Designing to Avoid Interactive Tune and Load Adjustments

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It can be annoying when tuning a tube amplifier if adjusting the loading control requires that we also re-dip the plate current. This happens when the loading capacitor changes the reactance seen by the final tube, rather than just the resistive part of its load. Setting the output power to a chosen value may require numerous readjustments of both controls.

The plate tuning capacitor is directly across the load seen by the tube, hence it only tunes for resonance. The loading capacitor is seen by the tube through the pi network and the network's phase shift will determine how the plate load impedance changes when the loading control is adjusted. For the loading capacitor to change only the resistive part of the tube load, choose a phase shift value for the pi network that is an odd multiple of 45 degrees. Since a pi network with 45 degrees phase shift will have very low Q, the best choice is a network with 135 degrees phase shift.

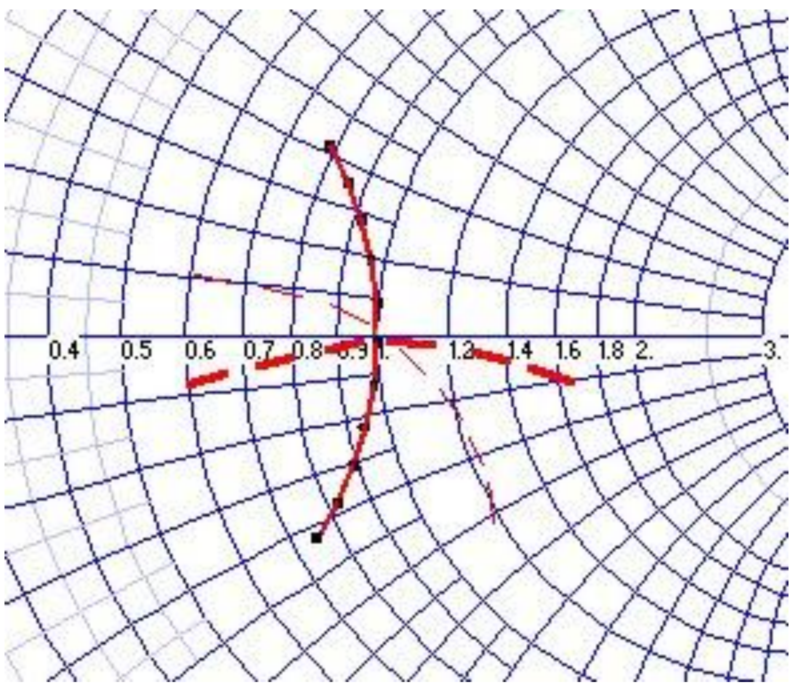

Figure 1 — Effect of plate and load capacitors for various phase shift values through the pi network.

The Smith chart in **Fig. 1** illustrates this effect. The solid line with dots shows the effect of adjusting the plate tuning capacitor. When close to resonance, it does not change the resistive part of the load seen by the tube, but does tune out the reactive part as shown by the fact that it crosses the horizontal resistance axis at a right angle.   When the load is purely resistive at resonance, we get a dip in the plate current.

The thick dashed curve shows what happens when we adjust the loading capacitor with a 135-degree pi network. The resistive part of the tube load changes as shown by the curve moving along the horizontal axis but the resonance is largely unaffected. The thin dashed line shows an example of what happens when we change the load capacitor with a network with a phase shift that is not 135 degrees. Both the resistive part and the reactive part of the tube load change, making it necessary to retune the plate capacitor to resonance.

The phase shift of a pi network is determined by the Q of the network and the impedance transformation ratio. The value of Q that will give us the "magic" 135-degree phase shift will thus depend on the plate load to output impedance ratio. For a 50 Ω load at the output of the pi network, the desired Q value can be determined from the upper curve of **Fig. 2**. Putting this value of Q into the *PI-L* design program will generate the pi network component values desired. For example, for 2500 Ω plate load we see that the desired Q of the tank will be 12.4, a reasonable Q to choose that is close to the commonly used value of 10. Thus, with a slight adjustment of the design Q we can get to a "non interactive loading control" design.

