amateur service newsletter
W6SAI

Pi and Pi-L Networks for Linear Amplifier Service

These graphs may be used to determine the values of components in Pi and Pi-L Networks. The graphs cover the most generally used operating Q's, load resistances and antenna impedances. To use the charts it is only necessary to know the plate voltage, peak plate current, the desired operating Q and the transmission line impedance.

Using the Pi Network Charts

A. Choose the amplifier tube(s) to be used. Select the plate voltage and determine the plate current for normal operation from the tube data sheet.

Assume, for example, that a Pi Network is to be designed for a pair of 3-400Z tubes operating at a plate potential of 2500 volts and a PEP input of two kilowatts. Peak envelope plate current is determined by:

$$\text{Peak envelope plate current (in amperes)} = \frac{\text{PEP Watts}}{\text{Plate Voltage}} \qquad (1)$$

$$= \frac{2000}{2500} = 0.8 \text{ ampere}$$

B. Determine the resonant load resistance from:

$$\text{Load resistance } (R_1) = \frac{\text{Plate voltage}}{2 \text{ x plate current in amperes}} \qquad (2)$$

For the case of the 3-400Z's, the load resistance is:

$$\text{Load resistance} = \frac{2500}{2 \text{ x } 0.8} = 1560 \text{ ohms}$$

C. Choose the operating Q. Good practice calls for a Q between 10 and 20. A Q of 15 is recommended for linear amplifier service.

D. Choose the antenna transmission line impedance (R_2). These charts are designed for use with either 52- or 72-ohm loads as coaxial cables for these impedances are generally available.

E. Find the reactance of the Pi Network coil from figure 1. For the case of the two 3-400Z's operating with a load resistance of 1560 ohms and a Q of 15, the reactance of the coil is approximately 120 ohms.

F. Find the reactance of the loading capacitor (C_2) from Figure 2. For the case of the 3-400Z's operating with a load resistance of 1560 ohms and a Q of 15, the reactance of the loading capacitor is about 20 ohms.

G. Find the reactance of the tuning capacitor (C_1) from figure 3. For the case of the 3-400Z's operating with a load resistance of 1560 ohms and a Q of 15, the reactance of the tuning capacitor is about 100 ohms.

Summary: For two 3-400Z tubes, operating at a plate potential of 2500 volts with a peak plate current of 0.8 ampere (two kilowatts PEP) and a Q of 15, the values of the Pi Network plate circuit are:

Tuning capacitor (C_1) = 100 ohms
Loading capacitor (C_2) = 20 ohms
Pi Network coil (L_1) = 120 ohms

Note: As a quick check, note that the sum of the reactances of the two capacitors is equal to the reactance of the inductor.

H. Determine the values of capacitance and inductance for the components of the Pi Network. Charts of the figures 2-44 and 2-45 show reactance values of inductors and capacitors in the range commonly used in r-f circuits for the h-f amateur bands. For the reactances determined for the 3-400Z tubes, the circuit components may easily be determined for each amateur band. In the case of the 20 meter band, for example, the values are:

Tuning capacitor (C_1) = 100 ohms = 133 pf
Loading capacitor (C_2) = 20 ohms = 565 pf
(above determined from figure 2-45)
Pi Network coil (L_1) = 120 ohms = 1.36 μH
(above determined from figure 2-44)

Using the Pi-L Network Charts

Figures 3,4,5 and 6 are used to determine the reactance of the components of the Pi-L Network.

A. Choose the amplifier tubes to be used. Select the plate voltage and determine the peak plate current for normal operation as outlined under step 1 for Pi Networks.

Assume, for example, that a Pi-L Network is to be designed for a single 3-1000Z operating at a plate potential of 3000 volts and a PEP input of two kilowatts. Peak envelope plate current (formula 1) is:

Peak envelope plate current (in amperes) = 0.667 ampere

B. Determine the load resistance, as outlined previously in formula 2:

Load resistance (R_1) = 2250 ohms

C. Choose the operating Q. (Let Q = 15).

D. Choose the antenna transmission line impedance. (Let R_2 = 52 ohms).

E. Find the reactance of the tank coil (L_1) from figure 4. For the case of the 3-1000Z operating with a load resistance of 2250 ohms, the reactance of the coil is approximately 215 ohms.

F. Find the reactance of the loading capacitor (C_2) from figure 5. In this case, the reactance is about 47 ohms.

G. Find the reactance of the tuning capacitor (C_1) from figure 3. In this case, the reactance is about 150 ohms.

H. Find the reactance of the loading coil (L_2) from figure 6. In this case, the reactance is about 140 ohms.

Summary: For a single 3-1000Z operating at a plate potential of 3000 volts with a peak plate current of 0.667 ampere (two kilowatts PEP), and a Q of 15, the value of the Pi-L Network plate circuit components is:

Tuning capacitor (C_1) = 150 ohms
Loading capacitor (C_2) = 47 ohms
Pi Network coil (L_1) = 215 ohms
L Network coil (L_2) = 150 ohms

I. Determine the values of the capacitance and inductance for the components of the Pi-L Network. Charts of figures 2-44 and 2-45 show reactance values of inductors and capacitors in the range commonly used for r-f circuitry for the h-f amateur bands. For the reactances determined for the 3-1000Z tube, the circuit components may be easily determined for each amateur band. In the case of the 80 meter band, for example, the values are:

Tuning capacitor (C_1) = 150 ohms = 275 pf
Loading capacitor (C_2) = 47 ohms = 900 pf
Pi Network coil (L_1) = 215 ohms = 9 μH
L Network coil (L_2) = 150 ohms = 6.5 μH

Note: Capacitance values are for resonance with a nonreactive load. It is suggested that the tuning capacitor have about 50% greater capacitance than indicated and the loading capacitor have 100% greater capacitance than indicated.

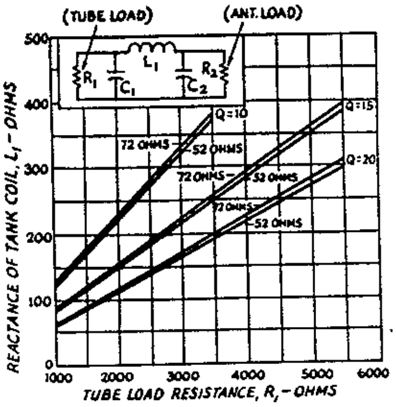

Fig. 1 — Reactance of tank coil, L_1, as a function of tube load resistance, R_1 (for pi networks).

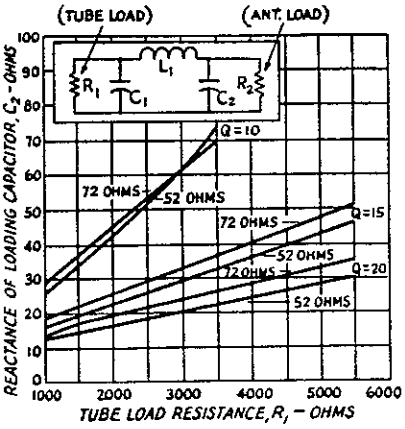

Fig. 2 — Reactance of loading capacitor, C_2, as a function of tube load resistance, R_1 (for pi networks).

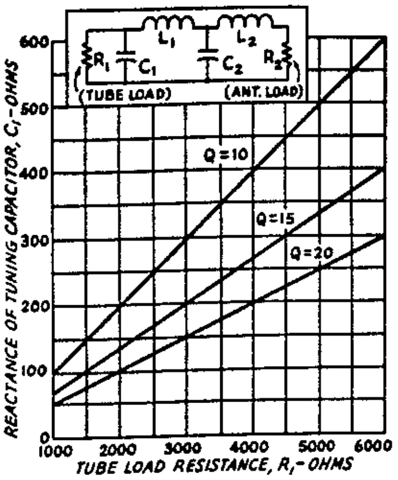

Fig. 3 — Reactance of tuning capacitor, C_1, as a function of tube load resistance, R_1 (for pi and pi-L networks).

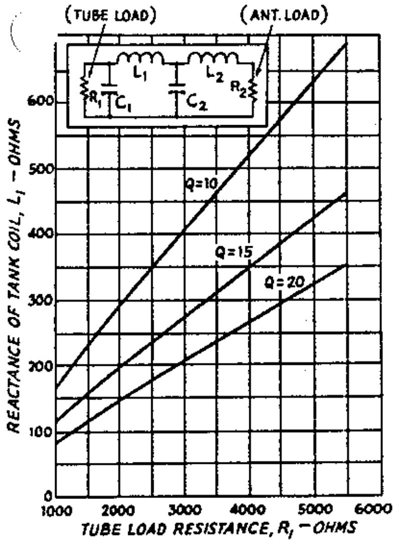

Fig. 4 — Reactance of tank coil, L_1, as a function of tube load resistance, R_1 (for pi-L networks).

