Fig. 1

Fig. 2

Fig. 3

INVENTORS
HORST ROTHE AND
WERNER KLEEN
ATTORNEY.
This invention relates to electron tubes and more particularly to a novel method of, and means for, the creation and technical utilization of negative input capacitances of vacuum tubes.

It is a well known fact that between the various electrodes confined in a discharge tube capacitances are set up, and that the value of the control grid to filament capacitance, and also of the filament to plate capacitance may be varied as a function of the working slope to which the tube has been adjusted. The invention is concerned with the fact, provable and demonstrable both by calculus as well as by actual experiments, that it is possible to insure in a discharge tube, in the presence of suitable discharge conditions, also negative capacity values which are utilizable in practice in widely different ways.

Suppose a tube comprises a cathode, a control grid, and an anode. The grid and the cathode constitute the coats of a condenser the capacity of which, in cold state of the cathode (cold capacitance), shall be designated by $C_e$. As soon as the cathode is heated and emits electrons, the discharge path becomes filled with electrons, and by virtue of influence actions, these occasion charges upon the condenser coats. As a result, a different, effective or active capacitance will arise between the grid and the cathode. Applying across grid and cathode an alternating potential of angular velocity $\omega$, there will flow between these two electrodes an alternating current which, in the presence of a negatively biased grid, comprises two components, that is to say (1) the capacitive displacement current which flows through the static capacity $C_{es}$, and (2) the influence current. The latter is due to the fact that the intensity of the electronic current passing over to the anode (convection current) is acted upon by the control action of the grid, and that it causes upon the grid a charge which is fluctuating in the same way. The influence current as a general rule comprises a reactive and an active component. In other words, the input impedance of the tube is a complex value, and it is representable by an ohmic resistance and a capacity in parallel. In this connection the value of this capacity shall be studied. In fact, what is of exclusive interest here is the departure $\Delta C_e$ from the static capacity value $C_e$ previously referred to.

For $\Delta C_e$ the slope of the tube characteristic at the adjusted input point is of decisive importance. Assuming for the characteristic the ideal shape, that is $I_a = kU^{3/2}$ then the increase of capacitance $\Delta C_e$ along the whole characteristic is positive and constant. If the exponent of $U$, also hereinafter referred to as $n$, exceeds $3/2$, no fundamental change occurs since each such characteristic is representable by the superposition of various characteristics with exponent $3/2$. However, the situation becomes different in the case of characteristics or portions thereof having an exponent smaller than $3/2$. Tracing the relationship between $\Delta C_e$ and the value of exponent $n$, it will be discovered that the capacity increment initially stays positive, but assumes smaller values as the value of $n$ decreases from $3/2$ towards zero. Approximately at the point where the exponent is unity ($n=1$), or where the slope of the characteristic begins to decrease again with growing emmission current, $\Delta C_e$ reverses in sign and changes from positive values through zero to negative values. The influence current flowing to the grid upon application of an alternating voltage is then inductive. $\Delta C_e$ finally attains a negative crest and returns to zero for $n=0$, and this corresponds to the saturation range of a characteristic.

The novel features which we believe to be characteristic of our invention are set forth in particularity in the appended claims; the invention itself, however, as to both its organization and method of operation will best be understood by reference to the following description taken in connection with the drawings in which we have indicated diagrammatically some circuit organizations whereby our invention may be carried into effect.

In the drawings:

Figs. 1 and 2 are graphical representations of potential relations in a vacuum tube,

Fig. 3 is a schematic circuit diagram for producing frequency modulation,

Fig. 4 graphically represents the grid-plate capacitance characteristic over the grid voltage,

Fig. 5 schematically shows a circuit diagram of an intermediate frequency amplifier embodying the invention, and

Fig. 6 is a circuit diagram schematically illustrating a modified arrangement embodying the invention.

