Feb. 26, 1946. L. F. CURTIS 2,395,615

RADIO-FREQUENCY CARRIER-SIGNAL LIMITING SYSTEM

Filed Oct. 28, 1941 2 Sheets-Sheet 1

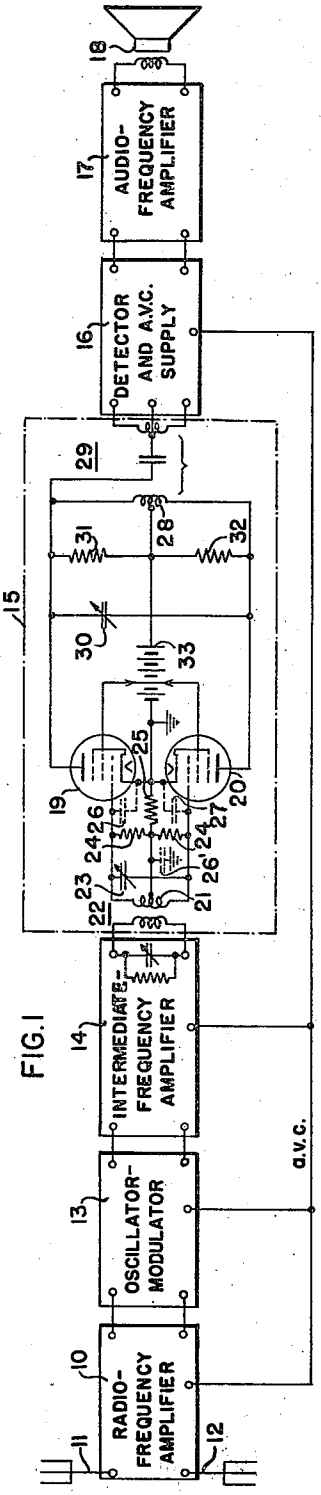


FIG. 1

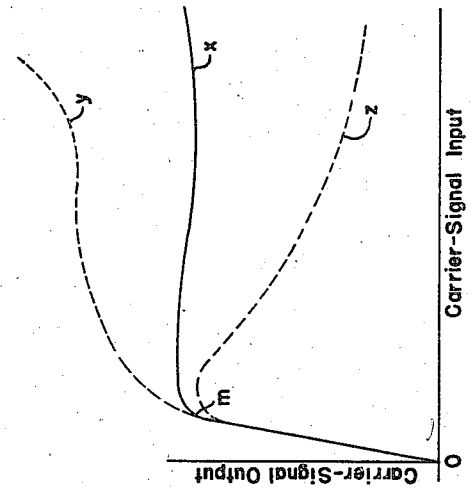


FIG. 3

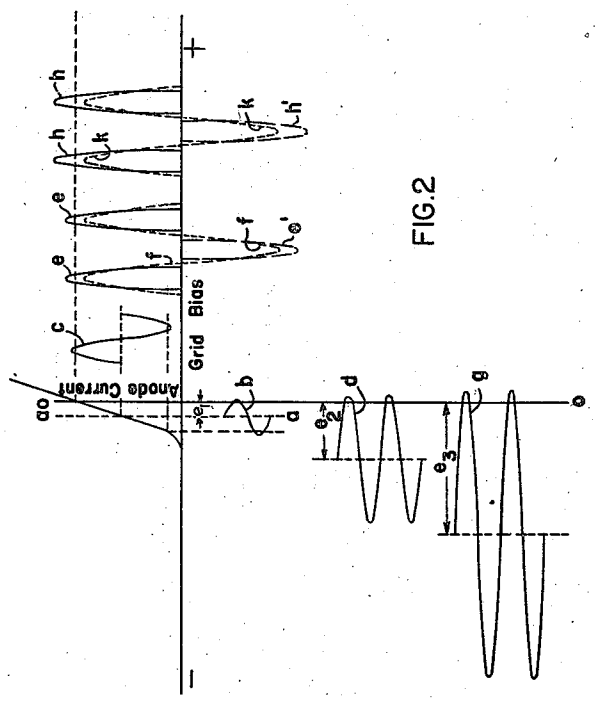


FIG. 2

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RADIO-FREQUENCY CARRIER-SIGNAL LIMITING SYSTEM

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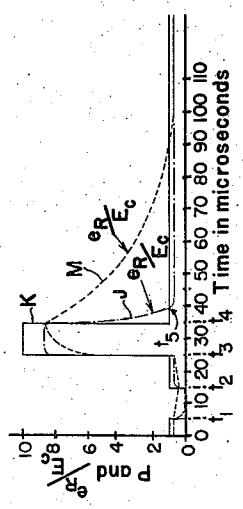