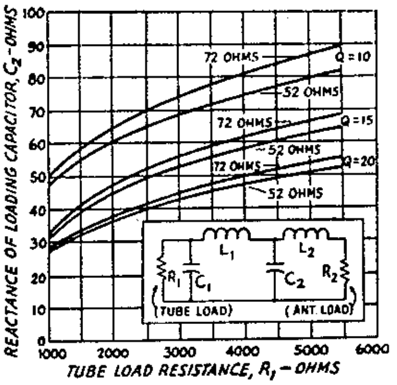

Fig. 5 — Reactance of loading capacitor, C_2, as a function of tube load resistance, R_1 (for pi-L networks).

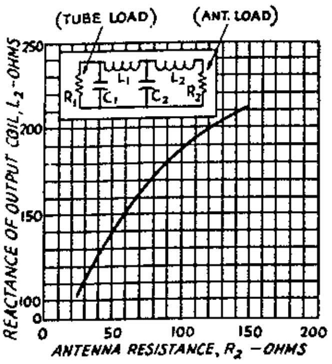

Fig. 6 — Reactance of loading coil, L_2, as a function of antenna load resistance, R_2 (for pi-L networks).

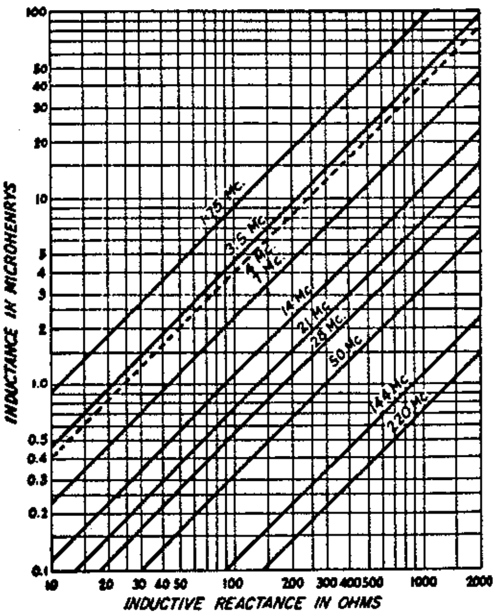

Fig. 2-44—Reactance chart for inductance values commonly used in amateur bands from 1.75 to 220 Mc.

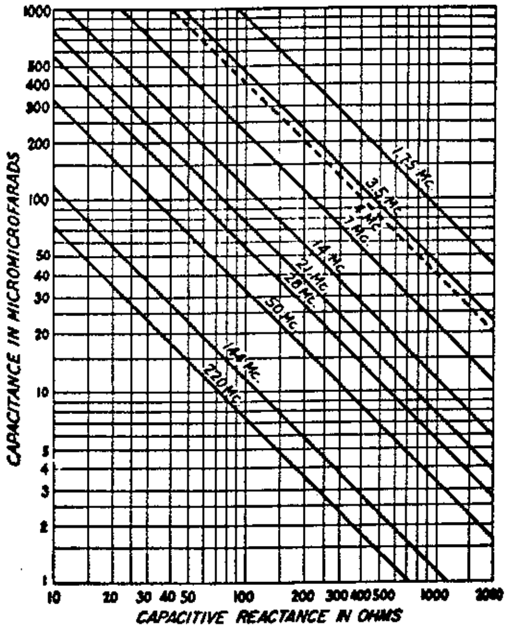

Fig. 2-45—Reactance chart for capacitance values commonly used in amateur bands from 1.75 to 220 Mc.

amateur service newsletter
W6SAI

Forced-Air Cooling of Transmitting Tubes

Some Considerations in the Selection of a Suitable Impeller

BY WILLIAM I. ORR,* W6SAI

We live at the bottom of a vast ocean of air. This invisible, life-supporting elixir provides the equipment designer with an inexpensive and efficient cooling medium for heat-generating devices, such as transmitters and receivers. Over the years, electronic equipment has grown more sophisticated and compact, and the problem of removing heat from the gear has become acute. Until someone miniaturizes the watt, heat-exchange systems will remain one of the major problem areas of equipment design. Aspects of forced-air cooling systems are discussed in this article.

Most electronic equipment generates heat, and this heat must be removed or the equipment will eventually burn up. The heat may be removed by radiation, conduction or convection [1], or by a combination of these methods. This article examines forced-air cooled systems (an efficient form of convection cooling), which are used in commercial transmitting equipments up to the level of tens of kilowatts and, in amateur gear, up to the so-called "two-kilowatt p.e.p." level. Generally speaking, from 20 to 70 per cent of the primary power drain of electronic equipment is dissipated in heat emitted from tubes and components, and the resulting temperature rise must be held within reasonable limits to insure satisfactory life for both the tubes and the other parts in the equipment.

The Air System

Two typical forced-air cooling systems for a power tube are shown in Figs. 1A and 1B. They consist of an air blower, or impeller; a conduit to guide the cooling air to the tube, or a pressurized chassis: the heat radiator of the tube: and an air exhaust exit. By stretching the imagination only a little, this air system can be compared to the electrical series circuit of Fig. 1C, in which each component in the air system is represented by a resistor which has a potential drop across it corresponding to the *back pressure* or resistance [2] that the original component offers to the flow of air. The sum of the back pressures in the air system must add up to the total pressure of air supplied by the blower, just as the sum of these voltage drops in the electrical analogy must add up to the generator voltage. The blower in the air system corresponds to the generator in the electrical system, of course.

The electrical analogy suffers in that the back pressure across a component in the air system does not strictly follow an equivalent of Ohm's Law for electric potential drops. Instead, the

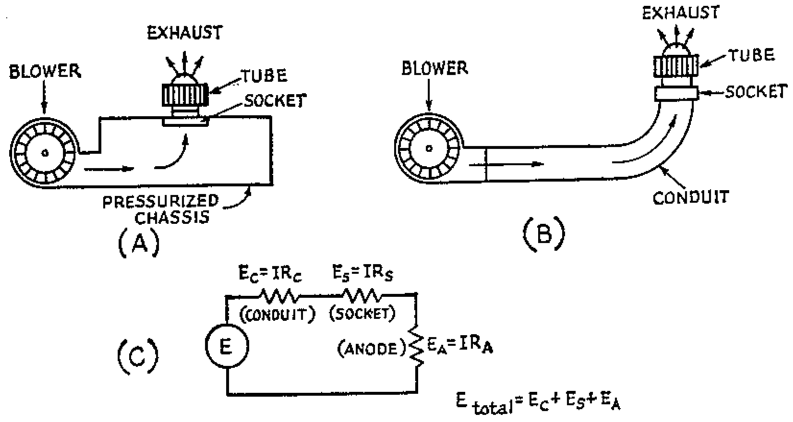

Fig. 1—A forced-air cooling system. In A, the blower is mounted directly on the chassis which is used as a plenum chamber. Air is exhausted past filament and plate seals of the tube. In B, the blower is mounted at some distance from the tube, and cooling air is conducted to the tube via a conduit or hose. C indicates an electrical analogy of the forced-air system. The blower is represented by generator *E*, and various unavoidable back pressures are represented by voltage drops across resistors *Rc* and *Rs*. Useful work (cooling the anode) is represented by voltage drop (E_A) across the tube.

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[1] Quinn, "The Stanley Steamer," *QST*, May, 1966.

[2] The resistance offered to the flow of air may also be expressed in terms of "pressure drop" or "static pressure."

back pressure across an air-system component varies approximately as the *square* of the airflow rate (volume per unit of time). Thus, if the volume demand is doubled, about four times the pressure will be necessary to meet the increased requirement. Even though the analogy is inexact, the transmitter designer who is comfortable in the presence of Ohm's Law for series circuits can gain insight of the action of pressure drops incurred in a forced-air cooling system.

The problem to be solved is that of determining the size and characteristics of an air blower that will satisfy the temperature limitations imposed upon a particular tube type by the manufacturer, and reconciling these limits with available blowers. Maximum operating temperatures and air requirements of forced air cooled transmitting tubes are generally supplied in the data sheet, or provided upon request by the tube manufacturer. This simplifies the problem considerably, as few engineers have the equipment or time to run temperature checks on transmitting tubes. Blower data, too, is supplied by the numerous impeller manufacturers. It remains, then, to translate this available and unfamiliar data into the proper hardware for the system at hand.

