the slope of susceptance or reactance, with a formula that we will not go into here. The important point is that a slope must be determined. If it is determined using two points that are close together, noise or measurement errors can make the slope extremely erratic. Therefore, it is determined by analyzing an interval of several points around the frequency being analyzed. The user chooses the number of points. A large number is good where the slope is relatively constant, as it is near resonance or far from resonance. A small number adapts better to rapid changes in slope. Generally, it is best to use the smallest number that does not produce an erratic graph.

When Analyze is clicked, the graphs are created and results are displayed in the text box for a particular frequency—the resonant frequency is shown if it is included in the data. In Figure 14, the calculated R, L, C and Q_U values are displayed at the resonant frequency. Results can be shown for other frequencies by using the –Freq and +Freq buttons. At the same time, special graphs are created to show the L, C and Q_U values. No special graph is created for R, which can always be viewed with the normal Series R or Parallel R graph selection available by double-clicking just outside a Y axis. Examples of these graphs will be shown below.

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IV. Example of RLC Analysis of an Actual Inductor
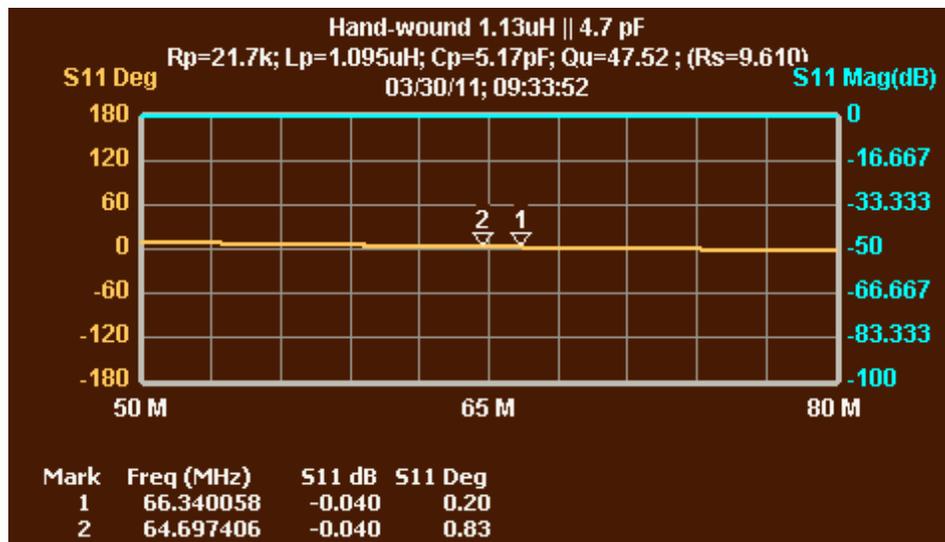## in Transmission and Reflection Modes

We will now look at the results of an actual 1.13 uH inductor hand-wound with number 22 wire on a T-68-6 core, in parallel with a 4.7 pF capacitor. The component values are based on measurement on an AADE meter. This was tested in Transmission mode in a Series fixture, with the following results:

> Hand-wound 1.13uH || 4.7 pF
> R=21.84 kohms; L=1.133 uH; C=5.032 pF;
> Qu=46.02 ; QL=4.746 ; (Rs=10.31)

Figure 15--Transmission Mode RLC Results
(Unfortunately, the rest of the image got ruined.)

The inductance measurement agrees closely with the AADE meter. The capacitance is a bit higher than the meter showed, which is the result of the parasitic capacitance of the inductor. Q_U of 46 might seem a bit low for a hand-wound inductor, but this toroid material is specified for use only to 50 MHz. In addition, the capacitor may be reducing the Q. I did not use an especially high Q capacitor because I was not trying to find the true Q of the inductor, but rather simply to show an example of RLC analysis. For present purposes, we will assume the circuit Q is due entirely to losses in the inductor.

This parallel circuit was then tested in Reflection mode, still using the Series fixture. Figure 16 show the S11 scan and the results using the two-frequency method for RLC analysis.

Hand-wound 1.13uH || 4.7 pF
Rp=21.7k; Lp=1.095uH; Cp=5.17pF; Qu=47.52 ; (Rs=9.610)
03/30/11; 09:33:52

Mark	Freq (MHz)	S11 dB	S11 Deg
1	66.340058	-0.040	0.20
2	64.697406	-0.040	0.83

Figure 16--Reflection mode scan, showing results of RLC Analysis
The two-frequency method was used, at markers 1 and 2

The graph of S_{11} magnitude in Figure 16 is rather boring, as the impedances of the parallel RLC circuit are very high in the area of resonance, forcing S_{11} magnitude near zero. In fact, it is so close to zero that it cannot reliably be measured with a reflection bridge, which is why we used the Series fixture. Marker 1 was placed near resonance, though that was not necessary. The results are very similar to those obtained in Figure 15 from Transmission mode.

