BOB’S TECHTALK

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Understanding the HF Reflectometer

Introduction:

For many years the reflectometer (AKA as the SWR bridge) was a staple in most every ham shack. This device measures relative power traveling in a transmission line in both the forward and reflected directions. It is a frequency dependent device, becoming more sensitive as frequency is increased in the HF bands. The meter scale is often calibrated in SWR and % reflected power. Since these are related to the ratio of forward to reflected power, the meter is first switched to forward power and adjusted to a specific reading (usually full scale) using a sensitivity control. Next the reflectometer is switched to read reflected relative power. The meter then reads in SWR and % reflected power. A reading of zero represents an SWR of 1.0:1; a reading of half-scale represents an SWR of 3.0:1 and a reading of full scale represents infinite SWR. This type of SWR bridge is based on *The Monimatch Mark II* article by Lew McCoy (QST February 1957 p 39). Lew developed it from an article in Naval Research Labs (See Lew’s earlier article *The Monimatch* - QST October 1956 p 11).

Newer bridge designs are often frequency independent to a large extent, and can read out both forward and reflected power directly in watts as well as the SWR.

In 1959 I built the Heathkit AM-2 reflectometer as a budding Novice. For years it mystified me as to how it worked. In college, with a little mentoring from a professor-ham, I worked out the principle. Perhaps others are curious? We’ll be doing math, but you can also follow along without working the math.

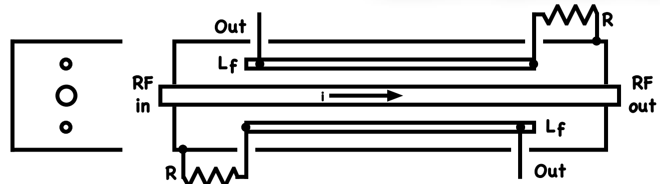
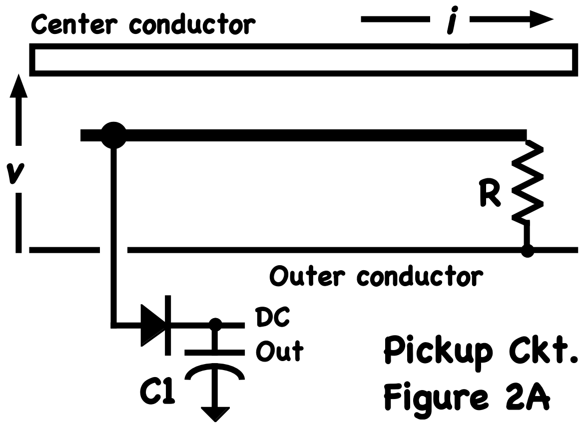


Figure 1

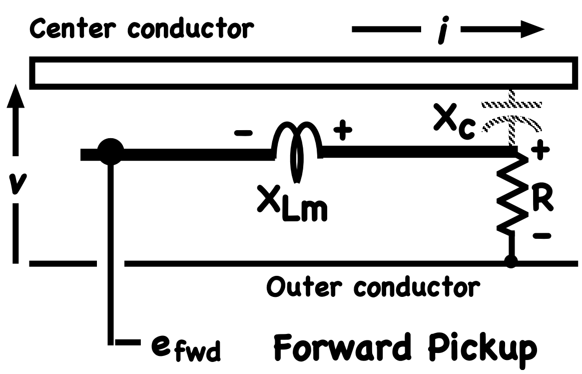
The Reflectometer:

Figure 1 depicts the inside of a typical reflectometer. The input and output are connected directly together through a transmission line section that approximates the nominal impedance of 50 - 75Ω. In the AM-2 this is done using a tube for the center conductor and a U-shaped trough for the outer conductor. Two separate pickup circuits are used; usually they are identical except one’s orientation is reversed from the other. The original Monimatch had the two pickup wires located serially along the center conductor; this made the instrument almost a foot long, an inconvenient size. Later instruments located the pickups in parallel on either side of the center conductor, similar to figure 1. Key to the operation of the reflectometer is that the pickup wire is not only coupled inductively to the center conductor, it is also coupled capacitively; This is something I didn’t consider in my younger days, but is important to the working of the bridge.

