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COMPLETE SPECIFICATION

Improved Cathode Follower

We, TEXAS INSTRUMENTS INCORPORATED, of 6000, Lemmon Avenue, Dallas 9, Texas, United States of America, a corporation organised and existing under the laws of the State of Delaware, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to an improved type of cathode follower circuit for connecting a high impedance source to a low impedance load. More specifically, this invention relates to a cathode follower circuit and a method wherein the voltage difference between the input voltage and the output voltage is amplified and fed back in such a manner as to reduce the output impedance of the cathode follower circuit and, in addition, reduce distortion in the output voltage. In the prior art there are several well-known devices for connecting the voltage developed across a high impedance source to a low impedance load. One of these devices is a transformer in which the primary side is impedance-matched to the source and the secondary side is impedance-matched to the load by winding each side with the number of turns of wire required to provide the necessary impedance transformation ratio. The number of turns on the secondary then is smaller than the number of turns on the primary and is in a proportion to the primary turns as the square root of the ratio of the source to the impedance of the load. Such a device is known as a step-down transformer and, according to transformer theory, the voltage in the secondary is to the voltage in the primary as the number of turns in the secondary is to the number of turns in the primary. Consequently, in a step-down transformer, the voltage in the secondary is reduced in direct proportion to the ratio of the number of secondary turns to the number of primary turns and thus, such a device is undesirable for use in connecting a high impedance source to a low

impedance load. In addition to voltage reduction from the primary to the secondary, transformers have a limited frequency response and, in applications where it is desired to feed back part of the output voltage to reduce distortion, interstage transformers tend to limit the amount of negative feedback which may be employed.

Another means well-known in the art for connecting voltage developed across a high impedance source to a low impedance load is the cathode follower, discussions of which can be found in Applied Electronics by Gray, Second Edition, pp. 428—435; Radio Engineering by Terman, pp. 308—311; and Electronic Engineering Principles by Ryder, pp. 179—183. In a cathode follower circuit, the plate load impedance is eliminated and voltage is developed across the cathode resistor and thus follows the voltage applied to the grid. An analysis of the cathode follower circuit reveals two important features. First, its voltage amplification, e_{out}/e_{in} , approaches $\mu/(\mu+1)$ as the load impedance becomes very large. Thus, the maximum voltage amplification obtainable is somewhat less than unity and the cathode follower is, therefore, not useful as a voltage amplifier. Second, its internal output impedance which the load faces is approximately $r_p/(\mu+1)$ and approaches $\frac{1}{g_m}$ as μ

becomes large compared with unity. As a consequence of this small output impedance, the cathode follower is useful for supplying a low impedance load and hence finds extensive applications as an impedance "transformer" between a source having a high impedance and a load having a low impedance. By virtue of the fact that it is possible for the output voltage to almost approach the input voltage, the cathode follower avoids the voltage loss inherent in the step-down transformer and has the added advantages of excellent response, high input impedance and low distortion. Further, even though it lacks voltage amplification, the

cathode follower can provide power amplification because the ratio of its input impedance to its output impedance is very large.

However, in spite of the general usefulness of the cathode follower as an impedance transformer, there are certain limitations to its use which must be considered. One limitation on the cathode follower is that, for a given ac input voltage, the cathode follower output begins to be clipped on negative peaks when the output load impedance is sufficiently low that the peak ac current through the output loads equals the quiescent current in the cathode follower load resistance. This follows from a consideration of the fact that if the load impedance is sufficiently low, the current through the tube flows mainly through the load impedance rather than the cathode load resistance. Since the current through the cathode resistance follows the voltage swings of the grid, the current through the load resistance is limited to the quiescent current through the cathode load resistance until the tube reaches its cut-off point and the negative peak voltages are then clipped at that level. Another limitation is that, on positive ac voltage peaks, the cathode follower can deliver positive current peaks far larger than its quiescent cathode current, but the output voltage begins to be distorted when the current required by the load produces an internal voltage drop across the effective internal resistance $1/g_m$ which is appreciable compared to the input voltage. Thus, with a load whose value depends on the voltage across it, larger and larger percentages of the input voltage appear across the internal resistance as the load increases while smaller and smaller percentages appear across the load. This distortion can be partly compensated by employing overall negative feedback around the entire circuit so that in the region of appreciable positive grid current in the output tube where the follower tends to limit on positive peaks, this feedback increases the grid voltage of the cathode follower and thus its output limiting on positive voltage peaks. The limits to this method of correction arise mainly from the limited voltage swing and distortion generation of the tube preceding the cathode follower.