FIG. 5

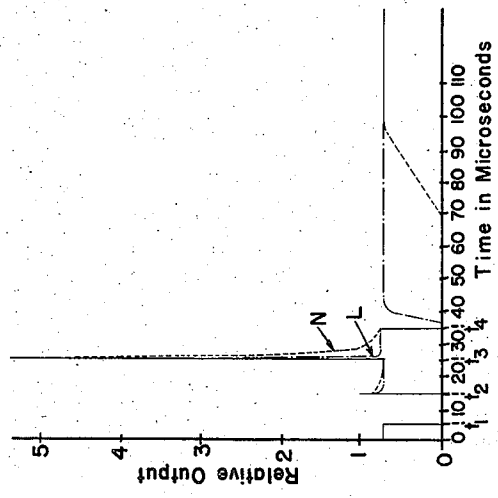


FIG. 6

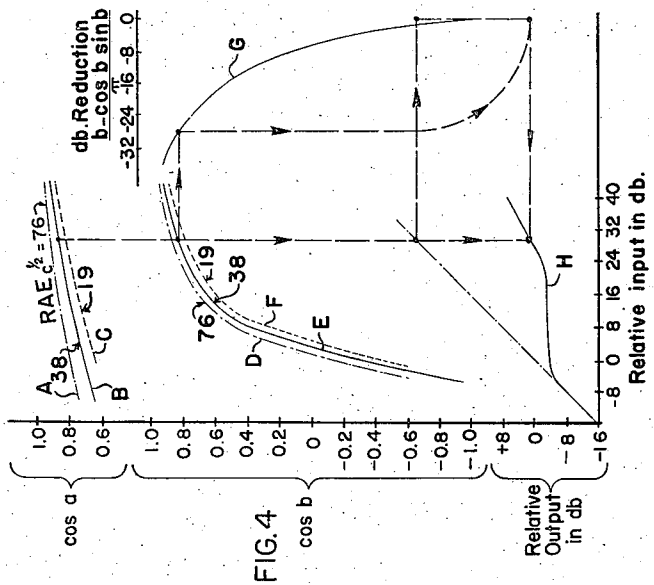


FIG. 4

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UNITED STATES PATENT OFFICE

2,395,615

RADIO-FREQUENCY CARRIER-SIGNAL LIMITING SYSTEM

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Application October 28, 1941, Serial No. 416,851

14 Claims. (Cl. 178—44)

The present invention relates to an improved carrier-signal limiting system and, particularly, to an improved limiting system of the type which utilizes multi-electrode vacuum tubes and accomplishes limiting action by operation of the tube beyond anode-current cutoff during a portion of each carrier-signal cycle.

Of the numerous types of limiting systems heretofore proposed, the self-biased vacuum tube type has perhaps the most promise by virtue of such outstanding advantages as its rapidity and uniformity of limiting action, its simplicity and ease of adjustment, its self-biasing feature which eliminates the necessity of fixed biases with their attendant disadvantages, and its freedom from the requirement of any form of neutralization. The prior art limiting systems of this nature have employed a single vacuum tube having a control electrode connected to an input circuit including a grid condenser and grid leak to develop its own control-electrode bias by peak rectification of carrier signals translated through the system. Limiting occurs on all carrier signals of intensity greater than that required to bias the vacuum tube to cutoff.

Such single-tube limiting systems of the prior art have the disadvantage that limiting is delayed in time more than is desirable due in large measure to the fact that the grid provides only half-wave rectification, a limitation which reduces the speed with which the bias potential can be developed. This delayed action is also due in part to the fact that the values of the grid leak and grid condenser required for adequate sensitivity are necessarily so large that the time constant of the system is appreciable. Transient disturbances cannot, therefore, be limited as completely as are the translated carrier signals and the output of the limiter system is materially reduced over an appreciable interval upon the application thereto of a large positive pulse of transient disturbance. Any attempt to decrease the time constant of the grid condenser and grid leak impairs the sensitivity of the system over its entire range of operation and increases the value of signal input at which limiting begins. There is the additional disadvantage that single-tube limiters of this nature do not have balanced input and output circuits, whereby even-order harmonics which occur by virtue of the limiting action appear in the output circuit of the limiter and cannot be balanced out in the coupling between the system and the succeeding amplifier or detector stage.

It is an object of the invention, therefore, to provide a new and improved carrier-signal limiting system which avoids one or more of the above-mentioned disadvantages and limitations of the prior art devices.

It is a further object of the invention to provide a carrier-signal limiting system having a self-bias circuit of relatively short time constant in which is developed the required self-bias potential and one which, therefore, provides extremely rapid limiting action.

It is an additional object of the invention to provide a carrier-signal limiting system having improved sensitivity over its entire operating range and particularly the portion thereof just before limiting begins.

In accordance with one embodiment of the invention, a radio-frequency carrier-signal limiting system comprises a pair of vacuum-tube repeaters having predetermined operating characteristics, and individual input and output circuits connecting the tubes in push-pull relation, the input circuits being adapted to have radio-frequency carrier signals applied thereto and the output circuits being highly selective against all harmonics of the carrier signals applied to the input circuits. The system also includes means for limiting to a predetermined value the maximum amplitude of carrier-signal output of the system comprising capacitance means composed primarily of the input capacitances of the repeaters and the distributed capacitances of the input circuits and an impedance common to the input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, the impedance being so proportioned with relation to the operating characteristics of the vacuum-tube repeaters that the carrier-signal translating characteristic of the system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias the tubes to cutoff.

For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings, and its scope will be pointed out in the appended claims.