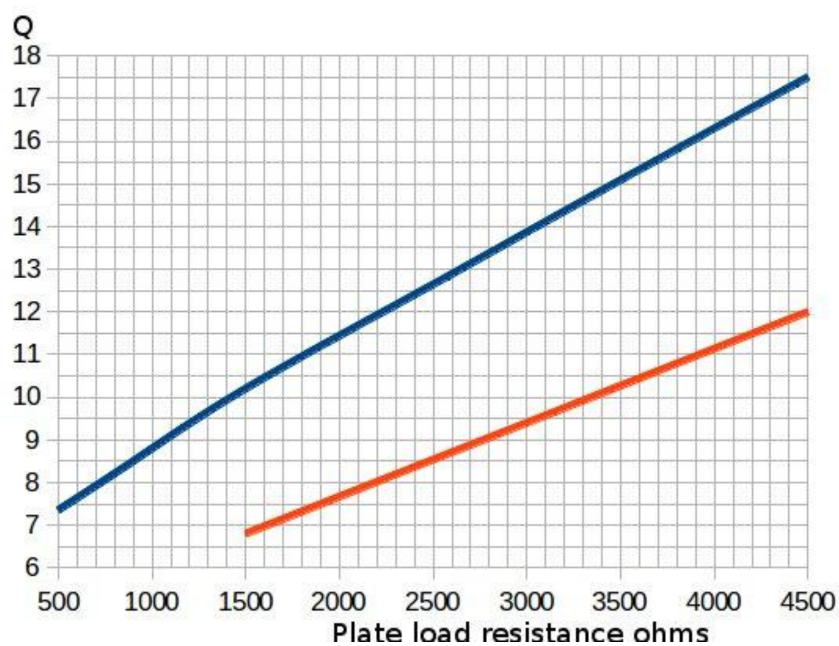

Figure 2 — Pi network Q versus plate load resistance for non-interactive tuning. Use the upper curve for a 50 Ω simple pi network and the lower curve for a pi-L network with a 100 Ω intermediate resistance value.

As we can see on the upper curve of Fig. 2, with very high or low plate load values, the excursion from the normally used Q value of 10 may be excessive and a fully non-interactive tuning solution not practical with the simple pi network. For a plate load of 4000 Ω we see that a Q of 16.4 would be required. This is somewhat high and would lead to excessive losses in the tank. An alternate approach would be to use the pi-L network, and allow the intermediate value to be 100 Ω. The lower curve shows this allows the pi-L network to be designed using a Q value of 11.2, which is more acceptable.

Effect of phase shifts on the interaction of tuning controls

If a phase shift network is used in a circuit, tuning controls can do different things than one might expect. An example of this is the use of 90-degree networks to change an inductor into a capacitor and vice versa. This effect is easily understood by using a Smith chart and rotating the load half way around the chart. For example, a capacitor that has a reactance of -*j*50 ohms, through a quarter-wave piece of 50 Ω coax will show a reactance of +*j*50 ohms. If rotated through a 45-degree (1/8th wavelength) piece of coax it will present a short circuit, and via a 3/8-wave line (135 degrees) will present an open circuit.

This also means that an open circuit rotated 45 degrees will look like a 50 Ω capacitive reactance and a short circuit will look like a 50 Ω inductive reactance. In all these cases we are rotating by measuring the reactance through a length of 50 Ω coax. If 300 Ω transmission line is used, the short will rotate to a 300 Ω inductive reactance, and the open to a 300 Ω capacitive reactance.

Th3 Smith chart display in **Fig. 3** may better illustrate the point. The yellow trace indicates a 50 ohm resistive load with a series LC network that allows us to "tune" the reactive elements between a slightly capacitive net reactance and a slightly inductive one. The trace moves along a line of constant R, but variable X. We then add a 1/8 wavelength of coax, thus rotating the curve 45 degrees. We will have a variable R part of the impedance with a (nearly) constant reactive part. Thus, we have produced a variable resistance by adjusting a variable capacitor. Using a coaxial delay line of 135 degrees would produce a similar result by rotating the red line an additional 180 degrees on the chart, making a smiling curve instead of a frowning one.

