The Anode Follower

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Possessing virtues far in excess of its namesake the cathode follower, the anode follower provides the audio engineer with a simple tool for achieving a wide range of high-quality audio circuits.

THE "ANODE FOLLOWER" is so called because, in its simplest version, the anode of the amplifier tends to reproduce the input signal in much the same manner as does the cathode in a cathode follower. It is a tool of unusual versatility to the electronic designer. Although the cathode follower is more or less limited to a gain approaching 1.0, the anode follower suffers no such limitation; gains of more or less than 1.0 are easily attained. In common with the cathode follower, the anode follower may have high input and low output impedances. Again, it is not greatly restricted in this sense.

The term "anode follower" is generally applied to single stages of amplification supplied, in addition to the active element, with a series input impedance and a feedback impedance. In its strict sense, the term is applicable only when the input and feedback impedances are identical, so that under the usual conditions, the gain approaches 1.0. For want of a better term, the plate of a tube, the collector of an *npn* transistor, and the colector of a *pnp* transistor, are all called anodes, even though the last is a negative element. The versatility of this type of amplifier arises from possibilities of using nonidentical impedances; in such cases, although the similarity to the cathode follower ends, the term "anode follower" persists.

Circuits of this type find manifold uses in the entire field of electronics. They may be used as simple mixers, to add several inputs with very little interaction or loss of gain; by their use, signal filtering may often be accomplished with minimum loss of gain; as impedance-matching devices, they are far more versatile than cathode followers; and in the audio field, such stages provide good amplification with wide frequency response and notable lack of distortion.

Design of such a stage involves more, however, than simple addition of two impedances to an ordinary vacuum-tube or transistor stage. If satisfactory results are to be obtained, attention must be paid to the choice of impedance values, and unless the impedances are properly chosen, the circuit is apt to perform somewhat differently than expected. Unfortunately, treatments accorded the circuit in various texts make assumptions that tend to obscure the factors affecting the proper choice of impedances. For this reason, it has appeared worthwhile to consider the circuit at some length; this article summarizes the results of that work.

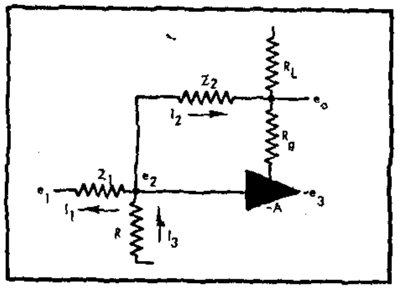

Fig. 1. Basic scheme of the anode follower.

ANALYSIS

Consider an amplifier (Fig. 1) in which a feedback element, Z_2, is connected between output and input. Z_1 is a series input impedance and R is an input shunt. In practical circuits, R may be very large (as in the case of tubes with a single input) or quite small. The latter situation arises when the amplifier has a low input impedance (e.g., a transistor) or when the amplifier is used for mixing a number of inputs, in which case R represents the paralleled resistances of all inputs other than the one whose behavior is being investigated.

The usual analysis of anode-follower circuits ignores the existence of R but, as will be seen, its effect upon the performance of the circuit may be quite profound.

With the currents as shown in *Fig.* 1, the following equation is obtained:

$$\frac{e_2}{R}=\frac{e_1-e_2}{Z_1}+\frac{e_0-e_2}{Z_2} \tag{1}$$

which, rearranged, yields

$$e_2\left(\frac{1}{R}+\frac{1}{Z_2}+\frac{1}{Z_1}\right)=\frac{e_1}{Z_1}+\frac{e_0}{Z_2}. \tag{2}$$

Equation (2) is the basic equation for the anode-follower circuit.

Gain

Let $e_2=-e_0/A$, indicating that the amplifier has a phase shift of $n \cdot 180°$ where n is an odd number. Then, equation (2) becomes

$$-\frac{e_1}{Z_1}=e_0\left[\frac{1}{Z_2}+\frac{1}{A}\left(\frac{1}{R}+\frac{1}{Z_1}+\frac{1}{Z_2}\right)\right]$$

from which

$$\frac{e_0}{e_1}=-\frac{1}{\dfrac{Z_1}{Z_2}+\dfrac{1}{A}\left(\dfrac{Z_1}{R}+\dfrac{Z_1}{Z_2}+1\right)} \tag{3}$$

The exact implications of this equation depend upon the use to which the circuit is to be put. Examples of such uses will be treated subsequently.