Referring now to the drawings, Fig. 1 is a circuit diagram, partly schematic, of a complete frequency-modulated carrier-signal receiver embodying the invention; Fig. 2 is a graph illustrating anode-current and control-electrode potential relationships for each of the tubes of the Fig. 1 limiting system, and is used in explaining the operation of the invention; Fig. 3 represents steady-state input-output characteristics of the limiting system over its useful range of operation; Fig. 4 is a graph illustrating a method of graphical solution of certain equations derived in a mathematical analysis of the operation of the invention; and Figs. 5 and 6 are graphs representing certain transient operating characteristics of the limiting system of the invention.

Referring now more particularly to Fig. 1, there is represented schematically a complete frequency-modulated carrier-signal receiver of a conventional design embodying the present invention in a preferred form. The receiver includes a radio-frequency amplifier 10 having its input circuit connected to an antenna system 11, 12, and having its output circuit connected to an oscillator-modulator 13. Connected in cascade with the oscillator-modulator 13, in the order named, are an intermediate-frequency amplifier 14 of one or more stages, a carrier-signal limiting system 15, more fully described hereinafter, a frequency detector and automatic amplification control system 16, an audio-frequency amplifier 17 of one or more stages, and a sound reproducer 18. The output of the automatic amplification control system of unit 16 is coupled through the conductor designated as A. V. C. to one or more of the input circuits of units 10, 13 and 14 in a conventional manner.

It will be understood that the various units just described may, with the exception of the limiting system 15, be of conventional construction and operation, the details of which are well known in the art, rendering detailed description thereof unnecessary. Considering briefly the operation of the receiver as a whole, and neglecting for the moment the operation of the limiting system 15, presently to be described, a desired frequency-modulated carrier signal is selected and amplified by the radio-frequency amplifier 10, converted to a frequency-modulated intermediate-frequency carrier signal in the oscillator-modulator 13, amplified in the intermediate-frequency amplifier 14, limited to a predetermined substantially constant amplitude by the limiting system 15, and detected by the frequency detector 16, thereby to derive the audio-frequency modulation components. The audio-frequency components are, in turn, amplified in the audio-frequency amplifier 17 and are reproduced by the sound reproducer 18 in a conventional manner. The automatic amplification control bias developed by the automatic amplification control system of unit 16 is effective to control the amplification of one or more of the units 10, 13 and 14 to maintain the signal input to the limiter 15 within a relatively narrow range for a wide range of received signal intensities.

Referring now more particularly to the portion of the system embodying the present invention, the limiting system 15 comprises a pair of pentode-type vacuum-tube repeaters 19, 20 having predetermined grid-cathode rectification characteristics and predetermined input voltage-output current operating characteristics providing relatively sharp anode-current cutoff. The pentode type of vacuum tube is, as is well known, one which includes a screen electrode between its control electrode and its anode electrode for reducing the capacitance between the last-mentioned electrodes. Each of tubes 19 and 20 thus includes means for reducing the capacitive coupling between the input and output electrodes thereof, the screen electrode comprising means for effectively decreasing the translation of carrier signals directly from the input to the output circuits of the repeater tubes by interelectrode capacitive coupling through the vacuum-tube repeaters. The input electrodes of vacuum tubes 19 and 20 are connected in individual input circuits comprising individual halves of the secondary winding 21 of an input transformer 22. The secondary winding 21 is tuned by a condenser 23 to the mid-frequency of the range of frequency deviation of the carrier signal applied to the transformer 22. The frequency response of the tuned circuit 21, 23 is broadened by resistors 24, 24 which are connected across individual halves of the transformer secondary winding 21. There is provided means for limiting to a predetermined value the maximum amplitude of carrier-signal output of the system comprising capacitance means composed primarily of the input capacitances of the repeater tubes 19 and 20 and the distributed capacitances of the input circuits and an impedance in a common portion of the input circuits of tubes 19 and 20, the last-mentioned impedance comprising a resistor 25 across which is developed a self-bias potential by grid rectification of the applied carrier signal. The input electrode capacitances of tubes 19 and 20 are represented by dotted-line condensers 26 and 27, respectively, and the capacitance to ground of the center-tap of the secondary winding 21 by the condenser 26', although these capacitances may be comprised in part by the distributed capacitances of the individual input circuits.

The output electrodes of vacuum-tube repeaters 19 and 20 are connected in individual output circuits comprising individual halves of the primary winding 28 of an output transformer 29 coupled to the frequency detector 16 in a conventional manner. The primary winding 28 is tuned by a condenser 30 to the mid-frequency of the range of frequency deviation of the carrier signal applied to the limiting system, and the frequency-response characteristic of the tuned circuit thus formed is broadened by the resistors 31, 32 which are connected across individual halves of the transformer primary winding 28. Vacuum tubes 19 and 20 are suitably energized from a source of space current 33. The individual input and output circuits thus connect the vacuum-tube repeaters 19, 20 in push-pull relation.

In considering the operation of the circuit just described, it will be evident that the control grids of tubes 19 and 20 have zero bias in the absence of a carrier signal applied to their individual input circuits. Assume now that a relatively weak carrier signal is applied to the input circuits of the tubes. The control grid of each tube rectifies individual half-cycles of the carrier signal to develop across the resistor 25 a unidirectional negative-bias potential. This self-bias potential, which charges the inherent input-circuit capacitances represented by the condensers 26, 26' and 27, increases in magnitude until the control grids are biased sufficiently negatively that peak rectification of the applied carrier signal occurs, which usually takes place in a few carrier-frequency cycles.