Tube Cooling Requirements

Forced-air-cooled transmitting tubes, such as the 4CX250B, 4CX1000A and similar external-anode tubes, require cooling air to be passed from base to anode[3]. Unless otherwise specified in the data sheet, cooling air should flow as long as the tube filaments are lighted. The external anode cooler of tubes of this family is usually composed of a number of copper fins arranged in a circle about the anode core, with the air passing vertically across the surface of the fins. An exchange of heat takes place between the fins and the passing air, the moving air extracting heat from the anode core and holding overall anode temperature at or below the maximum limit. As the air is impeded in its flow through the interstices of the anode structure, a back pressure is created, caused by friction of the air against the fin surfaces, and by turbulence of the air in the anode passages.

The cooling airflow requirement for transmitting tubes may be expressed in terms of the ratio of watts of anode dissipation to tube temperature (in watts per degree Centigrade) as a function of either the mass airflow rate in pounds of air per minute, or the volumetric airflow rate in cubic feet per minute[4]. This information may be expressed in graphic form (Fig. 2), enabling the design engineer to determine the actual cooling-air requirement in terms of specific tube temperature and system back pressure.

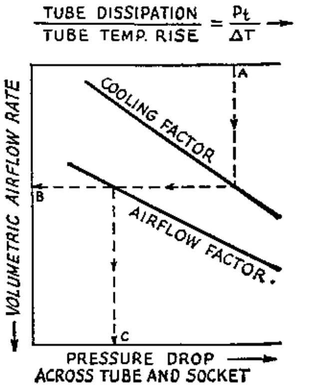

Fig. 2—Allowable temperature rise and dissipation (A) of power tube determine airflow rate (B) from laboratory measurements. Pressure drop (C) across the tube and socket may be measured by a manometer device. The interlocking relationship of cooling requirements may be expressed in graphical form, as shown here.

The total heat to be removed is determined from a study of the operating characteristics of the tube, and includes plate and filament dissipation (plus grid and screen dissipation where applicable). Maximum element dissipation rating is normally given in the data sheet. The operating temperature rise of the tube is found by taking the difference between the maximum measured tube temperature (at the hottest point of the tube) and the maximum inlet air temperature expected. The air requirements expressed by the plots of the cooling factor and the airflow factor are usually given as a pressure drop across the *tube and socket* expressed in *inches of water*, and a corresponding volumetric airflow is defined in *cubic feet per minute* (c.f.m.). This information is necessary to determine the size and speed of the blower required to provide the proper airflow through the system. Volumetric air flow may be calculated or determined by experimental means.

Air-Pressure Measurements

Air pressure in a forced air system may be defined in terms of an equivalent weight of water.

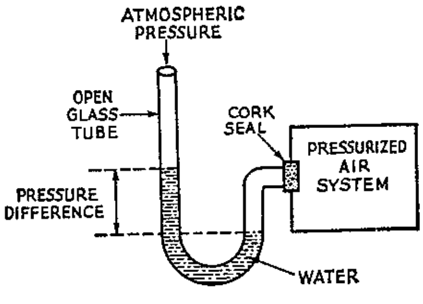

Fig. 3—A simple manometer compares system static pressure with atmospheric pressure. In this drawing, air flows at right angles to manometer input, i.e., into or out of this page. Pressure difference is expressed in "inches of water." Placement of manometer to avoid turbulence in the system should be determined by experiment.

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[3] Large convection- and radiation-cooled glass tubes (4-400A and 4-1000A, for example) also require forced-air cooling to hold seal temperatures within prescribed limits.

[4] Precise calculation of airflow in cubic feet per minute must take into account air humidity and barometric pressure. Equipment builders often design for a mythical user living in Denver, Colo., who operates the equipment on a hot, humid day.

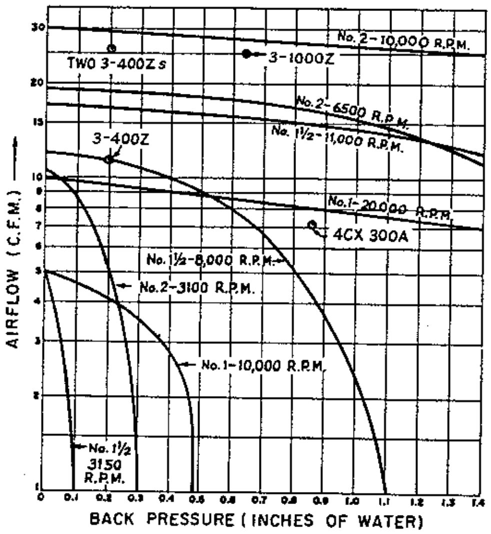

Fig. 4—Typical performance data for No. 1, No. 1½, and No. 2 centrifugal blowers. Performance of blowers of different sizes and speeds can be compared with the cooling requirements specified for various tube types. Notice that requirement points are shown for a pair of 3-400Zs as well as for a single tube. If the requirement point falls on or below the performance curve for a particular blower, that blower will give adequate cooling under the conditions outlined in the text. The curves show that blower efficiency drops rapidly after a critical value of back pressure is reached, and that the blower "windmills" (reaches zero output) at high values of back pressure. High-speed blowers can withstand more back pressure than can low-speed units (notice the curves for 10,000- and 20,000-r.p.m. blowers.

(The weight of a uniform column of water 27.7 inches high is 1 lb. per square inch of column base area.) The measurement is made by means of a *manometer* whose readings are expressed in inches of water (Fig. 3). A simple manometer for shop use may be constructed of a short length of ¼-inch glass tubing bent into a U shape, with one end left open to the atmosphere. The opposite end is inserted in the air system in proximity to the tube socket and *at right angles* to the airflow. Optimum position should be determined by experiment so as to make sure that the manometer is not influenced by eddy currents in the airstream. The bottom portion of the manometer is filled with water and, if the air pressure in the cooling system is equal to atmospheric pressure, the water will rest at equal heights in both vertical sections of tube. Under this quiescent condition, no air moves through the system or, if it moves, it encounters no back pressure. However, if a difference of pressure between the atmosphere and the inclosed air system is created by a blower, the water will be forced up towards the open end of the glass tube by the back pressure of the air moving through the system. The pressure within the duct or plenum, as compared to atmospheric pressure, may be noted by measuring the difference in height (in inches) of the two water columns, as shown in the illustration.

System Pressure Drops

Pressure drop in an air system is caused by physical obstruction to the flow of air, or by turbulence in the air. In the case of a tube anode which contains many fins over which the air must pass, the pressure drop is intentional and useful. Other system drops caused by air friction, pressure drops in the hose or socket, or a change in the air velocity in the system, are undesirable and not useful. All pressure drops caused by these factors must be added to the pressure drop of the tube and socket. Drops caused by an abrupt change in the cross-sectional area of a system include *both* expansion and contraction drops for variations in conduit area, and are additive. While these values may be calculated for a system of known dimensions, it is beyond the scope of this article to cover such calculations. Suffice to say that when the overall pressure-drop and airflow requirements are determined, it is possible to match the requirements to the blower characteristics to achieve satisfactory system cooling.

Blower Characteristics

Air blowers come in many shapes and sizes and some are "good" and some are "poor." The most commonly used impellers in air cooled systems are *squirrel-cage* (*centrifugal*) *blowers*, and *axial fans*. The important characteristics of an air cooling system are the relationship between blower-outlet back pressure (in inches of water) and the airflow (in cubic feet per minute), and these characteristics determine the blower to be used. It is foolhardy to determine the "good" air impellers from the "poor" impellers by intuition.

Graphs of typical squirrel-cage blower performance for various units are given in Figs. 4, 5 and 6. The areas under the curves are regions in which the blower does useful work. It can be seen that as the back pressure rises, the efficiency of the blower decreases until, at some critical value of back pressure, the blower ceases to function as a useful device and merely "wind mills" the air about the impeller blades and cavity. This is termed "blower cutoff." Blowers vary to a great degree in their ability to cope with back pressure: low speed, open axial fans are the least efficient, while high speed squirrel-cage devices have somewhat higher efficiency.

Squirrel Cages and Axial Fans

The typical squirrel-cage blower has a multi-bladed impeller wheel rotating within a tightly fitting housing.[5] Small units normally have the discharge edge of the blade inclined forward, in the direction of rotation. The inexpensive axial fan, on the other hand, has a few, large, wide blades (usually four), slowly rotating in the open air or in a short housing section. More expensive vane-axial impellers have more blades (five or six) and rotate at higher speeds.

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[5] The most efficient centrifugal blowers have a housing which closely fits the edges of the rotor. Excessive air gap between the rotor and the rim of the housing destroys the ability of the blower to work into back pressure.