Impedances

In equation (2), let $e_0=-Ae_2$; then

$$\frac{e_2}{e_1}=\frac{RZ_2}{(A+1)RZ_1+Z_1Z_2+RZ_2}. \tag{4}$$

An analysis of the voltage divider shown in *Fig.* 2 shows the voltage e_2 is related to the input e_1 by precisely the same equation (4) as was derived for the feedback amplifier. In *Fig.* 1, the current entering the circuit through Z_1 sees, at e_2, an impedance of R in parallel with $Z_2/(A+1)$. When viewed from the grid of the tube or the base of the transistor, therefore, the impedance Z_2 looks like $Z_2/(A+1)$.

In the expressions for gain and input impedance appears the term A for the amplification of the amplifier. This A is the gain that would be measured if the Z_2 were connected between the output and ground rather than between output and input. Calculations of A must therefore include the loading effect of the feedback impedance.

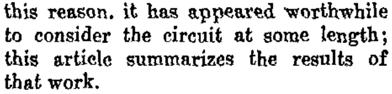

Fig. 2. Equivalent input circuit for the anode follower.

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The output impedance may be found by letting $e_1 = 0$ and considering a signal to be applied at e_0. A certain fraction, β, of this signal will be fed into the amplifier input, resulting in an output $e_2 = -\beta A'e_0$ which will cause more current to flow in R_g than would be the case in the absence of the feedback. The current is, as a matter of fact, multiplied by the factor $(1 + A'\beta)$ so that the generator resistance, R_g, appears from the output terminals as

$$\frac{R_g}{1 + A'\beta}.$$

In the general case, β is complex so the net generator impedance, R_g, will also be complex. A complete expression for Z'_g, applicable to *Fig.* 1, is derived simply by replacing β by its equivalent in terms of impedances:

$$\frac{Z'_g}{R_g} = \frac{1}{1 + A'\left[\dfrac{Z_1R}{Z_1R + Z_2R + Z_1Z_2}\right]} = \frac{Z_1R + Z_2R + Z_1Z_2}{(1 + A')Z_1R + Z_2R + Z_1Z_2}. \qquad (5)$$

It must be remembered that the actual output impedance of the circuit is Z'_g in parallel with R_L.

The gain A' that appears in equation 5 is the gain that would be realized from the amplifier with an infinite load resistance; it may be considerably larger than the quantity A that appeared in previous expressions.

Spurious Inputs

The effects of spurious inputs such as noise, drift, and microphonics are generally expressed in terms of an equivalent signal to the grid of the tube or the base of the transistor. If the spurious input is of magnitude δ, then the output of the amplifier in *Fig.* 1 is not given by $e_0 = -Ae_2$, but rather $e_0 = -A(e_2 + \delta)$. The effects of δ are therefore added to e_2.

If the above expression for e_0 is solved for e_2 and this e_2 is substituted into equation (2), the result is

$$-e_0 = \frac{e_1}{\dfrac{Z_1}{Z_2} + \dfrac{1}{A}\left(\dfrac{Z_1}{R} + \dfrac{Z_1}{Z_2} + 1\right)} + \frac{A\delta}{1 + \dfrac{ARZ_1}{RZ_1 + RZ_2 + Z_1Z_2}}. \qquad (6)$$

When this is contrasted to the open-loop equivalent, consisting of the passive filter of *Fig.* 2 followed by an amplifier A, for which the output is

$$-e_0 = \frac{e_1}{\dfrac{Z_1}{Z_2} + \dfrac{1}{A}\left(\dfrac{Z_1}{R} + \dfrac{Z_1}{Z_2} + 1\right)} + A\delta \qquad (7)$$

it is seen that the effects of the spurious signal are reduced in the anode follower by the factor

$$F = \frac{RZ_1 + RZ_2 + Z_1Z_2}{(1 + A)RZ_1 + RZ_2 + Z_1Z_2} \qquad (8a)$$

over that which would be observed with the open-loop circuit. This factor, of course, holds whether the spurious signal effects at the plate or the grid are under consideration.

