The Pi-Coupler

Although widely used for such purposes as output matching in radio transmitters, the pi-section coupling network still remains something of a mystery to many radio amateurs and technicians. This article explains how it works, and also gives the basic design procedure.

by JAMIESON ROWE

Probably a majority of modern transmitters and transceivers designed for use on the HF and lower VHF amateur bands employ a pi-section coupling network or "pi-coupler" to perform both output tuning and impedance matching between the power amplifier or "PA" stage and the aerial feeder cable. It is also used for the same purpose in many transmitters designed for other applications, and in industrial and medical equipment such as induction heaters and diathermy units.

In view of the widespread use of the pi-coupler, it is surely disappointing that the established radio textbooks and amateur radio reference manuals generally devote very little space to a discussion of its basic operation. Most simply give its basic circuit configuration, as in figure 1, together with a few basic formulae describing its properties. Small wonder that to many radio amateurs and technicians its operation is still something of a mystery!

The writer will try to dispel some of this mystery in the present article. The aim will be to show that as far as basic operation is concerned, the pi-coupler may be considered as virtually only a conventional parallel-tuned resonant "tank" circuit with a tapping system for impedance matching. The only difference is that it is rearranged into an unfamiliar form.

To begin, then. As figure 1 shows, the basic pi-coupler consists of a series inductor L, together with two shunt capacitors C1 and C2. Usually both C1 and C2 are made variable, as shown. The load resistance Ra presented by the aerial feeder cable is connected to the network across C2, while the plate or collector of the PA stage connects across C1 via a high-value DC blocking capacitor. An RF choke is used for the PA stage DC return.

It is possible to simplify the circuit of figure 1 by reducing it to the bare essentials as far as its RF operation is concerned. This is shown in figure 2(a), which also represents the way that the pi-coupler transforms the actual load resistance Ra into an effective load Rp suitable for the PA stage. Unfortunately the circuit of figure 2(a) still gives little clue as to the way in which the network operates.

As it happens, all that is necessary to make the operation more easily seen is to redraw the circuit with the various elements of the network juggled around a little. By drawing the symbol for L vertically, and tying the earthed ends of C1 and C2 together, we end up with the circuit of figure 2(b). Now it may be seen that C1 and C2 are really connected in series across L, forming a parallel resonant circuit which is quite normal apart from the minor detail that neither side of the inductor is earthed. Instead the circuit is earthed at the junction of the two series capacitors forming its "C" arm.

It should perhaps be noted in passing that although this re-arrangement of the pi-coupler network can be justified, on the grounds that it should help the reader to understand its operation as a resonant tank circuit and as an impedance matching device, it politely ignores the fact that the network also functions very effectively as an attenuator of signal harmonics. As a glance at figure 2(a) reveals, it does this by virtue of the fact that its configuration is the same as that of a pi-section filter, so that at frequencies above resonance its transmission falls away very rapidly. But this aspect of pi-coupler performance is fairly straightforward, and need not concern us further here.

When drawn as in figure 2(b), the action of the pi-coupler as an output tuned circuit is easily seen. Because the load Ra and the output of the PA stage are both coupled to the resonant circuit formed by C1, C2 and L, the circuit resonance is able to play a major part in determining the frequency components transferred from one to the other. But the reader may still not find it easy to see how the circuit is able to transform the load resistance Ra into the effective load Rp.