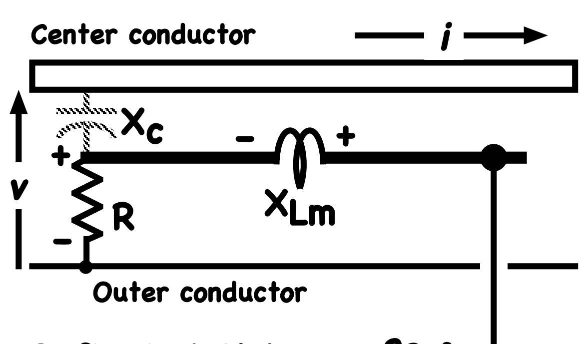
Figure 2A shows typical pickup circuitry. Figure 2B is the same circuit showing a phantom capacitive coupling with a reactance (X_C) and inductive mutual coupling with a reactance (X_{Lm}) between the pickup wire and the center conductor. Note that since the coupling is small, X_C is quite large and X_{Lm} is quite small. One end of each pickup is terminated by a fixed non-inductive resistor. A lead, exiting perpendicular to the transmission line to beyond the outer conductor, brings the RF voltage to a crystal diode where it is rectified and filtered by C_1. The resulting DC voltage is then routed to a metering circuit which



Pickup Ckt.
Figure 2A



Forward Pickup
Figure 2B



Reflected Pickup
Figure 2C

will be discussed later. In the following steps we'll be looking at the RF output voltage of each pickup before the diode. These voltages are designated e_{Fwd} and e_{Ref}.

In Figure 2A: $\boldsymbol{v}$ and $\boldsymbol{i}$ are the RF voltage and current in the transmission line. If the transmission line is terminated in its nominal impedance Z_0 then $\boldsymbol{v}$ and $\boldsymbol{i}$ are simply related by Ohm's law:

$$v = iZ_0 \tag{1}$$

The large center conductor has a small inductance as does the thinner pickup wire. Since they are in proximity and parallel, a mutual inductance L_m with an inductive reactance X_{Lm} exists in the pickup. A voltage is thus developed across L_m. The length of the pickup wire must be small in relation to the signal's wavelength to assume that the voltage $\boldsymbol{v}$ is constant over the length of the pickup. This is reasonable for a pickup 3" to 4" long to beyond 50 MHz.

The voltages e_{Fwd} and e_{Ref} are the sum of $\boldsymbol{v}_R$ (the voltage across R) and $\boldsymbol{v}_{Lm}$ (the voltage across L_m).

$$e_{Fwd} = v_R + V_{Lm} \tag{2}$$

Solving for the Resistor Voltage:

The voltage at the top end of R in figure 2B (and 2C as well), can be calculated by a simple voltage divider with R and X_c the two elements:

$$v_R = \left(\frac{R}{R - jX_C}\right)v \tag{3}$$

R turns out to be small, on the order of a few hundred ohms at most, and is much smaller than Xc across the HF band. Thus we can ignore R in the denominator and eq. 3 approximates to:

$$v_R = \left(\frac{R}{-jX_C}\right)v$$

but: $X_C = \frac{1}{\omega C}$ where: $\omega = 2\pi f$

The result, remembering that $\frac{1}{-j} = j$, is:

$$v_R = j\omega RCv \qquad (4)$$

Solving for the Inductor Voltage:
$\boldsymbol{v}_{Lm}$ is the voltage induced by the current in the center conductor, and is:

$$v_{Lm} = jX_{Lm}i$$

but: $X_{Lm} = j\omega L_m$

so: $v_{Lm} = j\omega L_m i \qquad (5)$

Solving for the Output Voltages:
Substituting eqs. 4 and 5 into eq. 2 yields:

$$e_{Fwd} = j\omega RCv + j\omega L_m i \qquad (6)$$

If you look at figure 2C for the reflected pickup everything is the same except that the polarity of the mutual inductance is reversed, hence:

$$e_{Ref} = j\omega RCv - j\omega L_m i \qquad (7)$$

Balancing the Bridge:
To balance the circuit, the output from the reflective pickup should be zero when the bridge output is terminated in Z_0 (SWR = 1:1). What we want from our reflectometer is to have e_{Ref} be zero when terminated by Z_0. From Eq. 7, this can only be true if:

$$j\omega RCv = j\omega L_m i$$

or: $\frac{v}{i} = \frac{L_m}{RC}$

Inserting eq. 1 and solving for R gives us:

$$R = \left(\frac{L_m}{CZ_0}\right) \qquad (8)$$

The value for R that results in balance can most easily be found by trial and error. L_m and C are hard to determine accurately but can be calculated roughly and a starting value for R installed. The bridge output is then terminated with a good dummy load of Z_0. RF is applied to the bridge input and e_{Ref} measured. This is repeated until a resistor is found that results in the closest null (5% resistors are adequate). While C is fixed by the geometry, L_m can be adjusted slightly by moving the location of the lead going to the diode. This final adjustment should result in a nearly perfect null.

Once R is determined and the bridge is balanced in the reverse direction, the forward pickup can be nulled simply by reversing the input and output so that the forward pickup in the circuit is now the reflected pickup, and vice versa. If the geometry is same for both pickups, R will be identical so only the lead adjustment need be done.

Solving R for another Z_0:
Looking at equation 8, note also that as Z_0 gets larger, R gets smaller. Thus the terminating resistor R for a 75Ω bridge will be smaller than for 50Ω bridge. Once R is determined <u>for a given geometry</u> it can be calculated for another close by Z_0. For instance say R=100Ω for a Z_0 = 50Ω bridge; then the correct R for a Z_0 = 75Ω bridge is:

$$R_{75} = \left(\frac{Z_{50}}{Z_{75}}\right)R_{50}$$

$$R_{75} = \left(\frac{50}{75}\right)100 \approx 68\Omega$$

While the bridge geometry (inner and outer conductors) are designed to represent a transmission line near Z_0 it is not critical enough to prevent a slight change in bridge Z_0. Thus many bridge designs work on both 50 and 75 ohms with just a change in the resistor values.

Balanced Pickup Output:

Using eq. 8 to substitute for RC, eqs. 6 and 7 may be simplified to:

$$e_{Fwd} = j\omega L_m\left(\frac{v}{Z_0} + i\right) \qquad (10)$$

$$e_{Ref} = j\omega L_m\left(\frac{v}{Z_0} - i\right) \qquad (11)$$

When the bridge is balanced these equations simplify, by substituting in eq. 1, to get:

$$\begin{bmatrix} e_{Fwd} = 2v\left(\dfrac{j\omega L_m}{Z_0}\right) \\ e_{Ref} = 0 \end{bmatrix} \text{Balanced}$$

Unbalanced Pickup Output:

When the bridge termination is different than Z_0, there is reflective energy traveling against the forward energy. The two voltages add, but the two currents oppose and subtract.

$$v = v_F + v_R$$

$$i = i_F - i_R$$

also: $$i_F = \frac{v_F}{Z_0} \text{ and } i_R = \frac{v_R}{Z_0}$$

Substituting first for ***i*** in eqs. 10 and 11 we get:

$$e_{Fwd} = j\omega L_m\left(\frac{v}{Z_0} + \left[\left(\frac{v_F}{Z_0}\right) - \left(\frac{v_R}{Z_0}\right)\right]\right)$$

$$e_{Ref} = j\omega L_m\left(\frac{v}{Z_0} - \left[\left(\frac{v_F}{Z_0}\right) - \left(\frac{v_R}{Z_0}\right)\right]\right)$$