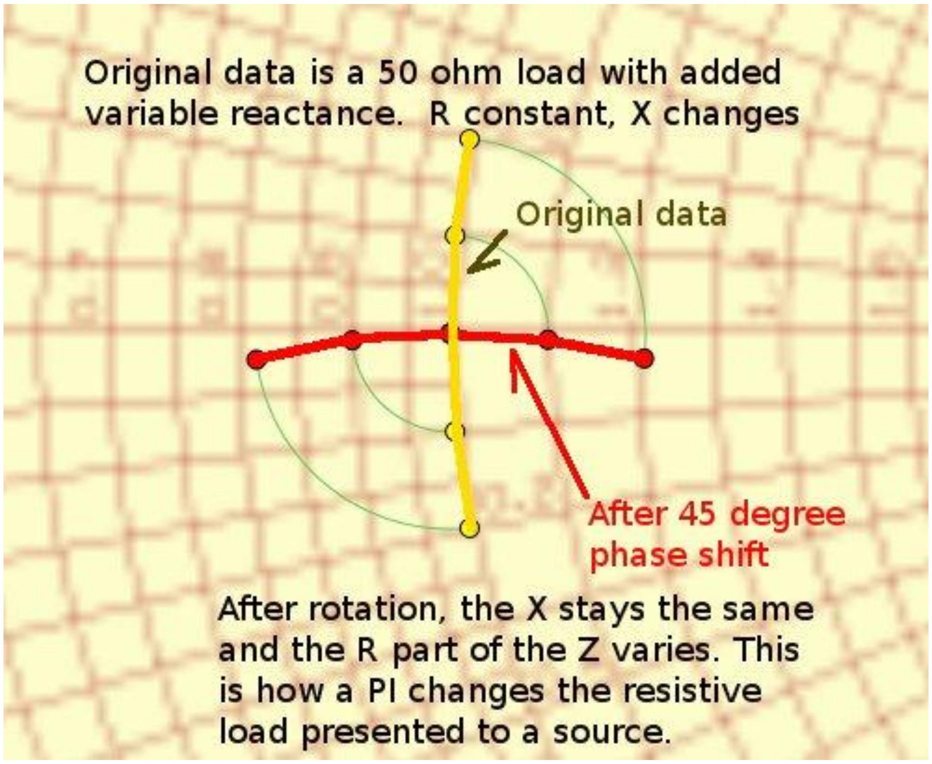

Figure 3 — 45 degree rotation of a tuned load

An analysis of a pi network using the Smith chart display shows that at the plate of the tube, where we want a relatively high purely resistive load for the tube, the plate capacitor will allow us to adjust for resonance as shown here. The tuning line in **Fig. 4** shows various complex impedances as seen by the tube as the plate tuning PLATE or TUNE capacitor is adjusted. At the point where this line crosses the horizontal resistance axis, the load is purely resistive and that resistance is constant as reactance changes. The value of the impedance is shown as 1 as the chart is normalized to the desired value of plate load resistance. As the plate capacitor is adjusted, there will be reactance, either inductive above the horizontal line or capacitive below it. Adjusting for a "dip" puts the plate circuit into resonance; that is, it adjusts for a purely resistive load.