Referring now to Fig. 2, which represents the operating characteristic of either of the tubes 19 or 20, the axis 0—0 is the zero grid-bias axis of the characteristic while the axis a—a represents the axis of the carrier signal applied to the control grids of the tubes, this axis being displaced from the axis 0—0 by an amount equal to the bias e_1 developed across the resistor 25 by peak rectification of the applied carrier signal represented by curve b. Since the amplitude of the carrier signal is sufficiently small that the substantially linear portion of the tube operating characteristic is not exceeded, the carrier signal is amplified in the limiting system 15 and appears in the output thereof with substantially undis-

torted wave form as represented by curve *c*. The time constant of the input circuit comprising the inherent capacitances **26**, **26'**, **27** and the resistor **25** is of the order of two or less microseconds, for example; or in terms of frequency is of the order of several cycles, for example, 3 to 5 cycles for an applied carrier signal having a frequency of 3 megacycles, so that for all practical purposes the bias developed across the resistor **25** may be considered a constant bias over any given carrier-frequency cycle, as represented by the linear axis *a*—*a*.

Assume now that the carrier wave applied to the limiting system increases in amplitude. The control grids of tubes **19** and **20** again peak-rectify the carrier wave to develop across resistor **25** a larger self-bias potential. Thus a carrier signal having an amplitude represented by curve *d* produces a self-bias potential of magnitude e_2 to bias both tubes beyond cutoff during a portion of each carrier-signal cycle, whereby only a portion of each positive half-cycle of the applied carrier signal is amplified and appears in the output circuits of tubes **19** or **20**, as represented by curve *e*. Since tubes **19** and **20** are connected in push-pull relation, the individual outputs of the tubes have a phase difference of 180 degrees and there is applied to the output tuned circuit **28**, **30** carrier signals having the wave form represented by the combined output signal curves *e*, *e'* for the two tubes in push-pull. The tuned circuit **28**, **30** selects only the fundamental-frequency component, represented by broken-line curve *f*, and applies this component through the output transformer **29** to the detector of unit **16**. Should the carrier signal applied to the input circuits of tubes **19** and **20** increase still further in amplitude, as represented by curve *g*, a larger self-bias potential e_3 is developed across resistor **25** and tubes **19** and **20** are biased even further beyond cutoff. There appears in the output circuit of each tube correspondingly smaller portions of positive half-cycles of the carrier signal as represented by curves *h*, *h'*. The fundamental component *k* of the output wave *h*, *h'* is here again selected by the tuned circuit **28**, **30** and applied to the detector of unit **16**.

The value of resistor **25** is so proportioned, in a manner presently to be considered in greater detail, in relation to certain operating characteristics of the vacuum tubes **19** and **20** and the capacitances of condensers **26**, **26'** and **27**, that the fundamental component of the resultant carrier signals developed in the output circuits of tubes **19** and **20** is substantially constant in amplitude for all values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias the tubes to cutoff during at least a portion of each carrier-signal cycle. By proportioning resistor **25** in this manner, the steady-state carrier-signal translation characteristic of the limiting system is substantially constant for all usual values of applied carrier signals in excess of such value.

It should be noted that the signal voltage appearing across the terminals of the input transformer secondary winding **21** divides substantially equally across the input circuit capacitances **26** and **27**, which are approximately equal. The magnitude of the carrier-signal voltage applied to the input electrodes of tubes **19** and **20** is, therefore, not appreciably affected by the inclusion of the resistor **25** in the common portion of the input circuits.

The solid-line curve *x* of Fig. 3 represents the steady-state translation characteristic of the limiting system of Fig. 1 with the resistor **25** proportioned in the manner presently to be described. It will be observed from this figure that the output of the limiting system increases rapidly to the point *m*, at which limiting begins, and that the output is thereafter substantially constant for increasing intensities of carrier signal applied to the limiting system. The steep slope of the portion *o*, *m* of this curve indicates that the limiting system has a high amplification for carrier signals of sufficiently low intensity that limiting does not occur, and that limiting begins at a relatively low amplitude of the carrier-signal input, both of which are highly desirable characteristics of a limiting system. If the value of the resistor **25** is chosen too small, the translation characteristic of the limiting system continues to rise for all values of applied carrier-signal amplitude, as represented by curve *y*. If the resistor **25** is too large, the output of the limiting system increases until limiting begins and thereafter rapidly decreases, as represented by curve *z*. The proper choice for the value of resistor **25** is, of course, that which renders the output of the limiting system substantially constant over the major portion of its translation characteristic. Actually, the steady-state translation characteristic of the limiting system depends not only upon the value of the resistor **25**, but additionally upon the control grid-cathode conductance characteristic of the tubes **19** and **20** and on the control-grid bias voltage necessary for anode-current cutoff. This will be clear from the following mathematical analysis of the operation of the limiting system.

The control-grid current of each of the tubes **19** and **20** is expressed by the following relation:

$$i_g = Ae_g^{3/2} \qquad (1)$$

where:

A=a constant derived from the actual grid voltage-grid current characteristic of the particular tube used and is equal to the grid current for a grid potential of one volt; and

e_g=the instantaneous positive control-grid cathode voltage.