The physical conditions shall be discussed a little more fully by reference to Figs. 1 and 2. Referring to Fig. 1, $T$ and $H$ denote two electrodes, and of these at least electrode $T$ is grid-shaped. At the same time there are plotted the potentials prevailing at different places of the discharge space, that is, also the potentials obtaining at the very electrodes. $O$ designates a source of electricity.
electrons (real or virtual cathode) whence a stream of electrons I’ flows through the grid I into the discharge space between electrodes I and II. The potential U2 of the electrode II shall also be positive, though variable. If, first, \( U_1 = U_2 \) there is produced between the electrodes I and II a distribution of potential corresponding to the dash-line graph I. In the space preceding the electrode II prevails a positive, that is electron accelerating, field intensity \( e \). If, then, the potential \( U_2 \) is reduced, at a very definite voltage \( U_* \) the field intensity in front of the electrode II will just be equal to zero (graph 2). As the potential of electrode II is diminished still further, say, to \( U'_2 \), there arises a distribution of the potential in accordance with graph 3, that is to say, the field intensity becomes positive again. Now, since for the charge Q upon the surface of the electrode II there holds this relation:

\[ e = \frac{Q}{4\pi \varepsilon} \]  

(1)

it follows that the charge upon the electrode II caused by electrons in the space, as a function of \( U_2 \), corresponds to the graph shown in Fig. 2. It is to be noted, however, that this curve is to give merely a qualitative view, for the accurate calculation is rather complicated.

The capacitance of electrode II in reference to electrode I is:

\[ C = \frac{\Delta Q}{\Delta U_2} \]  

(2)

In other words, equal to the differential quotient of the graph in Fig. 2. For \( U_2 > U'_2 \) therefore, the capacitance is positive, and for \( U_2 = U'_2 = 0 \) and for \( U_2 > U'_2 \) it is negative. Strictly speaking, however, that, from a purely theoretical viewpoint, in the presence of suitable conditions, the capacity may become negative and infinitely high.

If, then, at the place of the electrode II there is mounted a negatively biased control grid having a positive electrode (screen grid, plate) disposed to the rear thereof, it will be seen that the same considerations hold good for the control grid. In other words, the capacitance between electrode I and the control grid may decrease to the zero value and may even become negative. However, the same rule applies also for the capacitance between the control grid and the positive electrode disposed to the rear thereof so that, in the presence of convenient operating conditions, the total input capacity of a control grid may drop down to zero or may even become negative.

It has already been pointed out above that the influence current contains a reactive and an active component. While it is true that the size and the sign of both components are a function of the electron transit time, actual measurements made on the Telefunken tube SFI, for instance, have demonstrated that the change in capacity \( \Delta C \) for the customary electrode systems, down to wave-lengths of around 5 meters, is independent of the frequency, and that there occurs an appreciable decrease only for still shorter wave-lengths. Now, in order that in the light of what precedes, a negative capacity may be obtained between the grid and the filament of an electronic tube, it will be necessary that the grid and also sufficient to ascertain by suitable discharge conditions and more particularly by convenient choice of the grid biasing voltage, such a range of the plate current–grid voltage characteristic (mutual conductance) that is representable by an exponential function with an exponent \( n < 1 \). This feature is present, for instance, in all tubes with saturation properties, regardless of whether true saturation due to limited emissivity of the filament is present or merely the so-called pseudo saturation occasioned by space-charge phenomena. To the last group belong all tubes with metallic cathodes (tungsten filaments), with thoriated cathodes, or distillation cathodes, that is, oxide cathodes presenting a smooth surface. In the second group are found the tubes predicated for their operation upon current–distribution control as well as space charge grid type of tubes. The characteristics of the tubes based upon current–distribution control, as long as the current densities are low and as long as space-charge effects are not appreciably present, that is to say, especially in a state of dissolution of the virtual cathode, obey an exponential function with an exponent \( n < 1 \), and it is for this reason that they prove particularly appropriate for producing a negative capacity. It is also expedient that the grid characterized by the negative capacity arising between it and the filament be decoupled from the anode which is at an alternating potential by the aid of a screen grid maintained at a constant potential, with a view to precluding the effect of the alternating plate potential reacting upon the influence process, and to creating conditions so that a state exists in which calculation is easy and where reaction is absent.

The negative capacity could readily amount to a few micro-micro-farads and may thus exceed the cold capacity between the pair of electrodes referred to. This holds good particularly where this capacity is set up at a third or a succeeding grid in a tube operating with current–distribution control because the influence actions are then particularly marked.