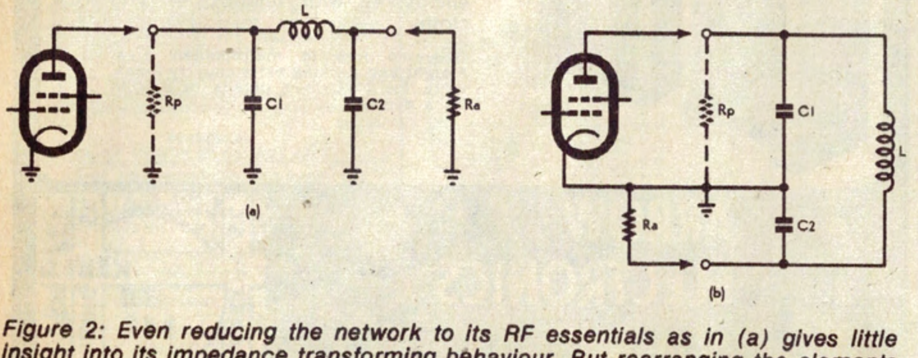


Figure 2: Even reducing the network to its RF essentials as in (a) gives little insight into its impedance transforming behaviour. But rearranging the elements as in (b) reveals that it is basically a tapped tuned circuit.

The clue to this aspect of pi-coupler operation is the fact that the load Ra and the PA stage are each connected across only a part of the capacitive arm of the resonant circuit: Ra across C2, and the PA stage across C1. The fact is that this series combination of C1 and C2 forms an impedance-transforming reactive divider. The junction of the two provides a low impedance "tap" into the resonant circuit.

Probably the reader will be more familiar with the tapped inductor method of transforming impedance, as shown in figure 3(a). This method is frequently used where a relatively low impedance circuit has to be coupled into the resonant circuit without causing it undue disturbance or damping its resonance behaviour. The position of the tap on the inductor is chosen to provide the desired impedance step-up ratio. The lower the position of the tap, the greater the extent to which the impedance of the circuit connected to the terminals is stepped up, as far as the resonant circuit is concerned.

Thus if the inductor is tapped in the ratio of "N" turns to "M" turns, and the external circuit of resistance R is connected across the portion having "N" turns, then its effect will be the same as that of the much larger resistance Rd connected right across the resonant circuit. The size of Rd is related to R by the square of the appropriate turns ratio:

$$Rd = R.\,((M + N)/N)^2 \qquad \ldots(1)$$

As it happens, virtually the same impedance step-up effect may be obtained by tapping the capacitive arm of the resonant circuit, instead of the inductive arm. Naturally it is not an easy matter to connect a "tap" into a single capacitor. However from basic circuit theory the same effect may be achieved quite simply, by using two capacitors in series. The junction of the two then becomes the "tap", with the impedance step-up ratio determined by the value of the two capacitors.

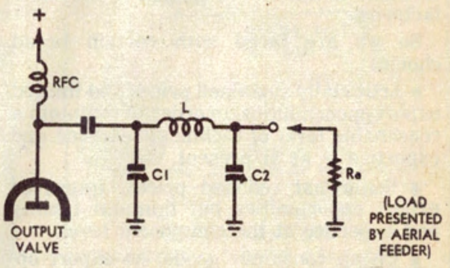


Figure 1: The basic pi-coupler circuit configuration.

It turns out that the impedance transforming ratio obtained with the capacitive divider system follows a similar "squares" relationship to that obtained with the inductive divider. Thus in figure 3(b), the effective resistance Rd connected across the resonant circuit is related to the actual resistance R connected across the terminals by the equation:

$$Rd = R.\,((Xc1 + Xc2)/Xc2)^2 \qquad \ldots(2)$$

This impedance-transforming action of the

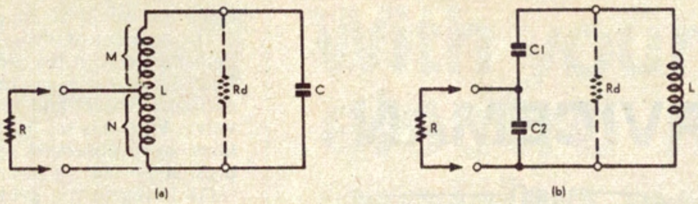


Figure 3: A comparison of the (a) inductive, and (b) capacitive tapping methods.