And then substituting for ***v*** we get:

$$e_{Fwd} = \left(\frac{j\omega L_m}{Z_0}\right)\left(v_F + v_R + \left[v_F - v_R\right]\right)$$

$$e_{Ref} = \left(\frac{j\omega L_m}{Z_0}\right)\left(v_F + v_R - \left[v_F - v_R\right]\right)$$

For the forward voltage, the $\boldsymbol{v_R}$ terms cancel; and for the reverse voltage, the $\boldsymbol{v_F}$ terms cancel. Thus :

$$e_{Fwd} = 2\left(\frac{j\omega L_m}{Z_0}\right)v_F = 2\left(\frac{X_{Lm}}{Z_0}\right)v_F \qquad (12)$$

$$e_{Ref} = 2\left(\frac{j\omega L_m}{Z_0}\right)v_R = 2\left(\frac{X_{Lm}}{Z_0}\right)v_R \qquad (13)$$

Equations 12 and 13 give the voltage output to the diode. The X_{Lm} term in the numerator of the two formulas means the voltage is frequency sensitive, increasing with frequency, since the reactance of an inductor increases with frequency.

Meter Circuit and Scaling:

The forward and reflected voltages are each converted to DC by a diode and filtered by a small capacitor (typically 1,000 to 5,000 pF). A switch selects either of the two voltages and directs it to the meter through a potentiometer that adjusts the sensitivity. The voltages are small and a fairly sensitive meter is required to give full scale deflection. Meters on the order of 100 µA to 200 µA are typical for HF bridges. One milliamp meters may be used for bridges at higher frequencies.

Figure 3 shows the meter face of the Heathkit AM-2. Note the SET mark at full scale. The percent reflected power is:

$$\%\ \text{Reflected Power} = \frac{P_R}{P_F} = \left(\frac{v_R}{v_F}\right)^2 \qquad (14)$$

and the SWR is calculated as:

$$SWR = \frac{(v_F + v_R)}{(v_F - v_R)} \qquad (15)$$

Fig 3: Heathkit AM-2 SWR Meter scales

or solving eq. 15 for v_R:

$$v_R = \frac{(SWR - 1)}{(SWR + 1)} v_F \qquad (16)$$

v_R (%FS)	%Ref Power	SWR
0	0.000	1.000
5	0.250	1.105
10	1.000	1.222
15	2.250	1.353
20	4.000	1.500
25	6.250	1.667
30	9.000	1.857
35	12.250	2.077
40	16.000	2.333
45	20.250	2.636
50	25.000	3.000

Table I:

From equations 12 and 13 we know that the voltages on the center conductor v_F and v_R are proportional to the meter voltages e_{Fwd} and e_{Ref}. Also when the meter is properly set, v_F is represented by full scale meter movement. Thus the percent of full scale (%FS) the meter moves represents the percentage of forward voltage reflected. From this we can easily calculate the reflected power from eq. 14, and the SWR from eq. 15. Eq. 16 can be used to calculate the reflected voltage for a given SWR.

Table I shows the calculated values for every 5% of meter scale for the first 50%. When v_F is set to 100, representing a full scale of 100%, v_R is then represented by the % of full scale of the meter.

Table II is similar to table I. It shows the % of full scale for various values of SWR.

SWR	v_R (%FS)	%Ref Power
1.10	4.762	0.227
1.20	9.091	0.826
1.30	13.043	1.701
1.40	16.667	2.778
1.50	20.000	4.000
1.60	23.077	5.325
1.70	25.926	6.722
1.80	28.571	8.163
1.90	31.034	9.631
2.00	33.333	11.111
2.20	37.500	14.063
2.50	42.857	18.367

Table II:

I hope this has taken some of the mystery out of the SWR bridge (Reflectometer)!

73, from AF6C

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