Inside the same range as the negative capacity there arises in most instances also a negative active component of the input impedance. This may be used either for general generation of oscillations or for the partial regeneration of an associated circuit; or by choosing suitable dimensions and sufficiently high damping of the associated circuits, conditions could also be so made that no self-oscillating will happen, that stable conditions are established. Since the negative real component of the input conductance, upon increase of the frequency, acts more and more de-attenuating (regenerating), it is thus possible to obtain an increase in plate resistance in the preceding stage growing with the frequency; and this insures an increase in the gain for the higher frequencies which is desirable in a great many instances.

So far as the utilization of the negative capacity is concerned, which is obtainable by ways and means as hereinbefore suggested, there are many possibilities to accomplish this. Fig. 3 shows a circuit organization adapted to frequency modulations. Tube R contains a saturable cathode \( K \) e.g. a thoriated cathode, a grid \( G \) and an anode \( A \). Between the grid and the filament is connected the resonant circuit LC which is tuned to the carrier wave. Upon the grid \( G \) is impressed from the source of direct current voltage supply \( U_0 \) such a biasing potential that the working point comes to lie inside the region of the characteristic in which both the input resistance \( R_K \) as well as \( W_{AB} \) assume negative values. The result is that the circuit LC is caused to generate oscillations; these latter are amplified by the tube so that across the plate-circuit...
impedance $Z_L$ amplified alternating potentials are set up which are taken off across the terminals $a$, $b$, and impressed upon additional amplified stages or a load resistance (antenna). If, then, the grid voltage $U_g$ is caused to vary at the rhythm or rate of modulation, or if in series with the shaded potential $U_E$, by the aid of a transformer $T$, a modulation potential is introduced, then $\Delta C_{sh}$, that is, a capacity in parallel relation to $C$, will vary and thereby the frequency of the generated oscillations will also vary. If the modulation potential is prevented from exceeding the range in which the grid resistance is made and capable of causing oscillations in the associated oscillatory circuit $LC$, there results steady generation of a frequency-modulated oscillation.

Another useful field of application of negative capacity is in connection with short-wave circuit organization of all kinds in which the input capacitance of the tube has heretofore been very annoying. Inasmuch as it is readily possible to obtain negative capacitances, the size of the cold capacity, between the input electrodes of a tube, adjustments could be made, for instance, in such a way that the cold capacitance would just be neutralized by the negative capacity. The natural frequency of a frequency-governing grid circuit would thus not be altered by inserting the tube. It is therefore possible also to permit a frequency standard, say, a crystal oscillator or a feebly damped circuit to operate actually at its real natural frequency, without being necessary to dispense with the fixed coupling of this circuit as in the past. It is more feasible to neutralize the cold capacitance also by the negative capacity. It is thus permissible to manufacture short-wave tubes with a base which was prohibitive in many instances in the earlier art. The base losses may be minimized by the use of a suitable ceramic material to a point where they are actually negligible.

If the negative capacity exceeds the cold capacitance of the input electrodes in magnitude, it becomes possible to neutralize part of the capacity of the input circuit. In short-wave circuit organizations the input circuit consists, for instance, only of an inductance coil or turn whose natural period is governed by the distributed capacitance of the winding (coil) and the leads. It has heretofore been impossible in the art to reduce the frequency of the oscillations generated in a circuit organization below the natural frequency of the externally associated oscillatory structure. However, by the aid of the negative capacity this has become feasible; as a result the lower frequency limit of wave generation may be reduced. It is immaterial in this connection whether the excitation of the oscillatory system is accomplished by the negative input impedance of the tube or by application of such means as are well known in the earlier art, for instance, feed-back or regeneration, etc.