Squirrel-cage blowers are often cataloged according to impeller wheel diameter and rotational speed. Thus a No. 2½ blower has a wheel diameter of 2½ inches, and may be available in a number of speeds, of which 2800, 3100, 6000 and 9000 r.p.m. are common off-the-shelf values. For a given wheel size and design, the c.f.m. delivered is proportional to blower speed, as is the ability to withstand system back pressure. Using the electrical analogy again, it may be said that the "voltage regulation under load" (ability to overcome back pressure) of any blower increases as the impeller speed increases. Unfortunately, as the impeller speed increases, the air noise, motor noise, vibration and unit cost also increase. While a 2800-r.p.m., or even a 6000-r.p.m. squirrel-cage blower may have a tolerable noise level, many 15,000-r.p.m. blowers create sufficient air noise to deafen even the most dedicated DX-contest operator.

Examination of the blower curves shows that a "trade-off" exists between rotational speed and wheel diameter and, generally speaking, a large impeller wheel running at moderate speed will be more satisfactory and less noisy than a smaller wheel running at a somewhat higher speed.

Inexpensive axial fans deliver large volumes of air at rather low rotational speeds and are generally fairly quiet, but suffer more than do squirrel-cage blowers from the effects of back pressure (Fig. 7). *Most small, low-speed axial fans and squirrel-cage blowers cannot move sufficient air into moderate values of back pressure to properly cool modern external-anode transmitting tubes, and their use should be tempered with caution.*

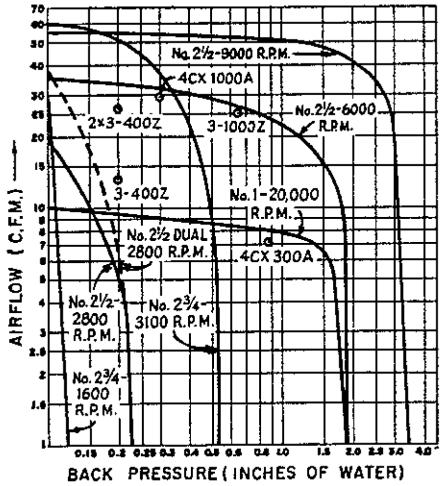

Fig. 5—Typical performance curves, similar to those of Fig. 4, for No. 2½, No. 2¾, and dual No. 2½ blowers. Notice that the No. 2½ 6000-r.p.m. blower will handle the cooling requirements of all of the tube types indicated, since the requirement points fall below the curve for this blower. "Wind-milling" is clearly indicated by the rapid drop of airflow to an unacceptable rate at the higher values of back pressure. Also notice that the use of dual blowers provides more airflow than a single blower of the same type at low back pressures, but does not project the "wind-milling" point.

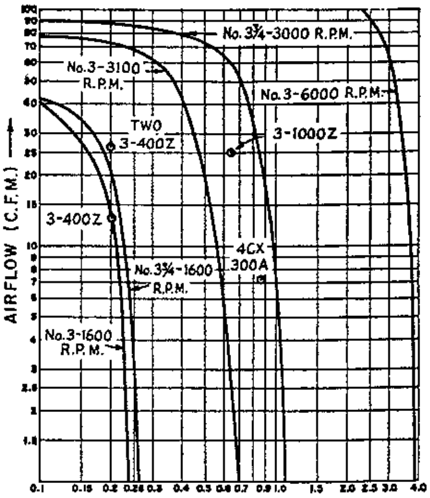

Fig. 6—Typical performance data for 3-, 3½- and 3¾-inch blowers. The low-speed (3100 r.p.m.) No. 3 blower cannot deliver the required flow of air into the back pressure offered by 3-1000Z or 4CX300A cooling systems. The 6000-r.p.m. unit, however, will handle the requirements of any of the tube types indicated, or, in fact, a pair of any of these tubes. Notice that doubling the speed of the blower more than triples the back-pressure capability. Although catalog-rated at "50 c.f.m.," the No. 3¾ 1600-r.p.m. blower is suitable for only low values of back pressure. When the speed is increased to 3000 r.p.m., the same-size blower will handle any of the tubes indicated.

Designing a Forced-Air Cooling System

An application of this design data, as a practical exercise, is the determination of a proper blower to cool a 4CX300A external-anode tetrode in an air-system socket, operating at various values of plate dissipation and 250° C. (maximum) anode temperature. If the ambient (room) air temperature is taken to be 50°C., airflow requirements to hold the tube temperature rise below 200°C at sea level, and at an altitude of 10,000 feet are graphed in Fig. 8. (These curves are based on figures taken from the data sheets for the 4CX300A and 4CX300Y.) If full 300-watt plate dissipation is desired at sea level, the air system must provide 7.2 c.f.m. of air *at the socket* of the tube under a combined tube and socket pressure drop of 0.58 inch of water. At an altitude of 10,000 feet (where the air is thinner), cooling requirements rise to 10.5 c.f.m. at a corresponding back pressure of 0.85 inch.

The additional pressure drops of the cooling system including back pressure developed by the cabinet structure, may be substantial, and must be added to the drop determined for the tube and socket. Unless a manometer is used to check the operation of the complete system, the additional back pressure caused by the duct coupling the blower to the tube and socket is a matter of speculation. If a pressurized chassis is employed having a large, internal open area (plenum chamber) into which the blower works, the additional system back pressure will be obviously less than if the blower has to force air through a flexible hose and around large under-chassis components. Experience has shown that it is generally safe to estimate an additional 50-percent back pressure requirement when the blower works directly into a reasonably clear pressurized chassis area, and this is the most common situation in amateur practice.

Taking the 50-percent extra back pressure requirement as par, an additional back pressure of 0.29 inch of water must be overcome for a total back pressure requirement of 0.58 + 0.29 = 0.87 inch of water for the system. The use of an inexpensive manometer to verify this educated estimate is recommended in the design of new equipment.

Turning to the squirrel-cage-blower data charts, it can be determined that a No. 1 wheel running at 20,000 r.p.m., or a No. 2 wheel running at a speed of 6500 r.p.m. will do the job, as will a No. 2½ wheel operating at 6000 r.p.m.[6] A No. 3 wheel operating at 6000 r.p.m. is more than satisfactory. The No. 3 wheel running at 3100 r.p.m., however, is unsatisfactory, as the graph of Fig. 6 indicates that the impeller "windmills" above approximately 0.6 inch back pressure, and that its output falls rapidly to cutoff zero slightly above this figure. In the interest of minimum noise it would seem prudent to choose a No. 2½ blower running at 6000 r.p.m. to properly cool the 4CX300A with a suitable safety margin. If blower size is a problem, it may be necessary to use a No. 2, higher speed blower at some increase in noise level.

Glass Tubes

Large glass transmitting tubes (above approximately 200 watts plate dissipation) require moderate amounts of cooling air passed over the filament and plate seals to hold the seal temperature below a safe maximum value. As a large quantity of heat is dispelled by infrared radiation from the hot anode, the air requirements of the glass-style tube are usually less than that amount required for an equivalent value of dissipation from an external-anode tube whose anode temperature is limited by the insulator seal. Proper cooling of the glass tube requires that the air pass over the filament seals and then be guided past the glass envelope by a chimney. The chimney must be transparent to infrared radiation from the tube. Lastly, the air passes over the plate seal and is exhausted from the system.

The 3-400Z zero-bias triode, for example, requires 13 c.f.m. at a back pressure of 0.13 inch at the socket, while the 3-1000Z requires 25 c.f.m. at a back pressure of 0.43 inch at the socket. While the amount of air required is of about the same quantity for comparable values of plate dissipation in external-anode tubes, the back pressure demand is considerably less for the glass envelope design, as the air is not required to flow through interstices of a cooling anode.

Referring again to the blower and fan charts, it can be seen that a 3-400Z may be adequately cooled by a No. 2 blower (6500 r.p.m.), or a No. 2¾ blower (3100 r.p.m.), when a 50-percent margin is allowed for extra system back pressure. Two 3-400Zs will require twice the c.f.m. at the same back pressure, or a total of 26 c.f.m. at a system pressure of 0.2 inch. In this case, the No. 2¾ blower (3100 r.p.m.) would suffice.

A single 3-1000Z requires 25 c.f.m. at a system back pressure of 0.64 inch (including the 50 percent safety factor), and a single No. 2½ (6000 r.p.m.) blower will do the job.

Either a single 3-400Z, or a pair, may be cooled by a 4-inch axial fan (2800 r.p.m. or higher), as such a device will work into a back pressure of about 0.2 inch. The 3-1000Z, however, cannot be properly cooled by the axial fans listed in Fig. 7.

In all of these examples, full plate dissipation is assumed, and the proper air-system socket and chimney for the tube in question is employed.