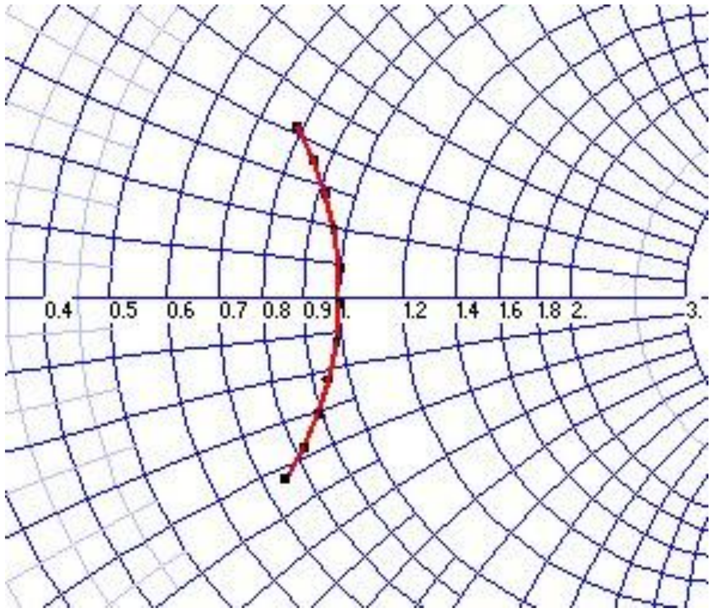

Figure 4 — Effect of plate tuning

At the output of the pi network, the LOAD capacitor is installed. As the capacity across the 50 Ω load changes, we move along a similar curve. In **Fig. 4** the Smith chart is not normalized as we know that the load will be 50 Ω. If we rotate this curve by passing it through a network with 135 degrees of delay, which also transforms its impedance to a higher value as in a pi network, it will appear as shown in the bottom chart.

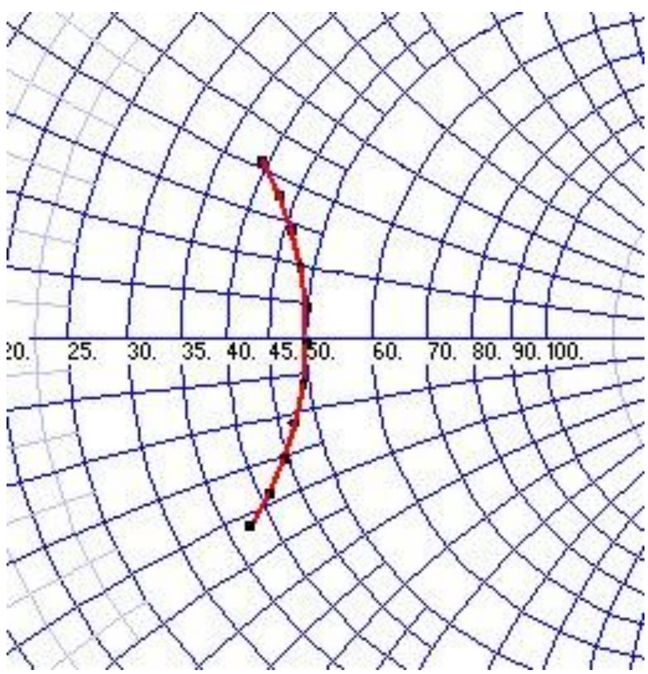

Figure 5 — Effect of plate tuning without normalized impedance

In **Fig. 5**, the solid line shows the effect of tuning the PLATE or TUNE control; the thick dotted line shows the effect of the LOAD control. The thin dotted line shows the effect of the LOAD control when the phase shift is more than 135 degrees. If the phase shift is less than 135 degrees the LOAD control curve would go from bottom left to top right. In either of those cases, the LOAD control would change the load, but also detune from resonance. For the 135-degree case, since the curve travels horizontally, the load changes, but very little detuning takes place. Of course, this is only true for moderate changes in loading. For a drastic change, the loading will cause some change in tuning, but much less than for other than 135-degree cases.

