The “Hairpin” Match

A hairpin match is a simple impedance transforming method that can sometimes be used to match low impedance Yagis, short antennas, and others, to higher impedance feed lines

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Introduction

Experimental antennas often do not immediately appear with a 50 ohm input that will provide a 1:1 SWR by just attaching your standard feed line. Numerous approaches are discussed to adding various matching devices at the antenna to cure this problem in the ham literature. Often the discussions of such methods do not dwell the question of how you start to make a selection of a matching method but just provide a solution for the author’s example.

In this article the simple and often cited[1,2,3] matching method often called hairpin matching will be discussed to help determine if a hairpin match can meet your needs, and indicate how to design and implement that match.

“Hairpin” matching is nothing more than adding an inductance directly across the feed point of the antenna. The inductance may be a simple wire coil or an extended U-shaped wire or rods. This U-shape is of course the reason for the name hairpin and many applications of this matching style use that form of inductance. Sometimes this method is called “shunt” matching, but beware because other forms of matching also use the word shunt although some are rather different.

You might ask why not use hairpin matches all the time since they are so simple. Unfortunately simplicity goes hand-in-hand with limited applicability and dealing with this is the key to matching success.

Why is Matching Needed?

The object of the game is to get as much of your transmitter’s power as possible to exit the antenna as RF radiation. If your transmitter, with its ability to match a nominal 50 ohm impedance, is well matched to the input impedance at the feed line, this transfer efficiency will be maximized. If the feed line has a SWR near 1:1, the ohmic losses in the feed line will be minimized to produce the best signal efficiency. As a result, operators attempt to have antennas with an input impedance near 50 ohms and then generally use coaxial cable with a characteristic impedance near 50 ohms. Of course, there is nothing wrong with using open wire feed lines.

Another reason for good matching is sometimes more practical. With a mismatched transmitter and antenna plus feed line system, some transmitters and amplifiers balk when presented with a higher SWR that is not to their liking. This can result in automatically reduced power output, or even shut down, to prevent damage. If you have a transmitter with an “antenna tuning unit (ATU)” or an outboard “antenna tuner” (really impedance matching networks) the only remaining potential source of loss is from a high SWR from the feed line mismatch to the antenna, which generally becomes important only for large SWR, long cable runs and higher frequencies. In any case, life is generally better if your antenna input impedance, after matching, is in the neighborhood of 50 ohms although concern about getting very low SWR is sometimes overrated. However, with resonant antennas and no tuner, a low SWR at its minimum value will give the largest bandwidth with a manageable SWR.

How Hairpin Impedance Transformation Works

If an antenna has an unmatched complex impedance of Za (Ra+jXa), adding an inductance across the antenna input (sometimes loosely referred to as a “shunt”) gives an equivalent circuit as shown in the figure, where Ro+jXo is the resulting transformed complex impedance output. The object is then to select the added inductance value to cause Ro to be close to the feed line characteristic impedance (often 50 ohms) with the net output reactance Xo near zero.

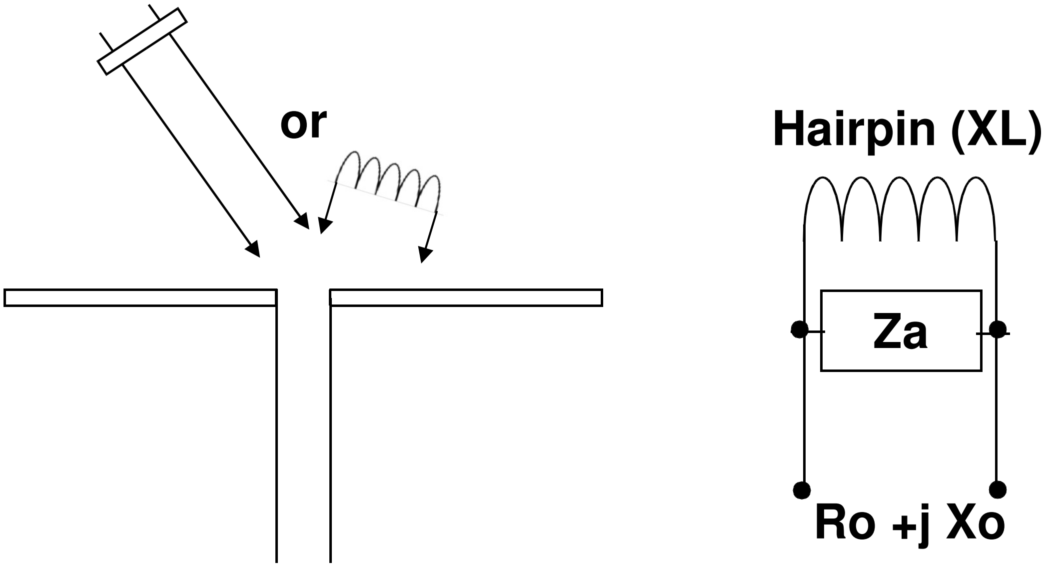

Figure 1. Schematic of hairpin addition and the equivalent circuit.