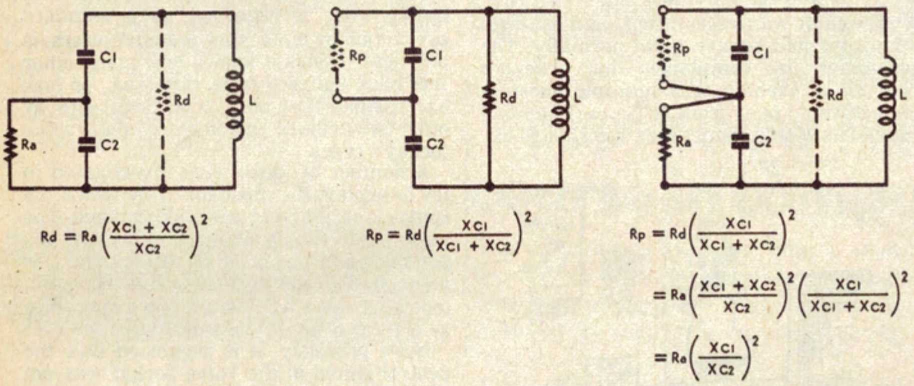
capacitive divider works in both directions. It can step down impedance as well as stepping it up. Thus if an actual resistance Rd were to be connected right across the inductor L in figure 3(b), instead of a resistance R across the terminals, then the action of the capacitive divider would be such that a circuit connected to the terminals would "see" an effective input resistance of value R. In other words we can quite validly rearrange equation (2) to read:

$$R = Rd.\,(Xc2/(Xc1 + Xc2))^2 \qquad \ldots(3)$$

If the circuit were to be connected instead across the upper capacitor C1, while the resistance Rd were still connected across L, it would also see a resistance lower than Rd. But in this case the value seen would be given by the equation:

$$Rp = Rd.\,(Xc1/(Xc1 + Xc2))^2 \qquad \ldots(4)$$

As many readers may have guessed by now, the capacitive divider can in fact be used to perform both the step-up and step-down operations at the same time. This follows because if a circuit of resistance R is connected across C2 of figure 3(b), not only does an effective resistance of value Rp appears across capacitor C1.



$$Rd = Ra\left(\frac{Xc_1 + Xc_2}{Xc_2}\right)^2$$

$$Rp = Rd\left(\frac{Xc_1}{Xc_1 + Xc_2}\right)^2$$

$$Rp = Rd\left(\frac{Xc_1}{Xc_1 + Xc_2}\right)^2 = Ra\left(\frac{Xc_1 + Xc_2}{Xc_2}\right)^2\left(\frac{Xc_1}{Xc_1 + Xc_2}\right)^2 = Ra\left(\frac{Xc_1}{Xc_2}\right)^2$$

Figure 4: The impedance transforming action of the network can be seen more readily if it is broken down into these stages.

This is precisely how the pi-coupler performs its impedance matching function. It uses the capacitive divider first to step up the low resistance load presented by the aerial feeder, and then again to step it down to a value suitable as a load for the PA stage. The diagrams of figure 4 should help make this clear. It may be seen that the final matching ratio between the actual load Ra and the transformed load Rp is simply given by the square of the ratio between Xc1 and Xc2:

$$Rp = Ra.\,(Xc1/Xc2)^2 \qquad \ldots(5)$$

Like any other resonant "tank" circuit used at the output of a transmitter, the pi-coupler must be designed to have a Q which is sufficiently high to attenuate undesired harmonics, yet low enough to ensure that an adequate proportion of the RF energy stored in the tuned circuit is transferred to the load. With most transmitters designed for telephony, a good compromise between these factors is achieved with a Q of around 10-12.

The operating Q of the pi-coupler is essentially the ratio between Rd, the effective damping resistance across the total resonant circuit, and the reactance of either L or the total effective capacitance at the operating frequency. Thus if Rd were known, it would be possible to calculate the inductive reactance X1, by giving Q a value of say 10. And this would allow one to calculate the required value of L knowing the operating frequency.

