ACCELERATOR DEPARTMENT

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Internal Report

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DESIGN OF REFLECTOMETERS FOR COAXIAL LINESUSED AT AGS LINAC

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MASTER

This report describes the design procedure for a reflectometer or directional coupler to replace the probe part of the DO7-1020 assembly which is presently used in the linac.

The loop type reflectometer is described in several places¹⁻⁵. *The loop shown in Figure 1 is considered much smaller than a wavelength so that the lumped element equivalent circuit may be used. C_1 is the capacitance

Figure 1

between the center conductor and the loop. The loop is considered to be magnetically coupled to the center conductor by a mutual inductance M .

*Much of the following analysis is taken from Parzen and Yalow¹.

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Usually the self inductance of the loop has reactance negligible compared to R and the reactance of C_2 , the capacitance of the loop to the outer conductor is very large compared to R . Under these conditions the output voltage will be the sum of voltages due to capacitive and inductive coupling.

$$e_o = e_c + e_M$$

$$e_c = V \frac{R}{R + \frac{1}{j\omega C_1}} \stackrel{*}{=} VRj\omega C_1$$

$$* \text{ assuming } R \ll \frac{1}{\omega C_1}$$

$$e_M = j\omega MI$$

$$e_o = j\omega(VRC \pm^* MI)$$

* denotes the fact that M can be changed by rotating the loop with respect to the center conductor

Since V and I in the above equations are voltage and current of a transmission line, they may be written in terms of forward and reverse components:

$$V = V_f + V_r \quad \text{and} \quad I = I_f + I_r$$

and it can be shown that

$$V_f = I_f Z_o \quad \text{and} \quad -V_r = I_r Z_o.$$

The reflection coefficient ρ is defined as

$$\rho = \frac{V_r}{V_f} = -\frac{I_r}{I_f}.$$

Now I can be eliminated in the expression for e_o :

$$\begin{aligned} e_o &= j\omega \left[RC(V_f + V_r) \pm M(I_f + I_r) \right] \\ &= j\omega \left[RC(V_f + \rho V_f) \pm M(I_f - \rho I_f) \right] \\ &= j\omega \left[RC(V_f + \rho V_f) \pm M\left(\frac{V_f}{Z_o} - \rho \frac{V_f}{Z_o}\right) \right] \\ &= j\omega V_f \left[RC(1 + \rho) \pm \frac{M}{Z_o} (1 - \rho) \right]. \end{aligned}$$

For perfect directivity set $RC = \frac{M}{Z_0}$, then

$$\begin{aligned} e_o &= j\omega V_f \frac{M}{Z_0} \left[(1 + \rho) \pm (1 - \rho) \right] \\ &= 2j\omega V_f \frac{M}{Z_0} \quad \text{or} \quad 2j\omega V_f \frac{M}{Z_0} \rho \\ &= e_p \quad \text{or} \quad e_n \end{aligned}$$

where e_p is the value of e_o when the + sign is used. Dividing these gives

$$\frac{e_n}{e_p} = \rho$$

and

$$VSWR = \frac{1 + \rho}{1 - \rho} = \frac{1 + \frac{e_n}{e_p}}{1 - \frac{e_n}{e_p}} = \frac{e_p + e_n}{e_p - e_n}.$$

To show that indicated power will be independent of VSWR, write power in terms of forward and reverse components:

$$P = V \cdot I = (V_f + V_r) \cdot (I_f + I_r) = V_f \cdot I_f + V_f \cdot I_r + V_r \cdot I_f + V_r \cdot I_r.$$

The mixed terms cancel since

$$V_r \cdot I_f = -I_r Z_0 \cdot I_f \quad V_f \cdot I_r = I_f Z_0 \cdot I_r$$

$$V_r I_f + V_f I_r = 0$$

$$\begin{aligned} P &= V_f \cdot I_f + V_r \cdot I_r = \frac{V_f \cdot V_f}{Z_0} - \frac{V_r \cdot V_r}{Z_0} = \frac{|V_f|^2}{Z_0} - \frac{|V_r|^2}{Z_0} \\ &= \frac{|V_f|^2}{Z_0} (1 - \rho^2) = \frac{|V_f|^2}{Z_0} \left(1 - \left| \frac{e_n}{e_p} \right|^2 \right) = \frac{|V_f|^2}{Z_0 |e_p|^2} \left(|e_p|^2 - |e_n|^2 \right) \end{aligned}$$

from the above
$$\frac{e_p}{V_f} = 2j\omega \frac{M}{Z_o} ; \left| \frac{V_1}{e_p} \right|^2 = \frac{Z_o^2}{4\omega^2 M^2}$$

$$P = \frac{Z_o}{4\omega^2 M^2} (e_p^2 - e_n^2)$$

which gives the (net) power flow. In the above lines the absolute value signs on the voltages mean "ignore any minus signs", i.e. power is still rms voltage times rms current.