By adding just one inductance of our choice, you want to both get Ro to be near the feed line impedance and make Xo be near zero. You might wonder if it is possible to do both with just one additional component. The answer is generally no. However, if Za has one of a range of appropriate values, it will work.

The equation that describes this parallel circuit is not difficult, although some may be put off by the need to deal with complex numbers. This is expanded on in the sidebar. The upshot is if Ra is less than Ro, there is always a capacitive Xa (negative) and a hairpin inductance XL that will produce a perfect match.

At first blush you might think if I just short out the antenna input with a bit of wire, won't much of the current coming up the feed line just go through the added wire and not the antenna - and that won't be so good. It turns out that the magnitude of the current in the hairpin is generally comparable with that in Za, and it can be larger than the feed line current. This is because the hairpin and Za currents are far from being in phase. But it turns out that this delicate balance makes the hairpin matched antenna appear as an impedance of Ro, even though there are (mostly) non-radiating currents in the hairpin .

How To Design A Hairpin Match

The first requirement for use of the hairpin is that the unmatched antenna resistive part, Ra, must be significantly less than the desired feed line impedance, Ro. Second, the unmatched antenna reactive part, Xa, must be capacitive (negative) and also must be near the required value calculated in the sidebar. Xa can often be adjusted by modest changes in the length of the driven element or by addition of loading. Once the appropriate Xa is available, there is a hairpin inductive reactance, XL, that can provide a perfect match.

Sometimes getting a perfect match is out of practical reach, primarily due to lack of knowledge or control of the unmatched antenna impedance. However, the match does not need to be perfect to be useful. It can be helpful to have the design information available in graphical form. With these things in mind, the following two pairs of plots show first contours of the best SWR that can be produced by a hairpin match for a wide range of Ra and Xa values, provided you have the right XL, and the second provides that optimal XL value as contours for all the Ra and Xa pairs. The black line is the SWR=1:1 curve corresponding to the perfect match equations in the sidebar. The first pair is for a target feed line impedance of 50 ohms and the second pair is for a target of 200 ohms. The plots appear similar but the scales for the two are different. Note that the SWR changes only slowly with Xa and XL so great accuracy in their selection is not required.

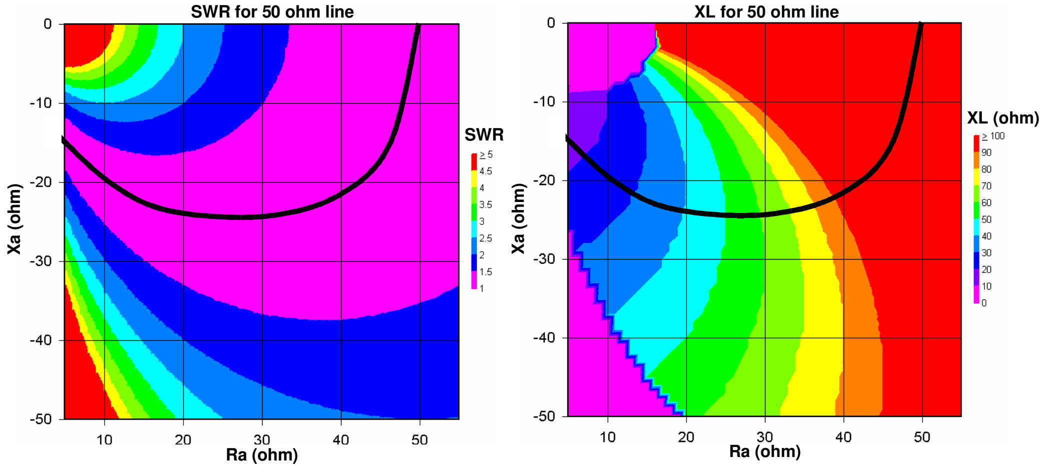

Figure 2. Plots of (a) SWR and (b) XL for hairpin matching to a 50 ohm line.