The anode current of each of these tubes is determined by the following relation:

$$i_p = g_m(E_c + e_g) \qquad (2)$$

where:

g_m=the transconductance of either of the tubes **19** and **20**; and

E_c=the control-grid bias necessary for plate current cutoff.

Since the control grid and cathode elements of tubes **19** and **20** act as a diode rectifier, the time constant circuits, comprising the condensers **26**, **26'**, **27** and the resistor **25**, develop a steady bias between the grid and cathode elements as previously pointed out, whereby the voltage e_g which produces grid current has a wave shape corresponding to the clipped peak of a cosine wave, the developed grid bias and the point of clipping being determined by the following relation:

$$e_g = E_a(\cos\theta - \cos\alpha) \qquad (3)$$

where:

E_a=the peak value of the applied signal voltage;

$\theta = \omega t$; and

α=the angle, having plus and minus values, during which grid current flows.

From Equations 1 and 3, the value of the instantaneous grid current may be expressed by the relation:

$$i_g=AE_a^{3/2}(\cos\theta-\cos a)^{3/2} \quad (4)$$

The total grid current during each cycle of the applied signal voltage is determined by integration between the angles $-a$ and $+a$ of the grid-current flow and has the value

$$I_{g0}=\frac{3\sqrt{2}}{16}AE_a^{3/2}(1-\cos a)^2 \quad (5)$$

The total grid current also has the value:

$$I_{g0}=\frac{E_a\cos a}{R} \quad (6)$$

where:

R=twice the value of the resistor 25 since the latter resistor is effectively two resistors in parallel, one of which is included in the input circuit of vacuum tube 19 and the other in the input circuit of vacuum tube 20 insofar as the present mathematical analysis is concerned.

Combining Equations 5 and 6 gives the relation:

$$RAE_a^{1/2}=\frac{16\cos a}{3\sqrt{2}(1-\cos a)^2} \quad (7)$$

The plate current flows over a larger angle b than the grid current as determined by the expression:

$$E_a\cos b=E_a\cos a-E_c \quad (8)$$

It is convenient to utilize a parameter P, where:

$$P=E_a/E_c \quad (9)$$

Then Equation 8 may be written:

$$\cos b=\cos a-\frac{1}{P} \quad (10)$$

The instantaneous plate current between the angles $-b$ and $+b$ has the value:

$$i_p=g_mPE_c(\cos\theta-\cos b) \quad (11)$$

Since the limiter system has a tuned output circuit, only the fundamental component of this plate current is useful in developing a steady-state voltage across the output circuit. The peak value of this component, which is determined by integration of Equation 11 between the angles $-b$ and $+b$, has a value expressed by the relation:

$$I_{p1}=g_mE_c\frac{P}{\pi}(b-\cos b\sin b) \quad (12)$$

The steady-state translating characteristic of each half of the limiting system, comprising one of the tubes 19 or 20, may be derived by simultaneous solution of Equations 7, 10, and 12. A general mathematical solution of these equations is not feasible but a graphical solution may readily be had. Thus, referring to Fig. 4, curves A, B and C are obtained by plotting cos a, calculated from Equation 7, against P (plotted conveniently as relative input in decibels) for assumed values of $RAE_c^{1/2}$. Curves D, E and F are obtained by plotting cos b, calculated from Equation 10 for the same limits of cos a, against P. Curve G is derived by plotting the function

$$\frac{1}{\pi}(b-\cos b\sin b)$$

calculated from Equation 12, against cos b. The method of graphically solving Equations 7, 10 and 12 by the use of curves A to G, inclusive, to determine any given point on the steady-state translation characteristic, represented by curve H, for any assumed value of $RAE_c^{1/2}$, is indicated in Fig. 4 by the horizontal and vertical construction lines, the arrow heads indicating the order of procedure from one set of curves to another. In this graphical solution, it is convenient to plot both P and

$$\frac{1}{\pi}(b-\cos b\sin b)$$

to a logarithmic or decibel scale. Root-mean-square values of the fundamental component of the plate current are

$$\frac{E_cg_m}{\sqrt{2}}$$

multiplied by the ordinates of relative output. The root-mean-square values of the input voltage are

$$\frac{E_cP}{\sqrt{2}}$$

multiplied by the ordinates of relative output.

It has been found that values of $RAE_c^{1/2}$ between 35 and 40 give a substantially constant or uniform steady-state input-output translation characteristic of the limiting system for values of P from 0.6 to 10 which is equivalent to a decibel range of −4 to +20 db.

The actual noise disturbance appearing in the audio output of the frequency-modulated carrier-wave receiver depends upon the nature of the interference, the band width and symmetry of the amplifier stages including the audio stages and any compensation for pre-emphasis in the latter, as well as upon the operating characteristic of the limiting system. If no amplitude transients are translated by the limiting system, the limiting action can be said to be perfect. No audio output is produced by amplitude variations in a perfectly balanced frequency detector in the absence of frequency deviation, but during the deviations accompanying desired frequency modulation sudden changes in amplitude produce noise output which depends on the product of the instantaneous deviation and the relative change in amplitude of the carrier signal applied to the frequency detector. The function of the limiting system is to maintain the carrier-signal output amplitude as constant as possible, and the amount of amplitude variation of the carrier signal as applied to the frequency detector is a measure of the effectiveness of the limiting system.