The unknown factor in the determination of the overall air-system requirement is the additional back pressure caused by the conduit system or plenum chamber arrangement. This is the reason that the tube manufacturer is reluctant to specify a particular blower for a given tube, as he does not know the characteristics of the overall air system to be used. If the blower works into a reasonably clear under-chassis area sealed for air leaks, and the air is exhausted through the tube socket, the safety factor of about 50 percent in back pressure mentioned earlier should be satisfactory. If, on the other hand, the blower is placed at some distance, with a connecting hose to the socket, blower requirements may rise by a factor of ten or more. *The only safe way to determine the actual requirements of a given air system*

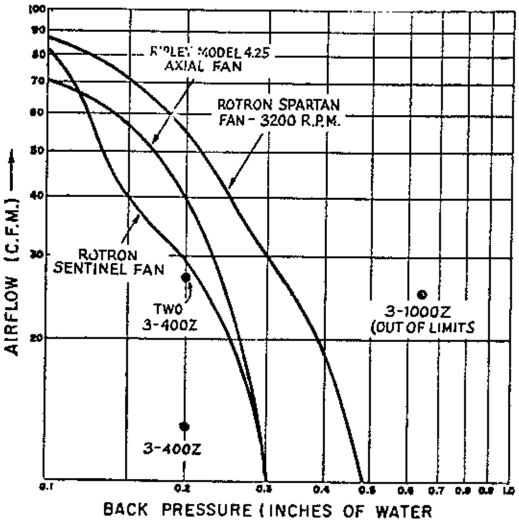

Fig. 7—Performance data for typical small axial fans. Medium-speed axial fans are suitable for a single 3-400Z, or a pair of this type. Axial fans must operate into a plenum chamber that transmits the air to the tube socket without introducing prohibitive additional back pressure. Tube date shown includes 50% extra back pressure, as discussed in the text.

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[6] The curves shown in Fig. 4 and those following, apply to specific models. All models of the same size number and rotational speed (even those of the same manufacturer) do not necessarily have the same performance ratings.

TABLE I

Air requirements and suggested blower data for various air-cooled tubes. Data is given for single tube, with 50 percent back-pressure allowance.

Tube Type	Socket	Chimney	C.F.M.[5]	Back Pressure (In. Water)[5]	Blower Size	R.P.M.
3-400Z	SK-410	SK-416	13	0.2	3	1600
3-1000Z	SK-510	SK-516	25	0.64	2½	6000
					3¾	3000
4-400A[1]	SK-410	SK-406	13	0.25	3	3100
4-1000A[2]	SK-510	SK-506	25	0.64	2½	6000
					3¾	3000
4CX250B[3]	SK-600 Series	SK-606 Series	6.4	1.12	2½	6000
4CX1000A 4CX1500B[4]	SK-800 Series	SK-806 Series	22	0.3	3	3100
5CX1500A	SK-840 Series	SK-806 Series	47	1.12	3	6000

[1] SK-400 socket requires 14 c.f.m. at 0.37 inch.
[2] SK-500 socket requires 25 c.f.m. at 0.9 inch.
[3] Data applies to 4X150A for 250 w. dissipation.
[4] Air requirement for 1000 w. dissipation.
[5] Sea level requirements.

is to make back pressure measurements with a manometer.

When in doubt as to the air-system requirements, it is wise to provide an oversupply of air at somewhat greater back-pressure values than estimated by a study of system requirements. It is impossible to damage a tube by too much air, unless the tube is blown out of the socket by the air blast! All low-speed blowers and axial fans should be avoided, too, unless a manometer is used to check out the system under full tube-dissipation conditions.

A summary based upon a 50 percent back-pressure safety factor for various tube and blower combinations is given in Table I.

Tube Temperature Measurements

Measurement of tube temperature is possible, and the most reliable technique is to use a thermocouple attached to the tube. A somewhat simpler technique for the radio amateur is to determine tube-surface temperature by the use of temperature-sensitive paint.[7] The paint is applied in a *very thin* coat to the tube and dries to a powdery finish after application. At its critical temperature, it melts and virtually disappears. After subsequent cooling, it has a crystalline appearance which indicates that the surface with which it is in contact has exceeded the critical temperature.

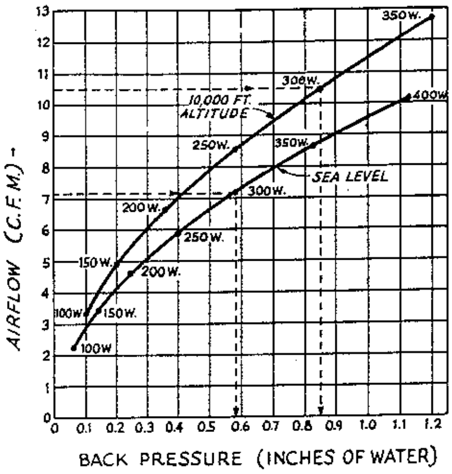

Fig. 8—Typical curves indicating how the cooling requirements increase with an increase in tube plate dissipation. These curves are for a 4CX300A mounted in an air-system socket. The dashed lines point out how the airflow requirements also increase with altitude because of the thinner atmosphere.

Reliable temperature measurements can be made with temperature-sensitive paint only if it is applied in a very thin coat over small areas of the surface to be measured. The substance as supplied by the manufacturer is too thick for use in the presence of forced-air cooling and must be thinned, using only the thinner recommended by the manufacturer. The paint is applied with an air brush or atomizer (or with an aerosol dispenser) in a well-diluted spray, as the amount required to produce a reliable indication is virtually unweighable. A convenient set of equipment for using the temperature-sensitive paints is an atomizer with several vials, each equipped with an airtight cap. One vial may be filled with thinner for cleaning the atomizer, while the re-

(*Continued on page 142*)

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[7] Temperature sensitive "decals" are also available

mainder are filled with properly-thinned paint sensitive to several different critical temperatures.

Measurements made with temperature-sensitive paint yield basic information sometimes obtainable in no other way, and are the "ounce of prevention" that is worth a "pound of cure."

Conclusion

Tube-surface temperatures are the ultimate criterion by which cooling adequacy may be judged. As tube life is closely related to surface temperatures, reliable temperature or cooling information is very important to the equipment-design engineer and the radio amateur. The proper choice of air blower is important, especially in cases where a high order of back pressure exists in the air system. Use of a manometer to determine back pressure, as well as the use of temperature-sensitive paint, allow the circuit designer to construct a satisfactory forced-air cooling system at the lowest possible cost.

Thanks and appreciation to Bill McAulay, W6KM, Ray Rinaudo, W6KEV, and Bob Sutherland, W6UOV for their suggestions and help in preparing this article.

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W6SAI

The Cathode-Driven Linear Amplifier

BY WILLIAM I. ORR,* W6SAI and WILLIAM H. SAYER, WA6BAN**

Neutralization and control of grid isolation within the cathode-driven amplifier permit the designer to adapt the basic circuit to the particular operating conditions at hand. Power gain and feedthrough power may be varied, and the amplifier can be stabilized for proper operation over a wide frequency range.

THE cathode-driven, or grounded-grid, amplifier[1] is ideally suited to amateur s.s.b. or c.w. service and seems to be gradually relegating the grid-driven amplifier to the junk box. The attributes of the cathode-driven amplifier are impressive: it has reasonable power gain, it usually requires no auxiliary neutralization below 30 megacycles or so, it offers lower residual circuit capacitance, and parasitic suppression is not difficult. Under certain conditions, moreover, inherent negative feedback exists in this configuration, to the benefit of amplifier linearity. Finally, a portion of the cathode r.f. drive power shows up in the output circuit, thus providing a degree of "free" output power not otherwise available from a conventional grid-driven circuit.

Strictly speaking, the extra output power is not "free," as r.f. power is expensive compared to d.c. plate power and may only be "free" if it is unavoidably available. It is generally referred to as *feed-through* power, but the implication in this term may be misleading, as this portion of the drive power does not appear in the load circuit of the cathode-driven stage until after it is converted to a varying d.c. plate potential effectively in series with the main amplifier power supply. This *converted drive power* performs a useful function in Class AB_2 and Class B linear service by swamping out the undesirable effects of nonlinear grid loading and presenting a reasonably constant load to the exciter[2].