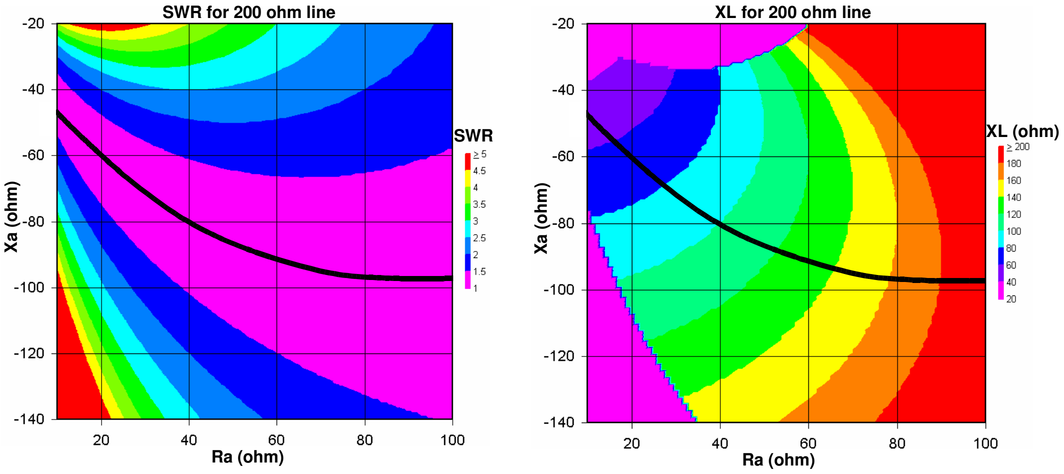

Figure 3. Plots of (a) SWR and (b) XL for hairpin matching to a 200 ohm line.

The plots can be used to design a hairpin match by using your measured or calculated Ra, then finding the corresponding required Xa along the 1:1 SWR curve. Then go to the XL curve to find the needed hairpin inductance. Finally adjust your antenna to have the needed Xa and apply the required inductor across the feed point. The inductor might be a simple coil or hairpin shaped unit. These results for Ra are essentially the same as provided in the plots in the Note 2 reference, but the value of Xa is now available.

As has been pointed out by a number of other authors, matching by use of a capacitive shunt for a positive Xa (inductive) case is really the same except for the change of signs of Xa and XL. However, the use of capacitors as shunt components presents other issues.

Dimensions for Hairpin Shaped Inductance

A hairpin shape of two parallel conductors with a shorting bar , perhaps adjustable, at the end can be viewed as a shorted transmission line. With the length less than a quarter wave, the impedance at the open end is inductive. This impedance smoothly increases with length so it can provide a simple way to produce an inductive element. This impedance is directly related to the characteristic impedance of the transmission line, often called Zo, and it is determined by the ratio of the center-to-center separation of the parallel conductors, S, and the diameter of the conductors, d. A good approximation is $Zo = 276\log_{10}(2S/d)$ for most cases of interest. The next figure provides a plot from the full equation for Zo that is a bit more complicated but not much different in result.