In case where R is much larger than Z_1 or Z_2

$$F' = \frac{Z_1 + Z_2}{(1 + A)Z_1 + Z_2}. \qquad (8b)$$

APPLICATIONS

Amplifiers

The equations so far derived may be used to design a stage of amplification with predetermined characteristics, or to find the effects of certain uncontrollable factors on the performance of an existing stage.

When straight amplification is being considered, the object of the anode-follower circuit is usually one of the following: (a) to devise a highly-stabilized stage whose amplification is substantially unaffected by a reasonably small change in tube or transistor characteristics, (b) to provide an amplifier of low output impedance, (c) to accomplish control over the input impedance, or (d) to control the frequency response.

In the usual case, it is desirable that the gain be controlled by impedances Z_1 and Z_2, remaining substantially independent of A. With the substitution $A \to \infty$ in equation (3), the gain expression becomes

$$\frac{e_0}{e_1} = -\frac{Z_2}{Z_1}.$$

and the problem is to determine the magnitudes of Z_1, Z_2, and A such that this condition can be closely realized. Now, the presence of the shunt input resistance R may greatly affect the performance of the stage. In the case of a vacuum tube, R is usually the grid-return resistor, around one megohm; but if a transistor is used R may be of the order of 2000 ohms. Because of its small input resistance, a transistor anode follower may not operate as expected unless attention is paid to the magnitudes of Z_1 and Z_2.

From equation (3) it may be seen that if the gain is to be determined principally by Z_1 and Z_2, then we must have

$$\frac{Z_1}{Z_2} > \frac{1}{A}\left(\frac{Z_1}{R} + \frac{Z_1}{Z_2} + 1\right).$$

(1) If $Z_1 \leqq Z_2$ and $Z_1 > R$, the condition is $AR > Z_2$.

(2) If $Z_1 \geqq Z_2$ and $R > Z_1$, the condition is $AZ_1 > Z_2$ or $Z_1/Z_2 > \dfrac{1}{A}$.

(3) If $Z_1 > Z_2$ and $Z_1 \leqq R$, the condition is $1 > 1/A$.

In the discussion that followed equation (4) it was shown that, viewed from the input terminal of the amplifier, Z_2 looks like $Z_2/(A + 1)$. Condition (1) above is tantamount to saying that $Z_2/(A + 1)$ must be small compared to the shunt resistance, R. Since the other two conditions apply when Z_1 R, it $\leqq$ may be concluded that a condition for the proper functioning of an anode follower is that the shunt resistor, R, multiplied by the gain of the amplifier, must be large compared to the feedback impedance.

Anode-follower feedback may be used to overcome the detrimental effects of certain inalterable amplifier characteristics. Consider a grounded-emitter transistor amplifier with an input resistance of 3600 ohms, a gain of 100, and a collector-base capacity of 36 mmfd. Suppose further that this amplifier must be driven from a source with an internal impedance of 30,000 ohms. Viewed from the input, the collector-base capacity looks like (101)(36) = 3636 mmfd and this, together with the source resistance, leads to a 3 db drop at about 1500 cps. If, for audio work, a response out to 40,000 cps were desired, a resistance equal to the reactance of 36 mmfd at 40,000 cps could be introduced between collector and base. The resistor would be about 100,000 ohms and the voltage gain of the stage (= output voltage/generator open-circuit voltage) would be 3. This gain is, of course, quite low and it points up the unsuitability of this type of transistor in a grounded-emitter transistor stage for use with high-impedance sources, in cases where good voltage gain and wide response are desired.

The amplifier, A, may consist of a single stage of amplification, or any odd number of phase-inverting stages. Because of instability problems, the number of stages is usually limited to three, but even a three-stage amplifier may have properties unattainable with a single stage. For example, by loading a low-impedance tape-playback head with about 10 ohms, a constant-current output is obtained which requires very little equalization. Given a grounded-emitter transistor stage with a gain of 100, the feedback resistor would have to be 1000 ohms to attain this low input impedance, but such a heavy load on the transistor output is apt to lead to low gain and excessive distortion. If, however, three stages are used ($gain = 10^6$) then the feedback resistor may be 10 megohms for the same 10-ohm input impedance.