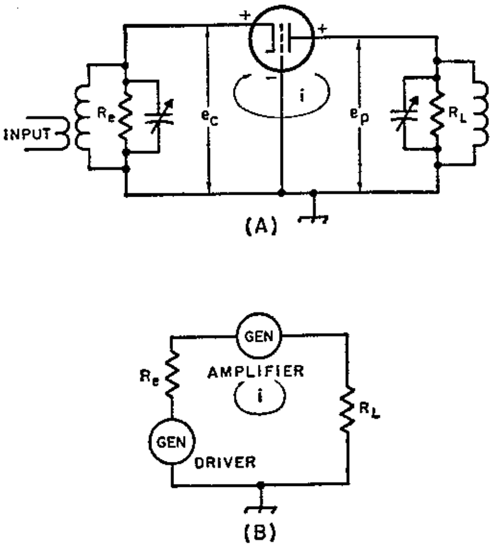

Fig. 1-A—The cathode-driven circuit. Driving voltage (e_c) is applied to the cathode of the amplifier and the output voltage (e_p) appears across the plate load impedance, R_L, in phase with e_c. The grid of the tube is at nominal ground potential. B—The driver and cathode-driven amplifier are in series with respect to the amplifier r.f. voltages. Amplifier cathode current (*i*) flows through the load resistance of the driver, contributing a degree of r.f. feedback.

The purpose of this article is to examine certain aspects of the cathode-driven amplifier, not widely recognized, that afford additional flexibility and versatility under particular operating conditions, and which permit accurate and complete neutralization to be achieved when needed.

The Basic Cathode-Driven Circuit

First discussed in *QST* in September, 1933,[3] the cathode-driven circuit has generated a considerable body of literature over the past few decades (see bibliography). The circuit is believed to have first been conceived circa 1920 by Ernst Alexanderson of alternator fame. Used about 1938 in European short-wave broadcast and TV service, this unique amplifier configuration became popular in U.S. post-war low-channel TV transmitters about 1944 or so.

The basic cathode-driven circuit is shown in Fig. 1. It may be operated either as an oscillator or as an amplifier by proper choice of components and potentials. The grid of the tube is nominally at r.f. ground potential and the exciting signal is applied to the cathode, or filament. For amplifier service, if it is assumed that the cathode is instantaneously driven positive with respect to ground (the grid), the plate will become more positive with respect to the cathode, and also with respect to ground. The instantaneous plate voltage, in effect, is developed in series and in phase with the exciting voltage, and the driver and amplifier stages may be thought of as op-

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[1] The term "cathode-driven," or "grid-isolation" is preferred over "grounded-grid," as the latter implies that the grid is at r.f. and d.c. ground. This is often not the case.

[2] Pappenfus, Bruene and Schoenike, *Single Sideband Principles and Practice*, McGraw-Hill Book Co., N. Y. (1964).

[3] Romander, "The Inverted Ultra-audion Amplifier," *QST*, September, 1933.

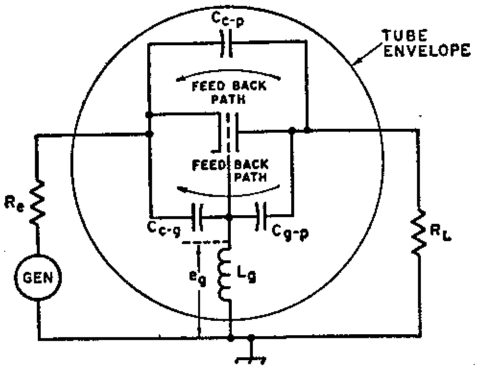

Fig. 2—Distributed constants of cathode-driven tube. Cathode-to-plate (C_{c-p}), cathode-to-grid (C_{c-g}) and grid-to-plate (C_{g-p}) capacitances, together with grid-lead inductance (L_g) make up feedback paths that must be neutralized for proper operation of the cathode-driven amplifier. Two feedback paths enter the picture: the direct path from plate to cathode via C_{c-p}, and a more devious path via series capacitors C_{c-g} and C_{g-p}.

erating in series to deliver power to the load, R_L. The delivered power is the sum of converted drive power and amplifier power, less any power from the driver required by the amplifier grid circuit. A parallel-tuned circuit is used in the cathode of the amplifier to enhance the regulation of the driver stage, to complete the plate circuit r.f. return path to the cathode, and to provide proper driver termination over the operating cycle.[4]

As the cathode-driven amplifier is effectively in series with the driver stage, the output current passes through the load resistance of the driver (R_e), causing a voltage drop across that resistance which opposes the original driving voltage. This indicates that inverse feedback is inherent in the cathode-driven amplifier to some degree if the driver has appreciable load resistance.[5]

Neutralization

The familiar cathode-driven amplifier used in h.f. amateur service is usually not neutralized. That is to say, no external neutralizing circuit is built into the amplifier. This omission has led to the general belief that the "grounded grid acts as a shield" and neutralization is not necessary in any and all cathode-driven amplifiers. The accepted proof of this belief is the fact that most h.f. amplifiers, in most instances, will not oscillate in use. Operation of an unneutralized cathode-driven amplifier in the upper portion of the h.f. spectrum, however, may provide unpleasant surprises. Many amateurs have found to their chagrin that such an amplifier is often a tricky "beast" to tame at 10 and 6 meters.

The reason for the unwanted instability is simple. Wires and leads represent finite inductances, and their position relative to each other and to other circuit components represents capacitance; both these quantitites may have an effect upon amplifier performance. Vacuum tubes have these distributed constants within their envelopes in the form of interelectrode capacitances and lead inductance.

Voltage feedback from output to input through the distributed constants of the tube has a deleterious effect on amplifier performance. The magnitude, phase and rate of change with respect to frequency of this feedback determine the dynamic stability of the amplifier, and control of feedback is termed *neutralization.* The purpose of neutralization of any amplifier, regardless of circuitry, is to make the input and output circuits independent of each other with respect to voltage feedback and the resulting reactive currents.[6] When a cathode-driven amplifier is operated at the higher frequencies, the internal capacitances and the inductance of the grid structure of the tube contribute to the degree of feedback (Fig. 2). To achieve stability, the various feedback paths through the distributed constants inherent in the tube structure must be balanced out, or nulled, in some fashion by neutralization techniques. Proper neutralization may be defined *as the state in which, when plate and cathode tank*

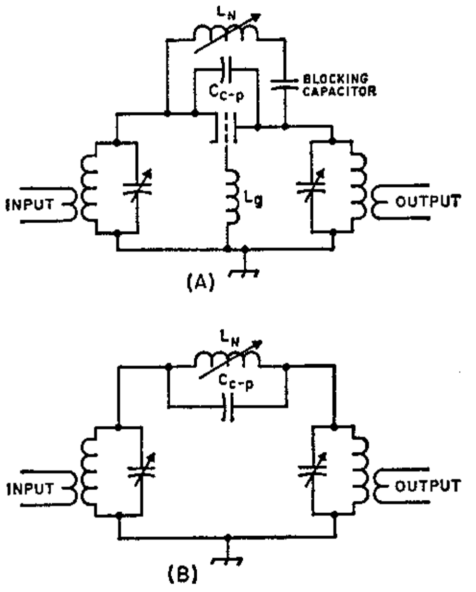

Fig. 3-A—Cathode-plate inductive neutralization. Capacitive feedback path between cathode and plate via C_{c-p} may be neutralized by making the capacitance part of a parallel-resonant circuit tuned to the operating frequency by the addition of L_n. A blocking capacitor is used to remove the d.c. plate voltage from the coil. Neutralization is frequency sensitive. B—Equivalent circuit; high-impedance parallel-resonant circuit nullifies feedback path between input and output circuits via plate-to-cathode capacitance.

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[4] C. E. Strong, "The Inverted Amplifier," *Electrical Communication* (England), Volume 19, No. 3, 1941.

[5] J. J. Muller, "Cathode Excited Linear Amplifiers," *Electrical Communication* (England). Volume 23, September, 1946.

[6] In fact, the cathode voltage is dependent to a degree upon the output voltage, as the input and output circuits are in series.

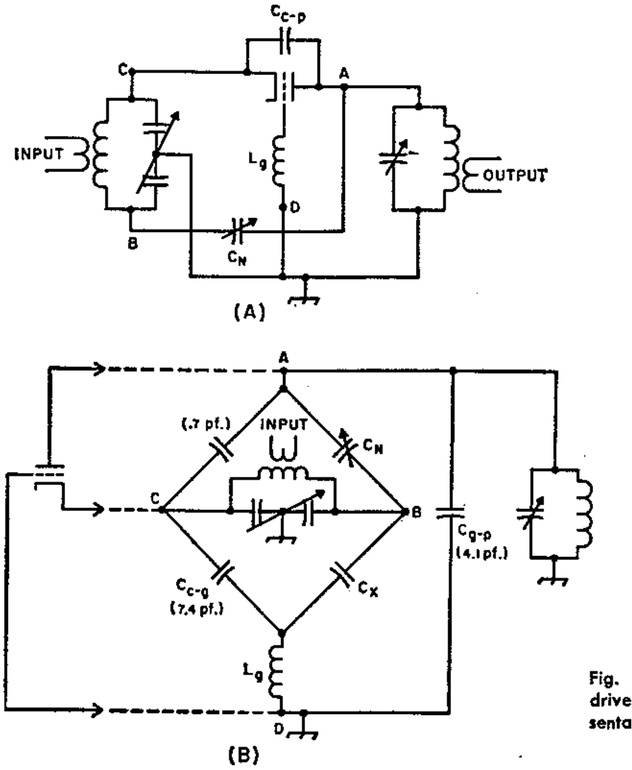

Fig. 4-A—Cathode-plate bridge neutralization. Balanced input provides euqal out-of-phase voltages at points *B* and C. When C_N is equal to $C_{c\text{-}p}$, equal out-of-phase voltages will cancel each other at point *A* and feedback path via $C_{c\text{-}p}$ is neutralized. B—Neutralization circuit redrawn in bridge form, with typical capacitance values for 3-400Z triode shown in parentheses. Bridge is balanced except for capacitance C_x, representing residual capacitance to ground at point *B*. If the balanced input circuit is high-C in comparison to interelectrode capacitances of tube, capacitances $C_{c\text{-}g}$ and C_x are swamped out and bridge may be considered to be balanced.