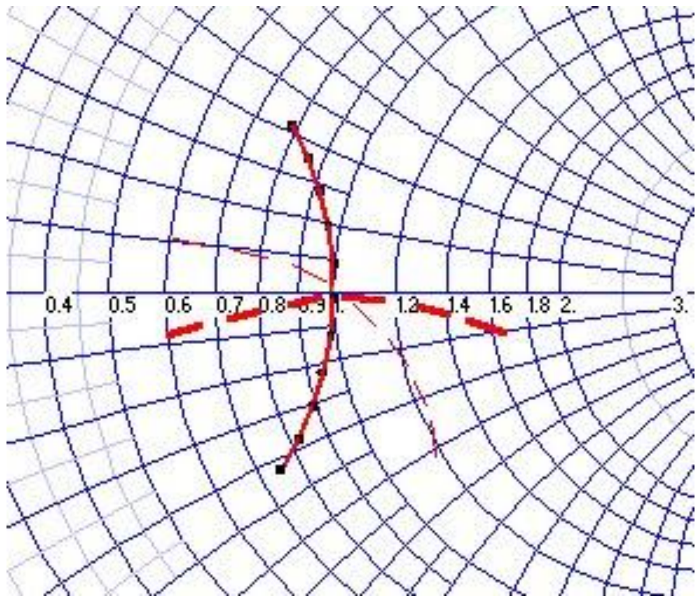

Figure 6 — Effect of plate tuning through 135-degree phase shift (not normalized)

The formulas for designing a pi network with a given phase shift can be found in standard references.[1] Calculated values are normalized to the output impedance. (Typically, this will be 50 **Ω**, so values for *a*, *b*, and *c* must be multiplied by 50 to get actual reactance values).

$$a=((r\sin\beta))/((\sqrt{r}-\cos b)) \quad b=\sqrt{r}\sin\beta c=((\sqrt{r}\sin\beta))/((1-\sqrt{r}\cos\beta))$$

where β is the phase shift, *r* is the ratio of the plate load impedance to the output impedance, *a* is the reactance of the plate tune capacitor, *b* is the reactance of the tank capacitor, and *c* is the reactance of the loading capacitor.

The sine of 135 degrees is .707 and the cosine is -.707 so the formulas can be reduced to:

$a=((.707r))/((\sqrt{r}+.707))$ $b=.707\sqrt{r}$ $c=((.707\sqrt{r}))/((1+.707\sqrt{r}))$

EXAMPLE: For a plate load of 2500 Ω and output impedance of 50 Ω, the ratio r = 50:

$a=((.707x50))/((7.07+.707))$ $a=((35.35))/((7.777))$ $a=4.54$ $a*50=227.27$

Thus, the plate tuning capacitor should have a reactance of 227 Ω, which at 10 MHz, requires a capacitor of 70 pF. In a similar manner, the values for the tank inductor and loading capacitor can be determined.   A spreadsheet to do the calculations is available along with this article. (Note that this spreadsheet does not give an indication of the Q of the network.) A typical run looks like this:

Plate load R	output R		
2500	50		
RATIO r	50		Frequency in MHz
beta (phase)	135		10
Sin beta	0.7071		
Cos beta	-0.7071		
a	b	c	
4.545	-5.000	0.833	
Za	Zb	Zc	
227.273	-250.000	41.667	
Plate cap pf	inductor uh	loading cap pf	
70	4.0	382	

Figure 7 – Calculation of pi network component values for a 135-degree phase shift

Q can be determined using the *PI-L* program (see the accompanying CD-ROM). However, you could use these calculated values to run a circuit simulation to verify that the loss and harmonic rejection are within acceptable limits. You can and should include the losses in the inductors where possible to verify loss in the network.

A Windows program for design of pi networks with phase shift as an input and which includes losses and Q can be found at: **www.smeter.net/feeding/impedance-matching-and-phase-shifting.php**.

Some examples of pi networks with 135-degree phase shift are shown in **Fig. 8**. These were generated by using *LT Spice*. That program will show that, at resonance, the phase shift is 135 degrees. One can also see the bandwidth and the network loss, provided component losses are specified.