Mixing

An anode follower may be used to mix several inputs, with good isolation between the signal sources. The various inputs are all connected, through their own series input resistances, to the anode-return resistor. The series resistor of each input looks into a shunt resistance equal to the paralleled input resistor of

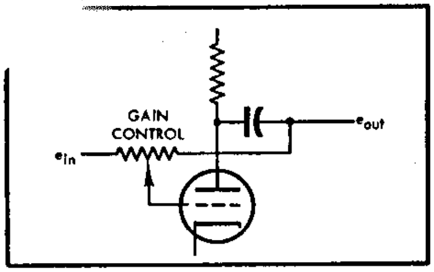

Fig. 3 Anode-follower gain control.

all other inputs. There is thus a limitation on the gain that may be obtained with a mixer.

Let it be desired, for example, to mix $(n+1)$ inputs, each having an internal resistance of R ohms, by means of an anode follower with a gain of about 1.0. For each individual input, Z_1 will be a resistance equal to R, while the shunt resistor will be R/n. Presumably, the feedback impedance Z_2 will also be R. In this case, obviously, $Z_1 \gg R$ (that is, $R \gg R/n$) so that the first condition of the previous section applies. Thus, we must have $AR/n \gg R$ which imposes a rough lower limit on A. If, for example, ten inputs are to be mixed, $n=9$, so we have $R \gg R/9$. If we let $AR/n = 9R$ (which introduces a sort of pseudo consistency) then $A = 81$.

The symbol "$\gg$" is, of course, much less definite than the symbol "=". If we wish to find how far the actual circuit departs from ideal performance, recourse must be made to the original equations. In the case of the 10-channel mixer we should find

$$\frac{e_o}{e_1} = -\frac{1}{1+\frac{1}{81}(9+1+1)} = -0.9$$

instead of the 1.0 that was expected. Were a gain of exactly 1.0 desired, an adjustment could be made to the value of Z_2 to obtain it.

Gain control

It is possible, by using the anode follower, to duplicate the gain characteristics of any combination of passive filter and simple amplifier. Although gain control is customarily carried out by means of resistive attenuators, it may also be performed by an anode follower (*Fig.* 3).

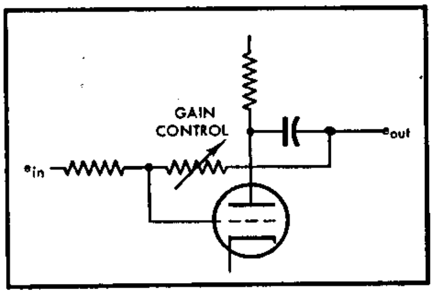

Fig. 4. Anode-follower gain control with fixed input resistance.

The anode-follower gain control has the advantage that the distortion of the stage is greatly reduced at low levels. For this reason, this type of gain control is particularly felicitous with transistors, which are generally operated with much larger ratios of signal-to-power-supply voltages than are tubes, and which are therefore more susceptible to distortion.

The input resistance of the gain-control stage varies, depending upon the setting of the gain control. A minimum input resistance may be set by introducing a small series resistor into the input; its effect is also to set the maximum gain of the stage. Where an approximately fixed input resistance is desired, an alternative arrangement can be used (*Fig.* 4) in which a fixed input resistor and a varying feedback resistor are employed. The maximum size of the feedback control is determined by conditions previously outlined.

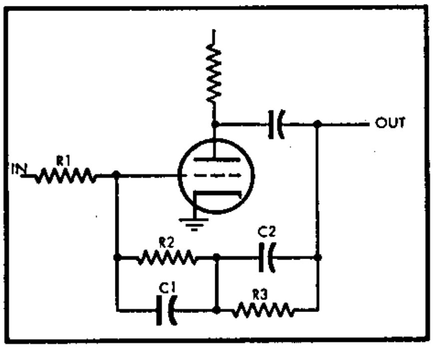

Fig. 5. RIAA equalizer stage.

Equalization

The anode-follower circuit permits a great deal of control over the frequency response of an amplifier. When equalization is the object, the impedances Z_1 and Z_2 may be complex, and their limiting values are determined by already-stated considerations.