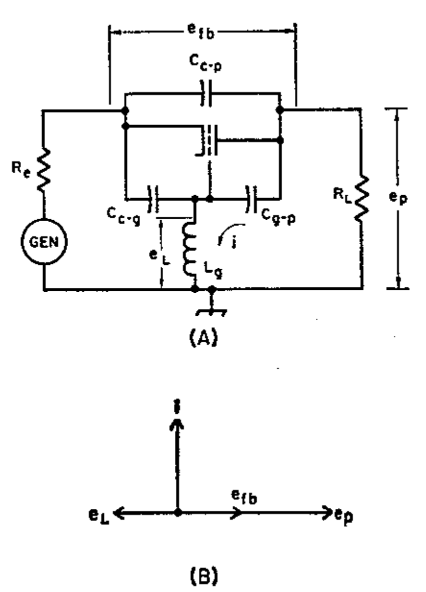

Fig. 5-A—Three-terminal representation of cathode-driven tube. See text for explanation. B—Vector representation of feedback voltages in cathode-driven tube.

circuits are resonant, maximum cathode voltage, minimum plate current, and maximum power output occur. This definition implies that the input and output circuits are independent of each other with respect to common reactive currents, and that tuning of the circuits reveals no interaction.

As the grid of the tube is at nominal ground potential in a cathode-driven amplifier, it appears that this element may act as a screen, or shield, between the output and input circuits and that instability or oscillation due to feedback paths through the interelectrode capacitances of the tube may be avoided, or reduced to negligible values. At the lower frequencies, particularly with respect to well-shielded, low-gain tubes, this belief may be true. However, in the higher-frequency region the practical tube (i.e., the tube that can be built) departs to an important degree from this simplified concept.

Neutralizing the Cathode-Driven Amplifier

Stable operation of the cathode-driven amplifier often requires some form of neutralization when the frequency of operation approaches the upper reaches of the h.f. spectrum. Complete circuit stability requires neutralization of *two* feedback paths, for which separate techniques are required.

The first feedback path involves the cathode-to-plate capacitance, $C_{c\text{-}p}$. Although the capacitance involved is small, the path is critical and requires neutralization. Neutralization may be accomplished either by a shunt inductance (Fig. 3) or by a balanced capacitive bridge circuit (Fig. 4). The first technique consists of connecting a reactance from plate to cathode of such magnitude as to transmit back to the cathode circuit a current equal in value but opposite in phase to the current passing through the cathode-to-plate capacitance. The bridge technique is a version of the well-known capacitance neutralizing circuit used in conventional grid-driven amplifiers to balance out the effects of grid-plate capacitance. The balanced input circuit provides equal out-of-phase voltages to which the cathode of the tube and the neutralizing capacitor are coupled. As the value of the neutralizing capacitor is equal to the cathode-to-plate capacitance of the tube, the voltages are balanced at the junction of the two capacitances, which is the plate termination of the cathode-driven tube. Both capacitances are usually quite small, and the effect of series lead inductance in the bridge circuit is relatively unimportant. Consequently a reasonable bridge balance over a wide frequency range may be obtained with a single setting of the neutralizing capacitance.

The shunt-inductance neutralizing circuit of Fig. 3, on the other hand, has the disadvantage of requiring adjustment for each working frequency, as the external inductance and cathode-to-plate feed-through capacitance form a frequency-sensitive parallel-resonant circuit at the operating frequency.

Either neutralizing circuit may be properly balanced[7] even though the grid of the tube may not be at actual ground potential because of internal grid inductance, L_g. Intrastage feedback resulting from this inductance requires a separate, unique solution, apart from the neutralizing technique just discussed.

Grid-Inductance Neutralization

The second feedback path in the cathode-driven stage includes the grid-to-plate capacitance, the cathode-to-grid capacitance and the series grid inductance, L_g, as shown in Fig. 2. The grid inductance represents the sum of all possible feedback paths *through* the grid structure, plus the actual series inductance of the grid structure. In practical tubes, there is no possibility of avoiding all inductance in the path between the active grid element of the tube and ground. This path exists because the grid is not a solid, intercepting structure. After all, openings must exist to permit electrons to pass from the cathode to the plate! Capacitance leakage can exist between the cathode and the plate through these openings. In addition, Maxwell's equations state that changing electric and magnetic fields propagate each other through space. In the vicinity of the real grid structure, the electric field about the "input" side of the structure gives rise to currents flowing in the structure which, in turn, cause an electric field to exist about the "output" side of the structure. In addition, electromagnetic coupling through the interleaved grid structure is also observed[8].

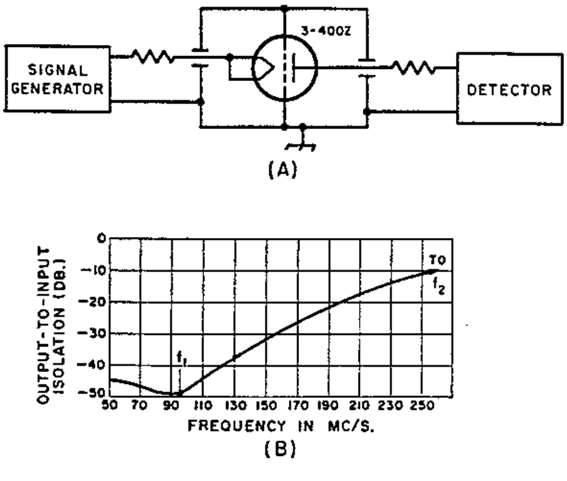

Fig. 6-A—The self-neutralizing frequency of a cathode-driven triode may be measured by observing the transmission properties of the cold tube when treated as a three-terminal network. B—Typical plot of intrastage isolation of 3-400Z triode mounted in test fixture. Self-neutralizing frequency of tube is about 100 megacycles.

These spurious coupling paths result in an apparent r.f. leakage through the cathode-to-grid and grid-to-plate capacitances that is often many times greater than that predicted by actual measurement of the internal capacitances. A simplified picture of this complex path may be seen as an inductance in series with the grid-to-ground path, common to both input and output circuits (Fig. 2). If this path is not neutralized, a voltage e_g appears on the grid of the tube which either increases or decreases the driving voltage, depending upon the value of internal capacitances and grid inductance. With sufficient spurious grid voltage, the cathode-driven stage may oscillate, or be unstable, even though the cathode-to-plate feedback path discussed earlier is completely neutralized.

The voltage e_g on the so-called "grounded grid" is determined by a complex action between the total cathode-to-plate capacitance and a separate low-Q circuit composed of a capacitive voltage divider ($C_{c\text{-}g}$ and $C_{g\text{-}p}$ in series) together with the grid inductance, L_g. A certain frequency at which these two feedback paths nullify each other is termed the *self-neutralizing* frequency (f_1) of the tube. This frequency usually occurs in the lower portion of the v.h.f. spectrum with small transmitting tubes. All the elements comprising the neutralizing circuit are *within the tube.* However, connecting the tube into the circuit by wiring or socketing will alter this frequency.

The self-neutralizing phenomenon comes about because of a frequency-sensitive voltage balance that takes place within this network, Fig. 5A, and which may be explained by a simple vector diagram, Fig. 5B. The r.f. plate voltage (e_p) causes a current (i) to flow through $C_{g\text{-}p}$ and L_g. If the reactance of L_g is small in comparison with the reactance of $C_{g\text{-}p}$ (as would be the case below the self-neutralizing frequency), the current i will lead the plate voltage e_p by 90 degrees. In flowing through L_g this current will develop a grid voltage (e_L) which is 180 degrees out of phase with e_p and with the voltage e_{fb} fed back to the cathode via $C_{c\text{-}p}$ and series-connected $C_{c\text{-}g}$ and $C_{g\text{-}p}$.