In many types of circuits, such as audio amplifier circuits, it is very desirable to transfer power to the output tubes at a high efficiency. Among the many ways in which high power transfer at high efficiency can be accomplished, one method is to operate the output tubes in either class A_2 , AB_2 , or B_2 amplification; but all of these modes of operation require that the grids of the output tubes be driven positive and draw grid current during part of each cycle. In the ordinary cathode follower, the fact that the cathode follower output begins to be clipped on negative peaks when the load impedance is sufficiently low is of no consequence when the cathode follower is used as

a driver stage since the load presented by the grid of the output tube will be very small until the output tube grid potential is driven near and above zero. The distortion, though, of the cathode follower output voltage as the current required by the load begins to produce an appreciable voltage drop across the effective internal resistance $1/g_m$ is important since the positive grid current which it can supply to an output tube grid is limited. Therefore, the present invention has been conceived to overcome some of the limitations on the use of the cathode follower as an impedance transformer and thus constitutes an improved type of cathode follower.

Accordingly it is the principal object of this invention to augment the impedance transforming characteristics of the cathode follower in such a manner that the output impedance of the cathode follower will be further decreased thereby making it suitable for use in a circuit between a high impedance source and an extremely low impedance load.

According to the invention there is provided in a cathode follower circuit for reducing output impedance and output voltage distortion, a cathode follower, a separate differential amplifier connected external to the main amplification path to sample the magnitude of the input and output voltages within said cathode follower circuit and develop an amplified error signal proportional to the difference therebetween, and amplifier means connected in circuit with said cathode follower to conduct in response to the amplitude of said amplifier error signal.

The invention may consist, for example, essentially of a tube with a resistor connected in the cathode path to ground or to a fixed negative potential as in the ordinary cathode follower and an additional tube connected either in parallel or in series with the first tube. The input voltage is applied to the grid of the first tube thereby producing an output voltage which is nearly equal to but smaller than that of the input voltage. The difference between the input and output voltage is then fed to a differential amplifier and this amplified error voltage applied to the grid of either the parallel or series connected tube and with such a phase sense that the error at the output of the first tube is reduced. The feedback is thus negative feedback and augments the cathode follower, or in other words, reduces its output impedance and the distortion in its output voltage. It should be noted here that, although the invention is described herein in terms of vacuum-tubes, suitable transistors such as field-effect transistors can be used to build up the improved cathode follower of this invention and achieve the same reduced output impedance and reduced output voltage distortion.

The invention provides an augmented cathode follower driver which may be used for direct coupling to and biasing of output tubes

in either single-ended or push-pull circuits.

The cathode follower circuit of the invention can considerably augment the range of loads over which an essentially undistorted output voltage can be maintained and in particular, loads consisting of a grid which draws high positive grid current during a portion of a cycle.

The invention will now be described by way of example with reference to the accompanying drawings, in which:—

Figure 1 is a schematic circuit diagram for an augmented cathode follower circuit wherein a tube is connected in parallel to the cathode follower.

Figure 2 is a curve of the theoretical and experimental ratio of the output voltage with total load R_L to the output voltage with only cathode lead resistance R_k plotted against the load resistance for the parallel augmented cathode follower driver circuit of Figure 1;

Figure 3 is a curve of the theoretical and experimental ratio of the error voltage normalized with respect to the input voltage plotted against load resistance for the parallel augmented cathode follower circuit of Figure 1;

Figure 4 is a schematic circuit diagram for an augmented cathode follower circuit wherein a tube is connected in series with the cathode follower; and

Figure 5 is a plot of the intermodulation distortion against rms output voltage for an ordinary cathode follower driver, a series augmented cathode follower driver all driving an output tube grid, and for a parallel augmented cathode follower driver with no added load.