As it happens, one does not usually know Rd when commencing the design of a pi-coupler. But it is generally possible to arrive at a fairly close estimate of Rp, the transformed load resistance, either from the valve manufacturer's literature, or from past experience. Therefore in order to calculate X1 and L one must substitute for Rd in the basic expression for Q, using expression (4). This gives the following equation:

$$X1 = (Rp/Q).((Xc1 + Xc2)/Xc1)^2 \quad \ldots(6)$$

Happily this slightly formidable equation can be simplified quite considerably whenever the pi-coupler is used to give a fairly high impedance transformation between Ra and Rp. And this is generally the case with radio transmitters, or at least those having a valve in the PA stage: Ra is usually either 50 or 75 ohms, while Rp is usually 1K or greater.

With such a high transformation ratio, capacitor C2 becomes so large compared with C1 that its reactance plays a negligible part in determining the total capacitive reactance and the working Q. The squared capacitive reactance ratio in equation (6) becomes so close to unity that it may be ignored, simplifying the relationship to:

$$X1 = Rp/Q \qquad \ldots(7)$$

In practice the first step in designing a pi-coupler is therefore a fairly simple one: with a suitable value for the desired PA stage load Rp, and Q = 10, use equation (7) to find X1. Then find the corresponding value of L using the familiar expression for inductive reactance, knowing the operating frequency.

It remains then to work out the values for C1 and C2, knowing that these must satisfy two requirements. In series they must resonate with L at the operating frequency, while at the same time they must provide the required transformation ratio to provide the desired Rp.

The second of these requirements will of course be met if the ratio between the two capacitors is such to satisfy equation (5). However to satisfy the first requirement they must also be able to satisfy the equation:

$$Fo = 1/2\pi\sqrt{L.C1.C2/(C1 + C2)} \quad \ldots(8)$$

This is simply the familiar equation for resonant frequency modified by substituting the equivalent series capacitance of C1 and C2.

Happily when the pi-coupler is used to give a fairly high impedance transformation ratio, this equation can again be simplified. As before, the relatively large value of C2 compared with C1 means that C2 plays a minor part in determining the resonant frequency. Hence equation (8) simplifies to:

$$Fo = 1/2\pi\sqrt{L.C1} \qquad \ldots(9)$$

In other words, one can neglect C2 and assume that only C1 resonates L at the operating frequency. This means that having found L, it is an easy matter to work out the value of C1.

And with C1 found, equation (5) may be used to find out the corresponding value of Xc2 and hence C2, knowing Rp and the actual load resistance Ra presented by the aerial feeder (50 or 75 ohms).

Although these design calculations will give specific values for L, C1 and C2, it should be remembered that one rarely has a very precise knowledge of the optimum PA stage load resistance Rp. This combined with the various simplifying assumptions used to arrive at equations (7) and (9) means that it is usually desirable to use variable capacitors for both C1 and C2, as shown in figure 1.

It should also be remembered that the output capacitance of the PA stage is effectively a part of C1. As the output capacitance is composed at least partly of strays, this is a further reason for making C1 a variable.

A variable capacitor for C2 also allows the coupler to be adjusted to cope with a load of other than the nominal 50 or 75 ohms design figure, as would in practice be presented to the transmitter when the aerial is not perfectly matched to the feeder. In other words, it allows the transmitter to be adjusted to cope with a range in loading and SWR situations.

It should be noted that the simplified equations (7) and (9) are not really applicable when designing a pi-coupler for use with a transmitter having a transistor in the PA stage. This is because the optimum load Rp for a transistor PA is generally much lower than for a valve. With high power transistor PA stages the required value of Rp may in fact be very much lower than Ra.

In such cases the pi-coupler is generally not the most appropriate coupling network to use, as other networks involve fewer design trade-offs. However if the reader seeks to try out a pi-coupler, it should at least be borne in mind that the full equations (6) and (8) must be used in the design calculations.

Although this discussion of the basic operation and design of the pi-coupler has been rather brief, the author hopes that it will be found helpful.