Cathode Phase Inversion

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Application of cathode phase inversion previously described is made to several practical circuits including symmetrical cathode-ray oscillograph amplification, high fidelity d.c. amplification, and differential or mixer amplifier operation. The theory of a symmetrical degenerative attenuator modification of the basic circuit is developed and practical applications are described.

The cathode phase inversion amplifier (Fig. 1) is a form of self-inverting push-pull amplifier which is now finding considerable application in scientific and in commercial apparatus. Essentially, the cathode phase inversion stage is a conventional push-pull amplifier stage in which the cathode resistor $R_K$, common to both tubes, has been increased until the product of its resistance with the mutual conductance of either amplifier tube is large with respect to unity, and in which the cathode return (−) is biased to a suitably high negative potential with respect to the control grid. Under these circumstances, a signal applied to either control grid appears almost symmetrically amplified, but in opposite phase, in the two plate circuits.

Since the degenerative voltage which is produced in the common cathode resistance when a signal is applied to one grid serves as an input signal in reversed phase to the second grid, amplification is not lost in the phase inversion process but totals between the two output circuits approximately as much as would be obtained with a single tube non-inverting amplifier.

For sufficiently large values of the common cathode resistance $R_K$, the amplified signal splits symmetrically between the two output circuits, but as the cathode resistance becomes small, a larger fraction of the total output signal appears in the plate circuit of the tube to which the input signal is applied. The ratio of the plate signal magnitude in the input tube to that in the other plate circuit is given by the expression

$$\frac{E_{p1}}{E_{p2}} = 1 + 1/G_m R_K,$$

where $G_m$ is the mutual conductance of one tube and $R_K$ is the cathode resistance. Tubes and plate circuits are assumed identical.

Because this phase inversion is accomplished without loss of amplification in the stage circuit is economically adapted to ordinary amplifier use. Here it can be employed in the final power stage, as well as in one or more of the preceding stages. In any case it eliminates...
The push-pull input transformer, and, when used in the low level stages, permits operation from quite poorly filtered power supplies because of the degenerative self-filtering action of the circuit.

While the negative cathode bias voltage, by means of which the control grids are held at earth potential in Fig. 1, is a luxury available in many research instruments, its presence is unnecessary if, as is the case in capacitance-coupled and many d.c. amplifiers, the grids may be at a positive potential. In these cases the circuit of Fig. 2 is used, the cathode return being made to earth and a positive bias from a bleeder resistor supplying the control grids. The bleeder, incidentally, need carry no appreciable current, since no current flows in the grid circuit. If pentodes or tetrodes are used, their control grids may conveniently be supplied from the same divider which energizes their screens.

The modification of the circuit shown in Fig. 3 is peculiarly adapted for oscillographic use, directly coupled to either magnetic or electrostatic deflection cathode-ray tubes, since here the circuit serves not only as a phase inverter and final amplifier but also provides a means of shifting the axis of the beam to either limit of the tube’s screen without requiring increased linear output characteristic of the final amplifier for complete tube face coverage.

On investigation of the relationship obtaining in the basic circuit Fig. 1, it will be seen that in response to a change in the average control grid potential, the average plate voltage of the two tubes in one stage changes in the ratio of the parallel resistance of the two plate resistors to the resistance of the common cathode resistor. As this ratio is normally small and can be reduced even below unity, the circuit is especially suited for use as a direct coupled amplifier using voltage divider coupling as illustrated in Fig. 4. Suppose the amplifier were to consist of three stages of 100 gain each, and the resistor ratio were allowed to remain as high as 3. In this case, the final stage drift occasioned by a 0.1-millivolt chance variation in the average input grid potential would appear as $10^{-4} \times (3)^2$, or 2.7 millivolts drift in the average output potential. Meanwhile the amplification of the system would be one million, so that the response to a difference of potential between the two input grids of 0.1 mV would be 100 volts. Asymmetric variations of current in the input tubes due to emission, microphonics, or other disturbances would, of course, be fully amplified along with the signal.

Additional advantages of this type of amplifier are that it responds equally well to a push-pull input, a single sided input with one input terminal grounded, or to the difference between two independent inputs each applied to a separate grid. Where the absolute value of the input potential is being measured, and where conditions make it awkward to connect the standard potentiometer either between the unknown source and earth or between it and the grid, the potentiometer can be plugged into the opposite grid circuit and, within a small ascertainable error, will read directly, and can simultaneously take up any amplifier drift. It will be noted, further, that so long as heater-cathode type tubes are used, any number of stages can be supplied from one filament source and one plate source. As all
cathodes operate at approximately the same potential there is no cascading of potentials. This form of amplifier has been found of considerable usefulness in studying bioelectric phenomena.