For instance, let us consider the design of an amplifier to provide correct RIAA recording characteristic for playback. As is well known, the desired playback equalizer shows a flat response up to 50 cps; between 50 and 500 cps it drops with increasing frequency at 6 db per octave. Between 500 cps and about 2100 cps the response is again flat, while above the latter frequency the response again drops, as the frequency increases, at the rate of 6 db per octave.

In the design of an equalizer stage, the gain at one particular frequency may be specified. For a phonograph equalizer, it is usually wise to set the low-frequency (below 50 cps) gain, which is the maximum gain over the audio spectrum, at from one-fourth to one-tenth that of the open-loop stage. *Figure* 5 shows the design of an anode follower for accomplishing the necessary equalization. At low frequencies, the gain of this stage is determined by the feedback resistances $R_2 + R_3$ and the input resistance R_1. At 50 cps, C_1 begins to shunt R_2 and the response begins to drop; this drop continues until the reactance of C_1 is equal to R_3, which should occur at 500 cps. At 2100 cps, capacitor C_2 begins to shunt R_3 and the response again drops off above this frequency.

Most phonograph pickups operate well with a load resistance of 27,000 ohms or more. Thus, R_1 may be 27,000 ohms. If the tube has a gain of 150, the gain at 50 cps may be set at about 15. Within the ranges of commercial capacitors and resistors, the values $R_2 = 330k$, $R_3 = 33k$, $C_1 = 0.01$ *mfd*, and $C_2 = 0.0022$ *mfd* meet the requirements quite accurately, and permit a gain at 1000 cps of about 1.22. R_1 may be reduced for pickups that can operate into lower resistances, with a resultant improvement in gain.

Tone control

A tone-control stage is a variable equalizer of rather simple characteristics. A tone control using the anode-follower circuit has been designed by Baxandall; a simplified and highly satisfactory version is shown in *Fig.* 6. The difficulty in its design is carrying out two control functions (i.e., bass and treble) independently. If it is remembered, however, that the bass-control capacitors present effective short circuits at high frequencies, then it can be seen that the components effective in the bass control are capacitors C_2 and C_3 along with resistors R_3 and R_4 and the bass control itself; the components effective in treble control are the capacitor C_1 and the resistors R_3 and R_4, along with the treble control.

This circuit is also very effective with transistors, provided suitable impedances are used. *Figure* 7 shows a transistor stage which permits as much as

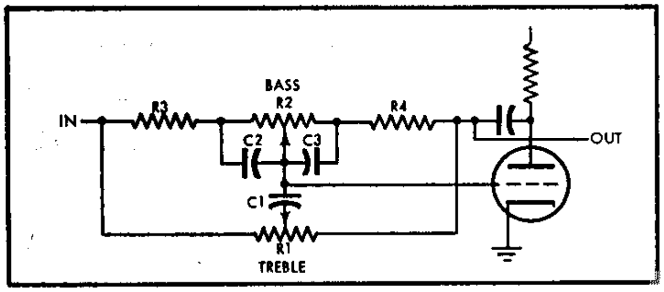

Fig. 6. Simplified Baxandall tone control.

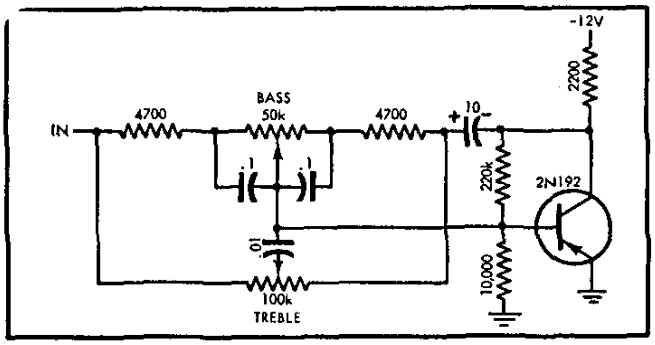

Fig. 7. Transistor anode-follower tone control.

15 db boost at 20 cps. Linear controls are used, and in the flat position the response is down only 1 db at 10 cps and 100,000 cps. The *IM* distortion (60/7000 cps, 4:1) with a 12-volt supply is less than 0.3 per cent at an output of 1 volt rms.