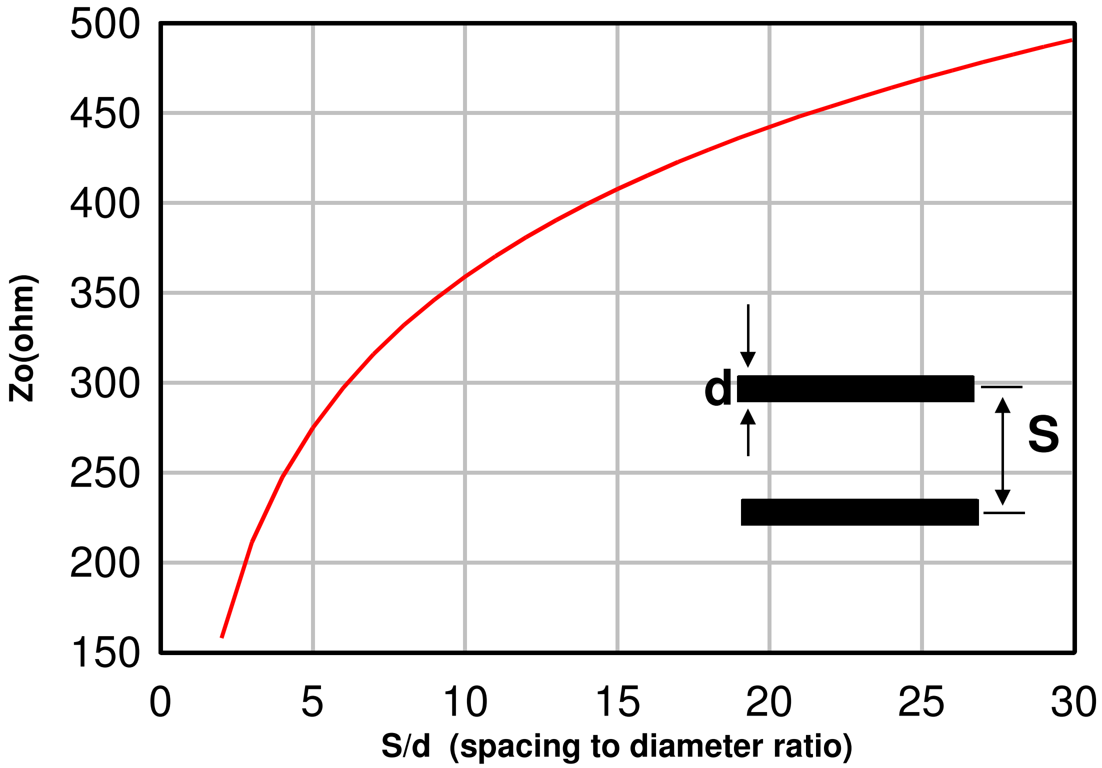

Figure 4. Characteristic impedance of a parallel wire transmission line.

Once the characteristic transmission line impedance is found, the impedance of the shorted line of length L can be found as $XL= Zo*\tan(2\pi L/\lambda)$ where λ is the wavelength and the argument of the tangent is in radians. Therefore the separation, S, might be chosen to get a practical hairpin length for a particular needed inductance.

If a coil is being used for the inductance, there are numerous calculators available on the internet and in reference books to assist.

Applications of Hairpin Match

The most common use of the true hairpin is for a monoband Yagi. Typically Yagis show an unmatched resistive component of a 10 to 20 ohms and the construction naturally lends itself to adding a hairpin shape, sometimes with a shorting bar adjustment, along the boom. As a bonus, the center of the far end of the hairpin can be attached directly to the boom putting the whole antenna at a common DC ground. In some cases, the Yagi design driven element length is directly selected at design to provide a suitable Za for matching. This may avoid tuning by cutting of tubes, from which there is no return.

Although not usually identified as hairpin matching, short loaded antennas for mobile or the lower bands often employ this method using a coil.[4,5,6] Short antennas have Ra well below 50 ohms and usually with a large negative Xa. With loading (coils with a mobile whip, or coil loading or “capacitive hat” with a fixed vertical), the value of Xa can be adjusted downward, often into the range of the hairpin match.

Multi-element higher frequency Yagis are sometimes hairpin matched to provide a balanced 200 ohm antenna impedance that is further transformed with a 4:1 λ/2 coaxial "step up balun." This provides a final 50 ohm unbalanced antenna impedance that is a good match to a 50 ohm (unbalanced) coaxial cable.[7]

At N6MW a 160 meter vertical of 17.5 m height with conducting guy wires attached at the top for loading and two elevated radials has been used with a hairpin coil match. EZNEC indicated that this is possible with this short antenna. Upon assembly, the unmatched impedance at 1.825 MHz was found to be about Za=8-j12. From the chart in Figure 2a the Xa is a smaller than needed. Reduction of the lengths of the radials to well less than a quarter wave brought the impedance into hairpin range and matching was done with a handmade 1.7µH (XL of 18 ohms) coil of #10 wire. That value is consistent with Figure 2b. The useful bandwidth is then about 40 kHz.

Drawbacks of Hairpin Match

The most glaring weakness of hairpin match, for Yagis, is the mechanical complication of the need to split the driven element into two insulated halves. The good news is that it is then easy to measure the unmatched impedance with a modest antenna analyzer.

While the Ra range for matching is pretty wide, the required Xa range is a bit less forgiving, with variations of about 25% from the optimal value leading to best case SWR above 1.5:1.

Adjustment of the driven element to get the optimal Xa may be difficult under those conditions where the length is largely fixed. Furthermore, the value of Ra also depends (but usually to a lesser degree) on the driven element length so it all can be a bit of a moving target.

The hairpin match will leave you with a balanced antenna. With a coaxial cable feed line, which is unbalanced, conventional wisdom is that a common mode choke or another style 1:1 balun will probably needed to limit potential distortion of the pattern from common mode currents.