Beginning now the description of the drawings, a parallel augmented cathode follower circuit is shown schematically in Figure 1. The input voltage e_i is fed by lead 10 to the grid of tube V1 which in this diagram is shown as one-half of a double triode tube. Tube V2, the other half of the double triode tube, is connected in parallel with tube V1 by means of lead 13 connecting the plates of the two tubes. The dc voltage to the plates of tubes V1 and V2 is supplied by a voltage source to the common plate connection, lead 13. Cathode resistor 11 is connected in series with tube V1 by a lead 14 and in series with tube V2 by a lead 15. The output voltage e_k is developed across resistor 11 and applied to a low impedance load by lead 12.

In order to augment the cathode follower action of tube V1, the input voltage e_i is fed through resistor 17 to the grid of tube V3 by lead 16 while the output voltage e_k is applied to the grid of tube V4 by lead 18. The cathodes of tubes V3 and V4 are connected together by a common lead 20 and in series with resistor 19. The plate of tube V3 is connected directly to a dc voltage source while the plate of tube V4 is connected to a second dc voltage source

through plate load resistor 21. The circuit consisting of tube V3, tube V4, and resistors 19 and 21 provides for amplification of the difference between the input voltage e_i and the output voltage e_k in a manner described in Vacuum-tube Amplifiers, Radiation Laboratory Series Volume 18, Section 11—10. Tube V3 is connected as a cathode follower and thus, the input voltage e_i to its grid is transmitted with very little drop to the cathode of tube V4. Tube V4, however, acts as an amplifier with its grid biased negatively with respect to its cathode. The difference between the input voltage e_i and the output voltage e_k is amplified by the voltage gain across resistor 21 to give the amplified error signal $(g_1 e_i - g_2 e_k)$ or, its approximate equivalent, $g(e_i - e_k)$ where g_1 and g_2 are as defined hereinafter. This error voltage provides a high stability and reduced distortion when fed back to the cathode follower V2. Further, this "active error" feed-back path of the augmented cathode follower is outside the main amplification path of any circuit into which it might be connected and thus allows greater overall negative feedback to be used in the entire circuit with no amplification of the distortion from stages ahead of the augmented cathode follower driver.

The error voltage from tube V4 follows a path through lead 22, condenser 26 and lead 25 to the grid of tube V2. Condenser 26 provides an ac bypass around resistor 23 and, since resistor 24 is of considerable magnitude compared with the reactance of condenser 26 at frequencies of interest, the error voltage feeds to the grid of tube V2 with very little or no voltage drop through resistor 24. The grid of tube V2 is provided with a negative dc bias equal to that of the negative dc bias on the grid of tube V1 by means of a voltage divider consisting of resistors 23 and 24. The voltage across resistor 21 is applied to the voltage divider and the voltage drop across resistor 23 reduces the voltage to the proper dc level for the grid of tube V2.

From the circuit described, it follows then that as the load requires more current, the output voltage e_k will tend to drop. This results in an increased error voltage which is amplified and fed to the grid of the parallel connected tube V2. Since tube V2 is a cathode follower also, the voltage across resistor 11 tends to increase to compensate for the current supplied to the load thereby reducing the error voltage. Expressing the circuit of Figure 1 by means of formulas, feeding the amplified error voltage into the parallel connected tube V2 results in a no-load voltage gain for the parallel augmented cathode follower equal to:—

$$G = \frac{e_k}{e_i} = \frac{\mu(1+g_1)}{\mu g_2 + 2(1+\mu) + r_p/R_k}$$

Where: μ = amplification factor of tubes V1 and V2

g_2 = voltage gain from grid to plate of V4

g_1 = voltage gain from grid of V3 to plate of V4

r_p = plate resistance of tubes V1 and V2, assumed identical

R_k = the cathode resistance of tubes V1 and V2 (resistor 11).