In this circuit, as in most push-pull systems, attenuation presents a serious problem, since exactly equal loss must be inserted into each side of the circuit to keep potential differences symmetrical, and because two variable elements must usually be inserted into each stage which is to be controlled. Since the total attenuation usually cannot be accomplished in one stage, this means a multiplicity of ganged resistance elements. In the case of d.c. amplifiers, further difficulty arises because attenuation must not occasion baseline shift. These troubles can be avoided by the slight change in the fundamental circuit illustrated in Fig. 5. Here the common cathode resistor $R_k$ has been replaced by separate ones (each having twice the original resistance) joined by a single variable element. It will be obvious that, as a limiting condition, this circuit passes over into the one illustrated in Figs. 1 and 2 when $R$ becomes equal to zero, but when $R$ becomes infinite, the over-all amplification becomes about equal to the ratio of the plate resistance of one tube to that of one cathode resistor. This ratio will usually be from 3 to 5. Between the two extremes the amplification changes continuously.

The approximate amplification may be calculated for any value of the attenuating resist $R$ with the aid of the formula

$$A = \frac{R_pR_eG_m}{R_p + R_s + G_m R_t R_s + R_t}$$

where

$$R_t = \frac{2RR_k}{R + 4R_k}$$

Here $A$ the useful amplification is given in terms of $R_p$ the dynamic plate resistance of one tube, $R_s$ the resistance of one load resistor, and $G_m$ the transconductance of one tube. This formula applies primarily to triodes and gives less accurate results for pentodes and tetrodes unless the transconductance to the screen is taken into account.

Upon inspection of this formula it will be noted that the introduction of resistance decreases amplification rapidly at first, then more slowly as the total amplification becomes smaller. Used with an ordinary logarithmic control, very nice control can be maintained.

Fig. 6 illustrates quantitatively the range of amplification available from a stage of 1852.
nodes as used to drive a cathode-ray tube of
7-inch variety.

It might be pointed out that the circuit A
(Fig. 7) is electrically replaceable by the circuit
(Fig. 7) by the delta-star transformation) if
\[ R_1 = \frac{2R_K}{(R+4R_K)}, \quad R_4 = \frac{4R_K}{(R+4R_K)}. \]

This allows convenient calculation of the output
symmetry introduced along with any desired
amount of attenuation since the calculated

equivalent value of \( R_1 \) can be inserted in Eq. (1).
As only one resistor element need be intro-
duced per stage, up to three stages can easily be
controlled from one knob, thus eliminating stage
changing or other complicated maneuvers. The

amplification of the whole amplifier is constant
enough at all but the highest gains to permit
pre-calculation of the resistor constants and
their construction into a tapped pad to be cal-
ibrated directly in terms of over-all gain. This

ability results from the effective negative
feedback introduced by the use of the cathode

to cathode resistor.

As usual, where attenuation is achieved
through use of negative feedback, the linearity
of the amplifier improves as greater attenuation
is introduced, and consequently a long linear
voltage output characteristic accompanies even
moderate attenuation. This is illustrated by Fig.

1 which plots the plate to plate output voltage
against unilaterally applied input voltage at
several attenuations for a typical 6J7G cathode-
ray pre-amplifier stage fed from a 225-volt
power supply. The pentodes, ordinarily bad
offenders in respect of linearity, are seen to give
260 volts of linear output at a stage gain of 50,
while they produce 300 volts of output at 14
gain. It should be remembered, however, that
this linearity is achieved as the result of cathode
feedback, and consequently is current linearity.
This is to advantage in certain systems—like
magnetically deflected cathode-ray tubes—where
current must remain constant independent of
frequency; it is, however, a detriment to high
frequency operation of capacitative systems,
like electrostatically deflected cathode-ray tubes.
Even in this case, however, frequency linearity is
easily obtained without compensation up to
10,000 cycles, and, with care, as high as 40,000
cycles.

In those cases where it is of no consequence
that an amplifier shall not respond well below,
perhaps, 10–20 cycles per second, the cathode
resistor may be replaced by a choke, or, if the
attenuation method is to be employed, by a pair
of chokes. In this case the grids may be main-
tained at a convenient zero potential and yet
have no large loss of plate supply potential in

the common cathode resistors. Often a choke can
be found having the correct d.c. resistance to
bias the tubes; if not, it can be supplemented
with small additive resistors.

Calculation of the necessary cathode resistance
in any case is extremely simple. If no attenuator
is to be employed, the value of \( R_K \) will be

\[ R_K = R_C + \frac{V}{I}, \]

where \( R_C \) is the published value of cathode
resistor for ordinary push-pull operation, \( V \) is
the voltage between control grids and the cathode
return and \( I \) is the desired value of total plate
current for the two tubes. For use with the
attenuator circuit, twice this resistance is inserted
in each branch of the circuit.