The assumptions used so far:

$$R \ll \frac{1}{\omega C_2}$$

$$R \gg \omega L$$

$$R \ll \frac{1}{\omega C_1}$$

are valid for a variety of useful couplers. At higher frequencies (in the KMC region) ωL becomes an appreciable fraction of R . In this case Allan and Curling³ adjust C_2 to compensate. The size of L and C_1 (and C_2) increases with the amount of coupling desired since

$$\frac{e_f}{V_f} = \frac{2\omega M}{Z_o} \quad \text{and} \quad RC_1 = \frac{M}{Z_o} .$$

To achieve the proper value of C_1 , the capacitance of a simple wire loop may not be enough. Making a loop long radially and short axially will increase C_1 independently of M , but this decreases the line breakdown voltage. A plate may be added to the loop to increase C_1 .

Dolder² gives the following formulae for plate area and loop area for the arrangement shown in Figure 2:

$$\text{Loop area} \quad A_L = \frac{2Mr_1}{\mu_o}$$

$$\text{Plate area} \quad A_p = \frac{C_1 t}{\epsilon_o}$$

where r_1 is the distance between the center of the loop and the axis of the coax

t is the average distance between the surface of the plate and the surface of the inner conductor.

Figure 2

For large coupling loop area must increase; plate area must increase to provide directivity. Increasing plate area increases C_2 at the same rate as C_1 so that the first assumption on page 4 may become invalid.

Parzen and Yalow consider another possible source of error, the case where the output is loaded down by meter impedance Z_m . Using the circuit in Figure 3,

$$Z_r = \frac{\omega^2 M^2}{Z_t}$$

Figure 3

where Z_r is impedance reflected into the loop circuit from the line, and Z_t is total impedance between inner and outer conductor, they show that the reflection coefficient is still the ratio of the voltages,

$$\rho = \frac{V_n}{V_p} .$$

They show further that if the following approximations are valid,

$$\frac{R(Z_t - jX_c)}{R + Z_t - jX_c} \doteq R \quad \omega L \ll R$$

$$\text{i.e. } X_c \gg R \text{ and } X_c \gg Z_t \quad \frac{\omega^2 M^2}{Z_t} \ll R$$

then indicated power is given by

$$P = \left(\frac{Z_m + R}{Z_m} \right)^2 \frac{Z_o V_p^2}{4 \omega^2 M^2} (1 - \rho^2) .$$

Thus, when the reflectometer is used to measure power, the meter impedance is quite important; going from an infinite Z_m to $Z_m = R$ changes the indicated power by a factor of 4.

Figure 2 shows a slightly different circuit, which is formed by replacing the resistor by a length of terminated line so that there are two outputs as shown in Figure 4.

Figure 4

Going through the same sort of analysis gives the directivity condition,

$$RC_1 = \frac{M}{Z_0}$$

and the coupling factor

$$\frac{e_p}{V_f} = \frac{\omega M}{Z_0}.$$

Notice that twice the loop and plate area is needed for the same coupling as in the single resistor case. Offsetting this is the advantage that forward and reverse voltages come from one reflectometer element or probe which is left in a fixed position (a single R loop may be rotated 180° to obtain the two readings).

Figure 5 shows a directional coupler manufactured by Sierra Electronic Corporation, which uses the 2R circuit in a slightly different physical configuration. The adjusting screw changes the value of C_1 to improve directivity. This arrangement allows smaller coupling than obtainable when the loop is inside the line. The coupler shown gives 43.5 dB coupling at 200 Mc. Coupling in dB is given by:

$$\text{Coupling} = 20 \log_{10} \frac{V_f}{e_p}$$

which is confusing since the number gets smaller for closer coupling. By a 30 dB coupler is meant one which couples out one thousandth of the power in the line.

Sierra Electronic Corporation Model 138

Figure 5

Figure 6 shows a 40 dB coupler designed to mount in the same housing as the present probe D07-1020. The coupling can be adjusted by changing the insertion in the housing and the directivity can be adjusted by rotating the probe thereby changing the effective loop area. One of these has been built; experimental results are given in Figure 7.

Figure 6

Probe assembly, Job No. D07-2M-2
Dwg. No. D07-4496-1C through D07-4500-1A

Figure 7

Coupling as a function of insertion

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