Since g_1 is approximately equal to g_2 , then:—

$$G = \frac{\mu g + 2\mu}{\mu g} = 1,$$

where g_1 and g_2 are denoted by their mean value g which is much greater than unity.

In so far as the voltage drop through the cathode follower is concerned, the internal resistance r_i for the augmented cathode follower is approximately equal to:—

$$r_i = \frac{1}{\mu g_2 + g_1 g_2 + g_2 g} = 1$$

When compared with the internal resistance of

essentially — for a well designed ordinary

cathode follower, it can be seen that by augmenting the cathode follower, the internal resistance is reduced by the factor g . In actual output impedance, this is a reduction in the output impedance from approximately 200—400 ohms for the ordinary cathode follower to approximately 5 ohms for the parallel augmented cathode follower of Figure 1.

As a further verification of the operation of the parallel augmented cathode follower of Figure 1, reference is now made to the curves shown in Figures 2 and 3. In Figure 2, a curve is drawn for the ratio of the output voltage with a total load R_L to the output voltage with only cathode resistance load R_k as the value of the total load resistance R_L increases. The solid line representing theoretical voltage amplification is comparatively small. However, as the load resistance increases, the voltage amplification increases until it approaches unity. The triangular points represent experimental points determined by introducing successively increasing values of load resistance across the output of the parallel augmented cathode follower. The close correspondence of the experimental points with the theoretically calculated curve shows that the theory of the augmented cathode follower is sound in actual practice. In Figure 3, a plot of the error voltage e_e normalized with respect to the input voltage e_i is shown for increasing values of the total load resistance R_L . The theoretically calculated curve shown by the solid line indicates that the error voltage should be large in comparison with the input voltage for low values of load resistance and that this ratio should decrease as the load resistance increases. Again, the experimental points shown by the small triangles indicate that the actual performance of the parallel aug-

mented cathode follower corresponds very closely with its theoretically calculated performance.

Another means for augmenting a cathode follower is shown by the series connection of Figure 4. In this figure, the input voltage e_i is fed to the grid of tube V5 through lead 40. The cathode of tube V5 is connected to a fixed negative potential through resistor 41. However, tube V5 is connected in series with tube V9 by the connection 50 between the plate of tube V5 and the cathode of tube V9. The output voltage e_o developed across resistor 41 is shown as being fed to an output tube V10 by lead 42.

As in the parallel augmented cathode follower, the difference between the input voltage e_i and the output voltage e_o is amplified in a differential amplifier. This is accomplished by connecting the output voltage e_o to the grid of tube V7 through lead 43. The input voltage e_i is connected into the grid of a cathode follower tube V8 and the voltage drop across resistor 45 in the cathode circuit of tube V8 is fed to the grid of tube V6 by lead 46. Tubes V6 and V7 are identical halves of a double triode tube, have a common cathode connection 47 and are connected in series with lead 48 to a fixed negative potential. The difference between the halves of the double triode lies in the fact that tube V6 is a cathode follower while tube V7 is an amplifier. As in the parallel augmented cathode follower circuit of Figure 1, the gain through tube V7 is equal to $(g_1 e_i - g_2 e_o)$ which is essentially equal to $g(e_i - e_o)$. This amplified error voltage is then fed by lead 51 to the grid of tube V9. Thus, the series augmented cathode follower is likewise provided with error feedback to increase its stability and reduce distortion and its "active error" feedback path is essentially out of the main amplification path of any circuit into which it might be connected.

The error voltage is applied to the grid of tube V9 by lead 51 and acts to augment the cathode follower tube V5 in the following manner. As current is supplied to a low resistance load such as the grid of the output tube V10 when driven positive, the voltage drop across the tube V5 increases. However, any internal resistance drop will be compensated by an increase in the plate voltage of tube V5 due to the error voltage e_e supplied to the grid of tube V9 by the amplified error voltage. This compensation effect continues as the load increases until the grid of tube V9 arrives at the zero bias condition for the tube. Compensation is limited at this point since there can be no further voltage drop across tube V9. Compared with the parallel augmented cathode follower circuit, the output impedance of the series augmented cathode follower is considerably higher, being in the order of 50—70 ohms as against 5 ohms for the parallel circuit. However, the series augmented cathode follower

considerably augments the range of loads over which an undistorted output voltage can be maintained when compared with an ordinary cathode follower, the reduction being in the order of 200 to 400 ohms to 60 ohms.