The transient or dynamic operation of the limiting system may be mathematically analyzed with a view to ascertaining the growth and recovery of the plate current of the tubes 19 and 20 under the assumption that the amplitude of the carrier signal applied to the limiting system is increased or decreased by a transient noise pulse, for example, a pulse of rectangular wave form.

In this analysis, it will be assumed that the changes of control-grid bias of the tubes 19 and 20 due to the transient noise pulse are sufficiently slow relative to the period of the carrier signal applied to the limiting system that the grid current during the transient may be expressed by Equation 5. This equation is not exact when cos a is negative, but this is a condition not normally encountered in practice so the error is not therefore significant. As will be seen later, the significant intervals are those when the control-grid current is completely cut off or is smaller than normal.

Equation 5 expresses the magnitude of the control-grid current as a function of the angle a

during which grid current flows. The magnitude of the grid current may also be expressed by the following relation:

$$i_{c0}=\frac{e_r}{R}+C\frac{de_r}{dt} \quad (13)$$

where:

e_r=the instantaneous magnitude of grid bias during the period of the transient amplitude change of the carrier signal applied to the limiting system;

R=the value of the resistor **25**; and

C=the total capacitance in shunt to the resistor **25**, this capacitance equaling the sum of the capacitance of condensers **26**, **26'** and **27**.

Combining Equations 5 and 13 gives the expression:

$$K\left(1-\frac{e_r}{E_a}\right)^2=\frac{e_r}{R}+C\frac{de_r}{dt} \quad (14)$$

where

$$K=\frac{3\sqrt{2}}{16}AE_a^{3/2}$$

A solution of this differential equation is:

$$K_1\epsilon^{\frac{t}{RC}\sqrt{1+4RK/E_a}}=\frac{\frac{2Ke_r}{E_a^2}-\frac{1}{R}-\frac{2K}{E_a}-\frac{1}{R}\sqrt{1+4RK/E_a}}{\frac{2Ke_r}{E_a^2}-\frac{1}{R}-\frac{2K}{E_a}+\frac{1}{R}\sqrt{1+4RK/E_a}} \quad (15)$$

where:

K_1=a constant depending on the initial conditions when time $t=0$.

Equation 15 may be simplified into the form:

$$K_1\epsilon^{\frac{qt}{RC}}=\frac{B\frac{e_r}{E_a}-1-B-q}{B\frac{e_r}{E_a}-1-B+q} \quad (16)$$

where:

$$B=\frac{2RK}{E_a};$$

and

$$q=\sqrt{1+2B}.$$

During the growth of the control-grid bias from zero at time $t=0$, the specific value of K_1 is:

$$K_1'=\frac{1+B+q}{1+B-q} \quad (17)$$

and

$$\frac{e_r'}{E_a}=\cos a'=\frac{B\left(1-\epsilon^{\frac{qt}{RC}}\right)}{1+B-q-(1+B+q)\epsilon^{\frac{qt}{RC}}}=\frac{(q^2-1)\left(1-\epsilon^{\frac{qt}{RC}}\right)}{(q-1)^2-(q+1)^2\epsilon^{\frac{qt}{RC}}} \quad (18)$$

During the decay of the control-grid bias from $e_r=E_a$ at time $t=0$ the specific value of K_1 is:

$$K_1''=\frac{1+q}{1-q} \quad (19)$$

and

$$\frac{e_r''}{E_a}=\cos a''=\frac{q+1+(q-1)\epsilon^{\frac{qt}{RC}}}{q-1+(q+1)\epsilon^{\frac{qt}{RC}}} \quad (20)$$

In either case, when t is infinity

$$\cos a'=\cos a''=\cos a=\frac{q-1}{q+1} \quad (21)$$

and the angle a becomes the same as for the steady-state condition.

When the carrier signal applied to the limiting system is suddenly reduced in amplitude, as during recovery after being abnormally high or on the application of a negative noise pulse, the total transient developed in the output circuit of the limiting system may be divided into three parts as follows:

1. *Grid bias greater than E_a+E_c*

During this phase, grid current and plate current of vacuum tubes **19** and **20** are both cut off. There is no audio output whatsoever except for the decay transients in the circuits following the limiting system, which transients are not further considered.

2. *Grid bias greater than E_a but less than E_a+E_c*

During this phase there is no grid current, but the plate current increases with time as the grid bias decays. The decay of grid bias during phases 1 and 2 is determined only by the time constant RC of the control-grid circuit and

$$e_r=E_r\epsilon^{-\frac{t}{RC}} \quad (22)$$

3. *Grid bias less than E_a*

During this phase, the grid bias decays according to Equation 20 and the plate current continues to increase until the steady-state condition is reached.

When the amplitude of the carrier signal applied to the limiting system **15** is suddenly increased, as by a positive noise transient, the control-grid bias increases according to Equation 18 until the steady-state condition is reached. The plate current of the tubes **19** and **20** initially assumes a large value and decays to the steady-state value.

The plate current during any of these phases may be determined by calculating the angle of plate-current flow corresponding to cos a' (or cos a'') from Equation 10, remembering that cos a' and cos b' now vary with time. Thus

$$\cos b'=\cos a'-\frac{1}{P}=\frac{e_r}{E_a}-\frac{1}{P} \quad (23)$$

During the time that grid current is cut off,

$$\frac{e_r}{E_a}$$

or the calculated value of cos a' is greater than unity. When the calculated value of cos b' is greater than unity, plate current is cut off.