The analysis was then repeated using the Slope method, per the dialog shown in Figure 14. That produced the graphs shown in Figure 17.
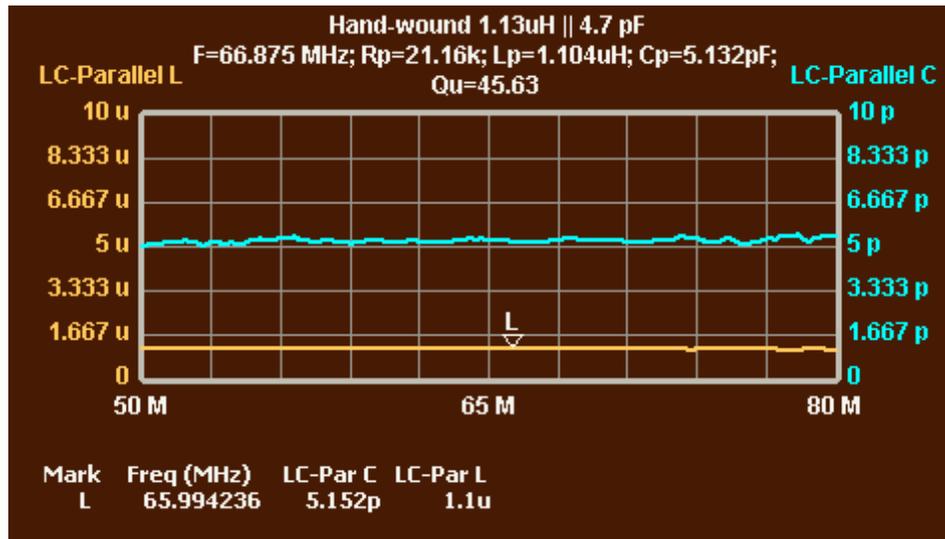

Figure 17—Graphs of L and C values from Slope method
Results from the RLC dialog were copied and pasted into the title.

These graphs are labeled "LC-Parallel L" and "LC-Parallel C" to distinguish them from the normal Parallel L and Parallel C graphs, which are based on RL and RC models, not the RLC model. Note that the graphed L and C values are fairly constant, right through resonance. (Marker L is near resonance.) A normal Parallel L graph would show the inductor having a value of infinity at resonance, because the net (parallel) reactance at resonance is infinite. The LC-Parallel L graph correctly shows that the inductor is still there, with its value almost unchanged, as is the capacitance.

There are two more graphs of interest after doing analysis with the Slope method. They are obtained by double-clicking outside each Y axis and selecting the desired graphs. They are shown in Figure 18.
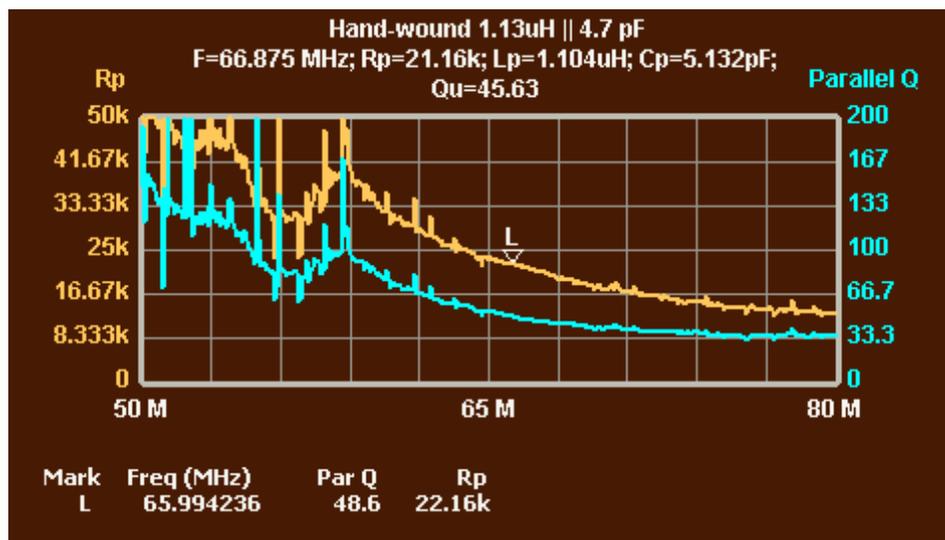

Figure 18—Parallel Resistance and Q_U
Shows that the inductor would provide much better Q at lower frequencies.

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The graph of "Parallel Q" is especially interesting. If we assume our capacitance is low loss, Parallel Q is effectively the inductor Q at each frequency. It shows at each frequency the Q_U value that would be obtained if the inductor were resonated at that frequency with a low-loss capacitor. This pretty much follows the graph of parallel resistance (higher R_P means lower loss and higher Q), although the Q graph is also affected by the inductor's change of reactance over frequency. The Q graph is somewhat erratic at high Q values (after all, Q near the left side of the graph is based on measuring resistances in excess of 20 kOhms in parallel with much smaller inductive reactance—somewhat of a needle in a haystack), but it is clear that the inductor would provide much higher Q at lower frequencies. As noted above, the iron toroid material used for the inductor is specified for use in resonant circuits only up to 50 MHz. (The term "Parallel Q" is merely meant to indicate that this Q was derived from RLC analysis of a parallel circuit. Maybe LC-Q would be a better term.)

Finally, one might ask why we analyzed the inductor in parallel with a capacitor rather than in series. With the series resistance near 10 ohms, which would become the resistance at resonance, the series RLC circuit could easily be analyzed with a reflection bridge. That would probably have worked fine in this case. Adding a series capacitor would have made a hybrid parallel/series circuit, since the inherent parasitic C of the inductor is parallel. This can create an issue in the accuracy of the measurement of the L value; the equivalent of Figure 17 would probably show a tilt in the L and C graphs. However, that would be a minor issue if the series capacitor is significantly larger than the parasitic parallel capacitance of the inductor.