An analysis of this series augmented cathode follower by means of its equivalent circuit shows that the no-load voltage gain from grid to cathode is approximately:—

$$G_1 = \frac{g_1 + \mu_1}{g_2 + \mu_1}$$

where: g_1 = the voltage gain from the grid of V8 to the plate of V7

g_2 = the voltage gain from the grid of V7 to the plate of V7

μ_1 = amplification factor of tubes V5 and V9, assumed to be identical.

Since g_1 and g_2 are very nearly equal and usually, in practice, considerably larger than the amplification factor μ_1 , G_1 will be essentially unity. As to tube V5, its output impedance is approximately:—

$$r_{p1} = \frac{1}{\mu_1 + g_2} = \frac{1}{g_{m1}(1 + g_2/\mu_1)}$$

where r_{p1} is the plate resistance of tubes V5 and V9 which are assumed to be equal. Therefore, since the output impedance of the ordinary

cathode follower is equal to $\frac{1}{g_m}$, the series augmented cathode follower reduces the output

impedance by the factor $(1 + g_2/\mu_1)$.

To illustrate the effect which augmenting the output of a cathode follower has on distortion, a series of curves are produced in Figure 5 where the intermodulation distortion in percent for frequencies of 60 and 5600 cps mixed in the ratio of 4:1 is plotted against rms output voltage. Taking the most extreme case of distortion, the curve for an ordinary cathode follower driver (CFD) shows that the percentage of distortion is approximately 0.24% at an output voltage of 30 volts rms, the point at which the grid of a succeeding output stage starts drawing positive grid current, and as the output voltage increases, the intermodulation distortion rises sharply until it is approximately 8.0% at an output of 45 volts rms. The intermodulation distortion increases at a lesser rate from that point on until the diode line of the tube is reached and there the distortion increases sharply. The diode line is reached when the grid of the output tube is sufficiently positive that it loses control of plate current and the tube then begins to act as a diode. The curve for the series augmented cathode follower driver (SACFD) shows considerable distortion over the range between approximately

30 volts rms and the diode line but still the distortion is considerably lower than in an ordinary cathode follower driver. The curve for the parallel augmented cathode follower driver (PACFD) shows an intermodulation distortion of less than 0.2% in the range of 30 to 50 volts rms and an intermodulation distortion which never rises above 0.9% until the output voltage approaches the point at which the output tube begins to act as a diode. This latter described curve follows very closely a portion of the no-load curve for the parallel augmented cathode follower driver which represents the distortion when no output grid current is drawn. This distortion arises almost entirely from the preceding amplifier stage (not shown). Thus, it can be seen that where distortion in the output voltage is concerned, the parallel augmented cathode follower driver is far superior to both the series driver and the ordinary cathode follower, while the series augmented cathode follower represents an improvement over the ordinary cathode follower driver. The dash line shows that the parallel augmented driver can deliver output grid currents up to 100 ma with an intermodulation distortion of less than 10% in the output stage.

What we claim is:—

1. In a cathode follower circuit for reducing output impedance and output voltage distortion, a cathode follower, a separate differential amplifier connected external to the main amplification path to sample the magnitude of the input and output voltages within said cathode follower and develop an amplified error signal proportional to the difference therebetween, and amplifier means connected in circuit with said cathode follower to conduct in response to the amplitude of said amplified error signal.

2. A circuit as claimed in Claim 1, in which said amplifier means comprises a second cathode follower connected in parallel with said first-mentioned cathode follower.

3. A circuit as claimed in Claim 1, wherein said amplifier means is connected in series with said cathode follower.

4. A circuit as claimed in Claim 1 or 3, in which said amplifier means comprises a plural element space discharge device connected in series in the anode circuit of said cathode follower.

5. A cathode follower circuit substantially as herein described and illustrated in the accompanying drawings.

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