The fundamental component of the plate current is

$$i_{p1}=g_mE_c\frac{P}{\pi}(b'-\cos b'\sin b') \quad (24)$$

from an adaptation of Equation 12 and where P is the value of E_a/E_c following the application of the transient noise pulse to the applied carrier signal.

The broken-line curve J of Fig. 5 represents the change of control-grid bias when the carrier signal applied to the limiting system **15** has the amplitude-modulation characteristic represented by the solid-line curve K, there being a negative transient pulse appearing during the interval t_1 to t_2 and a positive noise impulse during the interval from t_3 to t_4. Curve J has three components, one plotted from data calculated from Equation 18 for the condition of a positive increase of carrier-signal amplitude, as during the intervals t_2 to t_3 using one set of values for the

constants of Equation 18 and t_3 to t_4 using another set of values for the constants of this equation, one component from Equation 22 during the period of decreased amplitude of the applied carrier signal, as during the period t_1 to t_2 and t_4 to t_5 using the proper values for the constants of Equation 22 for these periods, and a third portion plotted from data calculated from Equation 20 as during the period of time from t_5 to infinity. The circuit constants of the limiting system 15, in deriving data for curve J, were assumed to have the following values:

$RAE_c^{1/2}=39.5$.
R=50,000 ohms.
Capacitance in shunt to the resistor 25=total capacitance of condensers 26, 26' and 27=40 micro-microfarads.
Time constant=2 microseconds.

The broken-line curve L of Fig. 6 represents the variation of plate current of either of vacuum tubes 19 or 20 when the amplitude of the carrier signal applied to the limiting system 15 changes in the manner represented by curve K of Fig. 5. Curve L is plotted from data calculated from Equation 24 when the circuit constants of the limiting system 15 have the values just stated.

In order to compare the transient limiting characteristic of the limiting system of the present invention with a prior art type of limiting system similar to that of the limiting system 15 except that only a single vacuum tube is used therein, the broken-line curve M of Fig. 5 and the broken-line curve N of Fig. 6 represent the change of control-grid bias and the change of plate current of this prior art type of limiting system when the amplitude of the carrier signal applied to the limiting system varies in accordance with curve K of Fig. 5, the circuit constants of the limiting system being assumed to have the following values:

$RAE_c^{1/2}=39.5$.
Self-bias grid resistor=100,000 ohms.
Capacitance in shunt to self-bias grid resistor=250 micro-microfarads.
Time constant=25 microseconds.

The curves L and N of Fig. 6 have perhaps the greatest comparative significance since the change of plate current of the limiter tube is a direct measure of the output of the limiting system and thus is a measure of the transient-noise disturbance applied to the frequency detector which follows the limiting system. From curve L, it will be evident that the output of the limiting system 15 of the present invention is reduced to zero during the time t_1 to t_2 when the applied carrier signal has zero amplitude, has a sharp peak of relatively low amplitude and extremely short duration immediately subsequent to the time t_2, has a much larger peak amplitude of short duration immediately after the carrier-signal amplitude has increased at the time t_3, and has zero output for a short time interval of approximately 3 microseconds immediately after the carrier-signal amplitude is reduced to normal value at the time t_4. In comparison, the prior art limiting system has a small peak amplitude over an appreciably larger interval immediately after the time t_2, has another which persists over substantially the entire interval t_3 to t_4 after the amplitude of the carrier signal is increased as by a positive transient noise pulse, is completely cut off for an interval of 35 microseconds after the carrier-signal amplitude is reduced to normal at the time t_4 and does not resume its steady-state output until approximately 65 microseconds after the amplitude of the carrier signal is again normal at the time t_4. The transient amplitude-limiting characteristic, represented by curve N, of such prior art limiting system produces distinctly audible components during the occurrence of, and the recovery from, transient noise disturbances which may be more serious than audible components produced by the original transient noise pulses without a limiting system. The audible components of the limiting system 15 of the present invention, on the other hand, are very small. The improved transient amplitude-limiting characteristic of the limiting system of the present invention is effected in large part by the very small time constant of its input circuit. This time constant is determined by the resistor 25 and the inherent capacitances 26, 26' and 27. Consequently, the transient amplitude-limiting characteristic of the limiting system 15 is greatly improved by any reduction of the inherent capacitances of its input circuit, there being no need for physical capacitance in shunt to the resistor 25 as is necessary in the prior art limiting system discussed, the characteristic of which is represented by curves M and N of Figs. 5 and 6 respectively.

The limiting action of the limiting system 15 is substantially independent of the anode potential of tubes 19 and 20 as long as the anode potential is above that required for distortionless translation of relatively weak carrier signals. By virtue of the use of a pentode type of tube which operates essentially as a constant current or current regulated device the limiting action is also substantially independent of the anode load, which affects only the gain of the limiting system for carrier signals of intensity below that at which limiting occurs.