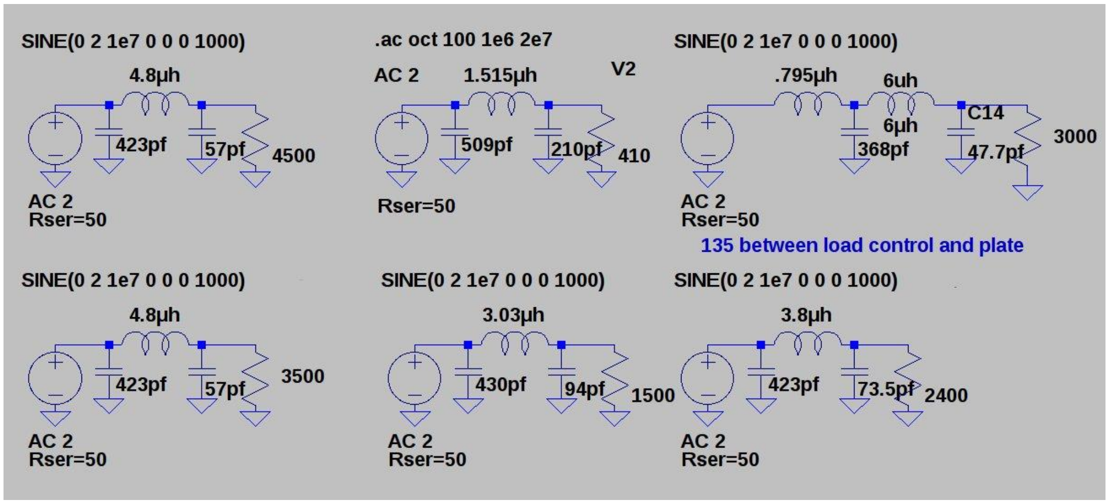

Figure 8 – Examples of 135-degree phase shift networks

In these examples, the source is 50 Ω and the load is the desired plate resistance. The response and phase shift will be identical no matter in which direction the circuit is analyzed.

The plot in **Fig. 9** shows the frequency response with a 2400 Ω plate resistance (lower right circuit in Fig. 8). The dotted line is the phase shift and the solid line is the amplitude response of the network. Each of the above networks will have a similar response, but the bandwidth will change depending on the Q of the pi network. The phase shift in each case will be seen to be 135 degrees at resonance.

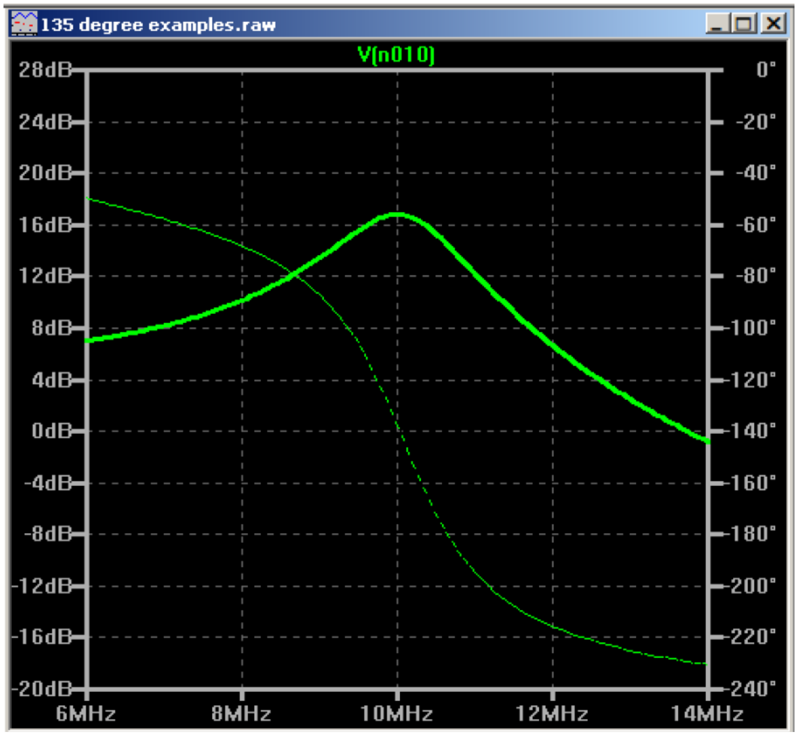

Figure 9 - Phase shift and amplitude response of 135 degree network

Note that with the pi-L circuit (upper right in Fig. 9) the phase shift must be measured between the loading capacitor and the plate of the tube, not between the 50 Ωsource and the plate of the tube.

1. *Standard Broadcast Antenna Systems*, Carl Smith and Daniel Hutton, Smith Electronics Cleveland Ohio, 1969. Also included in various editions of the *NAB Engineering Handbook.*