There will be significant current flowing in the hairpin inductance so the size of the wire and the quality of the connections need to be considered to assure there are no significant ohmic losses.

Some antenna analyzers do not provide the sign of Xa. This can be resolved by looking at the behavior of Xa with frequency as compared to the model, if your model is reasonably close to reality. It is also possible to add a short length of coax and find the transformed Za change compared to predictions of a code like TLW for Ra and +/-Xa. In another regard, this change in impedance at the end of different length feed lines can be confusing when measuring poorly matched antennas remotely since the impedance at the antenna can be quite different from that at the far end of the feed line, unless you happen to have an exact multiple of a half wave of cable. However, the SWR does not depend significantly on cable length so looking for an SWR minimum is still a useful strategy.

Other At-the-Antenna Matching Methods

For some writers a Beta match is the same as a Hairpin match. Others use Beta match to mean the case of a true hairpin on a Yagi where the center of the hairpin is electrically in contact with the boom. The matching capabilities are the same either way.

Gamma matches include a conducting rod running parallel to part of one side of a solid driven element. The rod is then connected to that element at the end of the rod. It usually has a capacitor in series with the rod. Gamma matches are very commonly used with Yagis, base fed towers and some other verticals. The Gamma match is an alternative to Hairpin in some cases and provides an unbalanced antenna feed point without a split driven element. The tuning of Gamma matches with dual adjustment the Gamma rod length and capacitor is sometimes difficult and some published information on parameter selection is problematic. Omega matches are similar to Gamma matches but a second capacitor is place in shunt between the Gamma rod and the driven element allowing tuning with just the capacitors. A Tee match is essentially a two-sided Gamma match which gives a balanced antenna feed point.

The quarter wave length of transmission line of characteristic impedance Zo can sometimes be useful transformer since it will convert an antenna impedance of Za into an output impedance of Zo^2/Za. A half wave length of coaxial cable can be made into a 4:1 transmission-line balun that transforms, for example, 200 ohms into 50 ohms, that can both match and provide an unbalanced feed point.

Computer Programs for Modeling

The popular EZNEC code is a valuable modeling tool for antenna evaluation and matching. First it will provide the unmatched antenna impedance and allow you to adjust the elements, in simulation, to get a hairpin-matchable impedance, if possible. Then you can add a parallel inductive load to the model to provide the match and explore the resulting variation of SWR with frequency. Of course, models will provide guidance for a starting point, but generally not final solutions so some experimentation will usually be needed. There are some software tools that can be helpful for hairpin design including ON4UN's Yagi Design/Matching Systems and TLW/Tuner High-Pass L-Network, but they are both have limited application.

Summary

If your split driven element antenna has an unmatched resistance of well less than the impedance of your desired feed line and it has, or can be made to have, a similar magnitude unmatched capacitive reactance plus some adjustability for that reactance, then you may be a candidate for a simple "hairpin" match consisting of an inductance shunted across the antenna feed point.

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Sidebar: Equations

The equivalent circuit in Figure 1 shows the unmatched antenna complex impedance Za = Ra + j Xa in parallel with an inductance with reactance XL. The resulting impedance for the combination, Ro + j Xo, can be found in the standard way for a parallel circuit as

$$\frac{1}{Ro + jXo} = \frac{1}{jXL} + \frac{1}{Ra + jXa} \quad . \tag{1}$$

A perfect match will have Ro equal to the feed line impedance (often 50 ohms) and a Xo of zero. This is clearly possible only if Xa is negative (capacitive). If we take Xo=0 and solve the resulting complex equations (both real and imaginary parts), after some algebraic manipulations the values are

$$Xa = -\sqrt{Ra(Ro - Ra)} \tag{2}$$

and

$$XL = -|\,Za\,|^2 \big/ Xa \;=\; Ro\sqrt{Ra/(Ro - Ra)} \quad . \tag{3}$$

These together will provide a perfect match. Note that the equation for Xa could also provide a correct solution with a plus sign, indicating an inductive unmatched antenna. Then the XL becomes negative indicating a capacitive shunt. This is an alternate matching method but under different conditions.

[1] Gooch, Gardner and Roberts, QST April 1962 p11
[2] ARRL Antenna Book 21st Ed. 26-11
[3] ON4UN's Low-Band DXing 4th Ed. 13-38
[4] ARRL Antenna Book 21st Ed. 16-14
[5] Clement, QST Jan 2011 p39
[6] Salas, QST Dec 2009 p30
[7] ARRL Antenna Book 21st Ed. 18-27