As illustrative of a specific embodiment of the invention, the following circuit constants are given for an embodiment of the invention shown in Fig. 1:

Tubes 19 and 20	Type 6SJ7
Resistors 24, 24	12,000 ohms
Resistor 25	50,000 ohms
Capacitance 26'	10 micromicrofarads
Capacitances 26 and 27	Approx. 15 micromicrofarads
Condenser 23	70 micromicrofarads
Transformer secondary winding 21	45 microhenries
Anode and screen-grid potentials of tubes 19 and 20	60 volts
Operating frequency	3 megacycles

It will be evident from the above description of the invention that a carrier-signal limiting system embodying the invention has the advantages, first, that the system has improved gain over its entire translation characteristic and especially over that portion of its characteristic prior to the occurrence of limiting, and, second, that the magnitude of the self-bias potential of the system increases rapidly with increasing values of carrier-signal intensity, whereby limiting begins at low values of carrier-signal input amplitude. The limiting system has balanced input and output circuits so that even-order harmonics of the translated carrier signal are balanced out in the coupling to the succeeding amplifier or detector stage. The system is extremely effective in lim-

iting transient noise disturbances, since the time constant of the circuit across which the self-bias potential is developed is relatively short, being only of the order of a few microseconds or, in other words, a few cycles of the carrier signal. Transient noise disturbances of either polarity are effectively limited by the system. The limiting system of the invention has the additional advantages that it is of simple circuit arrangement, is easily adjusted for proper limiting action, and its operation is stable and substantially independent of changes of anode energization and anode loading.

While there has been described what is at present considered to be the preferred embodiment of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention, and it is, therefore, aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said operating characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

2. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and a resistor common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of applied carrier signals, said resistor being so proportioned with relation to said operating characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

3. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating and relatively sharp anode-current cutoff characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said operating and anode-current cutoff characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to plate-current cutoff.

4. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating and grid-cathode rectification characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for deriving by grid rectification of said applied carrier signals a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said operating and grid-cathode rectification characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

5. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating and grid-cathode rectification characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for deriving by grid peak-rectification of said applied carrier signals a self-bias potential the magnitude of which varies in

accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said characteristic that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

6. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics and predetermined input circuit capacitances, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of said input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being proportioned with relation to said capacitances of said limiting means to cause said limiting means to have a time constant of the order of only a few microseconds, whereby the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

7. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics and predetermined input circuit capacitances, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of said input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being proportioned with relation to said capacitances of said limiting means to cause said limiting means to have a time constant less than two microseconds, whereby the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

8. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having the operating characteristic that a control-electrode voltage E_c biases the anode current to cutoff and the control-electrode current is $A e_g^{3/2}$ where e_g is the instantaneous positive voltage applied to the control electrode and A is a constant equal to the value of control-electrode current for a control-electrode potential of one volt, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising a resistor R common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of applied carrier signals, said resistor being so proportioned with relation to said cutoff bias E_c and said constant A that the product $RAE_c^{1/2}$ is substantially between 35 and 40, whereby the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals from 0.6 to 10 times said bias E_c.

9. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having the operating characteristics that a control-electrode voltage E_c biases the anode current to cutoff and the control-electrode current is $A e_g^{3/2}$ where e_g is the instantaneous positive voltage applied to the control electrode and A is a constant equal to the value of control-electrode current for a control-electrode potential of one volt, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and having predetermined input capacitances and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising a resistor R common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of applied carrier signals, said resistor being so proportioned with relation to said cutoff bias E_c and said constant A that the product $RAE_c^{1/2}$ is substantially between 35 and 40, whereby the steady-state carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals from 0.6 to 10 times said bias E_c, said input circuit capacitances being sufficiently small with relation to the value of said resistor that said capacitances and said resistor have a time constant of the order of only a few microseconds, thereby to minimize the effect in said output circuits of undesired transient amplitude variations of the applied carrier signals.

10. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input and output circuits being tuned to the mean frequency of radio-frequency carrier signals applied to said input circuits and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the

applied carrier signals, said impedance being so proportioned with relation to said operating characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

11. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, means for effectively decreasing the translation of carrier signals directly from said input to said output circuits by inter-electrode capacitive coupling through said vacuum-tube repeaters, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitive means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said operating characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

12. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics and including means for reducing the capacitive coupling between the input and output electrodes thereof, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said operating characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

13. A radio-frequency carrier-signal limiting system comprising, a pair of vacuum-tube repeaters having predetermined operating characteristics and each including a screen electrode between the control electrode and anode electrode thereof for reducing the capacitance between said last-mentioned electrodes, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said operating characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

14. A radio-frequency carrier-signal limiting system comprising, a pair of pentode vacuum-tube repeaters having predetermined operating characteristics, individual input and output circuits connecting said tubes in push-pull relation, said input circuits being adapted to have radio-frequency carrier signals applied thereto and said output circuits being highly selective against all harmonics of the carrier signals applied to said input circuits, and means for limiting to a predetermined value the maximum amplitude of carrier-signal output of said system comprising capacitance means composed primarily of the input capacitances of said repeaters and the distributed capacitances of said input circuits and an impedance common to said input circuits for developing a self-bias potential the magnitude of which varies in accordance with the amplitude of the applied carrier signals, said impedance being so proportioned with relation to said operating characteristics that the carrier-signal translation characteristic of said system is substantially constant for values of applied carrier signals in excess of that necessary to produce a self-bias potential of sufficient magnitude to bias said tubes to cutoff.

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