At some frequency the voltage e_L developed across L_g will just equal the voltage fed back through the interelectrode capacitances (e_{fb}). The frequency at which e_L is equal to e_{fb} is the self-neutralizing frequency. At this frequency a cancellation of feedback voltages occurs and the complex feedback path is nullified, or "neutralized." (A second, somewhat higher, frequency at

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[7] With physically large tubes having appreciable series input inductance, in-phase neutralization is often required. This may be achieved by adding external cathode-to-plate capacitance, or by detuning the shunt inductor from the condition of parallel resonance.

[8] Feedback admittance also is enhanced by the self-inductance of the grid wires, which provides common coupling between input and output circuits. The inductive coupling may partially compensate for the feedback through the cathode-to-plate capacitance. (See Bibliography, item 3.)

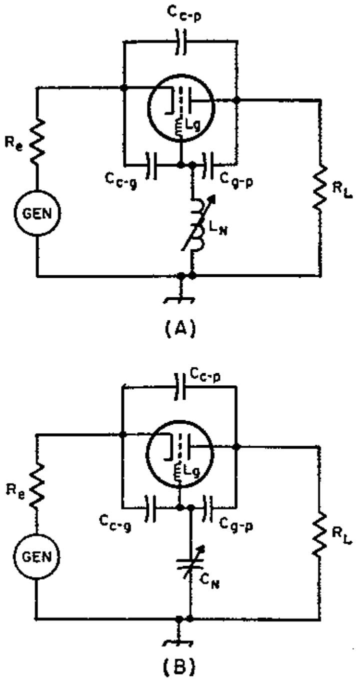

Fig. 7-A—The point of self-neutralization may be shifted lower in frequency by the addition of an inductance (L_n) in series with the grid-to-ground termination of the tube. B—The point of self-neutralization may be shifted higher in frequency by the addition of a capacitor (C_N) instead of an inductor.

which the complex grid configuration is in a series-resonant state with respect to intrastage isolation is called the *grid series-resonant frequency* (f_2) of the tube.)[9]

The Self-Neutralizing Characteristic Curve

The self-neutralizing characteristic of a cathode-driven triode may be determined by treating the tube as a passive three-terminal network and measuring transmission as a function of frequency. The tube is placed in a test fixture which is contrived to insure that the frequency measured is dependent on the tube and socket only (Fig. 6). A signal is applied to the "cold" tube through an appropriate attenuator and a detector is used to measure the transmission voltage through the tube. Investigation over a range of frequencies will produce a typical plot such as shown in Fig. 6B. The point of maximum isolation is the self-neutralizing frequency, f_1. Measurements are not quantitative, as nothing is known about the impedance of the input or output circuits. The relative isolation with respect to frequency, however, is the interesting parameter.

The self-neutralizing frequency (a broad null of several hundred kilocycles) may be moved about by manipulation of the external grid-to-ground circuitry of the tube, or by changing the capacitive feedback path. Or, if desired, a secondary point of neutralization may be created, as described later. If the desired frequency of operation is above the self-neutralizing frequency the voltage developed on the "grounded grid" will be too great and the series grid inductance, L_g, must be reduced, or the feedback path adjusted to establish self-neutralization. If the operating frequency lies below the self-neutralizing frequency, the voltage on the "grounded grid" will be insufficient to cancel the feedback voltage and the series grid inductance must be increased.

The portion of the plot around the point f_1 has been experimentally verified by observing the intrastage leakage (transmission) properties of a 3-400Z zero-bias triode mounted in an SK-510 socket and fixed in a partition in an r.f.-tight enclosure. Observation was over the range of 50 to 250 megacycles, and the self-neutralizing frequency was seen to be in the neighborhood of 100 megacycles (Fig. 6B). Above this frequency, the intrastage isolation gradually deteriorated as the series-resonance frequency, f_2, of the grid element was approached. Near the latter frequency, tube operation is impractical, being further complicated by transit-time effects and other v.h.f. phenomena.

The Self-Neutralizing Frequency

The self-neutralizing frequency of a cathode-driven triode depends to a large degree upon the size of the tube, the interelectrode capacitances, the physical configuration of the grid structure and the inductance of the grid leads and terminals. Below this frequency, the tube can be neutralized by the addition of a small inductor (L_N, Fig. 7) in the grid-to-ground path. Above this frequency, neutralization may be achieved by reducing the reactance of the path by the addition of a suitable series capacitance, C_N. To demonstrate this a variable capacitor was placed in series with one grid terminal of the 3-400Z mounted in the test fixture. At any frequency between f_1 and 250 megacycles the shape of the plot could be altered by adjustment of the capacitor, providing a neutralizing "null," Fig. 8, in the curve of about the same amplitude as observed at the lower frequencies. The Q of the neutralizing circuit (one grid lead plus the capacitor) was considerably higher than the Q of the grid system, and the neutralizing adjustment proved to be rather frequency-sensitive. The original self-neutralizing frequency (f_1) was little altered by the addition of the auxiliary circuit.

A second test conducted on a larger tube (the 3X2500A3, a 2.5-kw. low-μ triode) showed that it could be neutralized on the lower-frequency side of the self-neutralizing frequency f_1 by the addition of a suitable inductor between the grid terminal and ground. Both techniques are shown in Fig. 7.

It should be noted that intrastage self-neutrali-

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[9] "Care and Feeding of Power Grid Tubes", application bulletin No. 13, EIMAC, a Division of Varian, San Carlos, Calif.

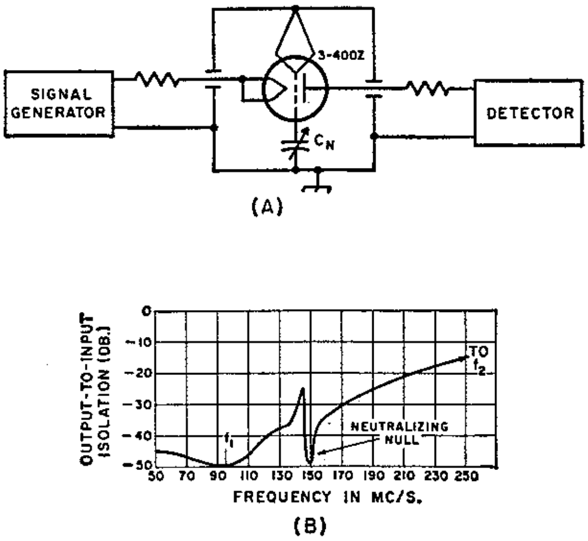

Fig. 8-A—The 3-400Z may achieve neutralization over a wide v.h.f. range by the addition of a series capacitor in one grid lead. Neutralization adjustment is frequency sensitive and must be peaked for maximum intrastage isolation of the operating frequency. B—Plot of intrastage isolation of 3-400Z, showing neutralizing null added by the series grid capacitor. Null may be moved about between f_1 and f_2. A similar neutralizing effect may be obtained at frequencies lower than f_1 by the circuit shown in Fig. 7-A.

zation and cathode-plate neutralization are interlocked. In the lower portion of the v.h.f. spectrum only one technique may be necessary to achieve a satisfactory degree of neutralization, at least as far as amplifier stability goes. At 6 meters, for example, either system will completely stabilize many amplifiers in most situations. At higher frequencies such is not the case, and both feedback circuits may require attention and manipulation to allow the amplifier in question to be properly neutralized.

General Remarks

Conclusions to be drawn as to the degree of intrastage isolation, or as to the requirement for neutralization in a cathode-driven amplifier, tend to be clouded unless backed by measurements made on the equipment, just as is the case with grid-driven amplifiers. In the latter instance, neutralization of the circuit is almost taken for granted. Not so with cathode-driven amplifiers, as adequate isolation and stability have often been achieved at the lower frequencies even with tubes that were not designed for this purpose. It is unwise to jump to the general conclusion that this special situation exists in all cases.

At the lower frequencies, particularly with well-shielded, low-capacitance tubes, neutralization may not be necessary, and this permits the circuit designer to make use of circuit techniques and practices that afford variation of power gain, converted drive power, and degree of inverse feedback to the cathode driven amplifier. Specifically, these parameters may be varied to meet the demands of the system or to adjust the converted drive power requirement of the amplifier to match the available drive power of the exciter. These circuit schemes, however, should not be confused with the separate problems of amplifier neutralization, discussed in this article.

A future article will discuss *super-cathode-driven* and *semi-cathcde-driven* circuits. The authors wish to thank W. H. McAulay, W6KM, and R. I. Sutherland, W6UOV, for their help and suggestions in preparation of this article. QST

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