Capacity pickups

Capacity pickups are useful devices for the measurement of small displacements, particularly where it is important to avoid loading the unit being measured. An excellent phonograph pickup may be designed by causing the stylus to move a small metallic plate closer to, and farther from, a fixed plate. Often, the maximum permissible dimensions of the capacitor plates are very small, so that the capacity between them is minute, particularly in comparison to stray capacities that exist elsewhere in the circuit. For example, in a capacity pickup, the capacity between plates may be 2 mmfd. while the stray capacities between each side of the connecting line and ground may be over 200 mmfd. If an attempt is made to obtain an output from the pickup by polarizing one plate, grounding the other, and obtaining the signal from the polarized plate, the effect of the stray capacities is to attenuate the signal severely.

An anode follower may be used to overcome these effects. Here, the capacity pickup is, *in effect, connected* between the anode and input terminals of an amplifier. It has already been demonstrated that by this means the capacity is effectively multiplied by $(A+1)$. At the same time, the strays are split, half of them being shunted between the anode and ground, and the other half between the input terminal and ground. By this means, the stray-capacity attentuation of the signal is reduced to a considerable extent.

D.c. amplification

A d.c. anode follower can be constructed by inserting a v-r tube in the feedback path of the conventional circuit to attain a favorable distribution of d.c. voltages (*Fig.* 8). An amplifier of this type has a large useful gain, reasonably low drift, low output impedance, and input and output terminals at approximately ground potentials in the quiescent state. If it is necessary that the input and output terminals be exactly at ground potential, a small resistor may be inserted in the cathode of the amplifier tube to adjust to this equality.

Because the plate-load resistor of the tube must carry not only the plate current of the amplifier, but also the v-r tube current, it is generally of somewhat lower resistance than it would have been in a similar a.c. amplifier. For this reason, high-perveance triodes are very useful in d.c. anode-follower amplifiers.

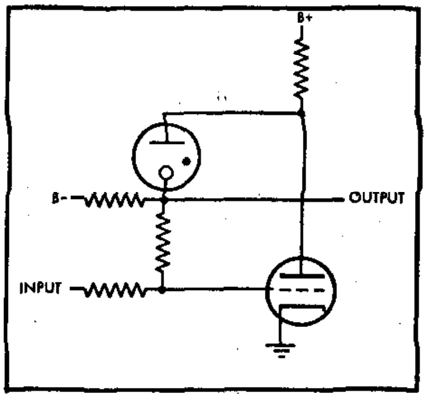

Fig. 8. D.c. anode-follower amplifier.

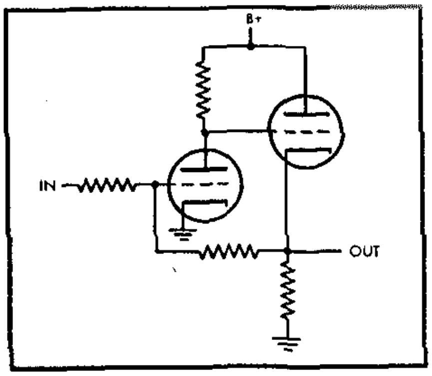

Fig. 9. Amplifier with extremely low output impedance.

Amplifiers of extremely low output resistance

It will be remembered from equation (5) that the effect of anode-follower feedback is to reduce the effective generator resistance of the amplifier; that is, the plate resistance of the tube or the collector resistance of the transistor. The benefits of this reduction are much more noticeable with triodes, for which the plate resistance is usually lower than the load resistance, than with pentodes or transistors, for which the generator impedances are quite high.

The addition of a cathode follower to the amplifier, as shown in *Fig.* 9, permits amplifiers of extremely low output resistances to be obtained with great economy of parts. In this circuit, the open-loop generator resistance is the output resistance of the cathode follower —already a low value—and it is reduced appreciably by the anode-follower connection. For example, a 12AX7 cathode follower has an output resistance of some 500 ohms, while the same tube operated as a voltage amplifier may easily show a gain of 60. By using the two halves of a 12AX7 in the circuit of *Fig.* 9, and proportioning the resistors to yield a voltage gain of 1.0, an output resistance of some 17 ohms is obtained.

The connection of *Fig.* 9 is also very useful with transistors. Output resistances lower than one ohm can be obtained in this manner. Thus, high-impedance techniques may often be brought to bear on circuits which are presently considered low impedance, such as 250- or 500-ohm audio circuits. Æ

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