Another chance to utilize the variability of the capacitance between the input electrodes of a tube exists in connection with the so-called sharp-tuning of a receiver apparatus or of a wave generator. In modern receiver sets possessing a high degree of sensitiveness and high selectance it is very important that the set be precisely tuned to the carrier of the station to be received lest part of the one side-band be cut off or portions of an adjoining side-band be passed. Suggestions have been made in the art to the end of relieving the listener of the work of effecting exact tuning to the desired carrier wave. In fact, all the listener is called upon to do in such a case is to set the apparatus coarsely, while the apparatus will automatically adjust itself to the middle of the frequency band to be received. Such automatic tuning, however, in the past required mechanical drive mechanisms for the tuning means, and hence made the scheme rather complicated in construction. Now, the use of negative capacity according to the invention introduces an essential simplification and great convenience.

In Fig. 4 the capacity variation $\Delta C_{sh}$ has been plotted as a function of the grid biasing voltage $U_g$. It will be seen that the capacity variation changes from a positive maximum to a negative crest value and thereafter decreases again towards zero. The region bounded by the points $p, q, r$ is to be used for sharp tuning of a circuit, the quiescent (neutral) point being at $r$.

Fig. 5 shows schematically an exemplified embodiment of a receiver design for precise tuning according to the invention. The oscillations picked up by the antenna $ANT$ are fed into the input circuit of a mixer stage $M$ in which combination with the oscillations furnished from a heterodyne $U$ is effected, the frequency of the latter being governed by a resonance circuit $LC$.

The latter shall be assumed to be included between the grid and the cathode of a tube whose capacity variation $\Delta C_{sh}$ corresponds to the curve shown in Fig. 4. It is immaterial in this connection whether the wave generation standard is also produced by this tube or whether the tube is solely provided for the production of the variable capacitance.

The beat frequency formed in the mixer tube is fed to an I. F. amplifier $Zio$ which comprises sharply tuned (highly selective) band-pass filter circuits. The I. F. is demodulated in a succeeding rectifier $D$ as shown in the art and then amplified in an audio frequency amplifier $NF$ to which the loudspeaker $LeP$ is connected.

In coupling relation with the output of the I. F. amplifier are two resonant circuits $K_r$ and $K_r'$ one of these being first tuned to a frequency slightly above the I. F., while the other circuit is tuned to a value being an equal amount below the I. F. Each of the resonance circuits feeds a rectifier $Gi$ and $Gi'$ respectively, the rectified currents being caused to traverse a resistance $W$ in opposite directions. If, then, the ensuing I. F. corresponds to the prescribed or rated value, the effects of the current flowing through the resistance $W$ cancel one another. But if the I. F., owing to inaccurate tuning of the oscillation circuit $LC$ of the heterodyne differs from the rated value, then one of the two rectifier currents will predominate over the other, and a drop of potential will be occasioned across the resistance $W$ in a definite direction. If this fall of voltage is impressed upon the grid circuit of the tube furnishing the negative resistance, the operating point will be caused to shift either in the directions $p$ or towards $q$ (Fig. 4), with the consequence that either a positive or a negative capacity is connected in parallel to the capacity $C$, and thus either an increase or a decrease in the beat frequency is obtained.

Finally, the utilization of the rectifier capacity occasioned by influence actions shall be discussed as applied to amplifier circuit organizations. In the operation of resistance-coupled amplifiers designed to amplify a broad band of frequencies, the invariable demand is that the gain should drop as little as possible for the high frequencies. The cause of such decrease in gain...
with increase of frequency resides in the capacitances of the tube and associated circuits which inevitably arise in parallel relation to the outer resistance. Now, according to the invention the suggestion is made to use in one, or in several, or in all stages of a resistance-coupled amplifier, especially an amplifier adapted to handling broad-frequency bands, tubes which are operated under such conditions that by the influence action of the electronics the input capacity of the succeeding stage being in parallel relation to an outer resistance is diminished. As a result the capacitive shunt of the outer resistance is diminished and thereby the frequency response curve improved; or else, for an unchanged frequency-response curve, a higher outside resistance may be chosen and thus a higher gain be obtained. For the said purpose suitable tubes are used in which the capacity decrease is as marked as possible. The dynamic input capacity of each tube shall suitably be less than 70 per cent of the cold capacity. Most favorable is the use of tubes the input capacity of which is negative, as a consequence of the above described influence action seeing that this input capacitance has connected in parallel to itself in addition the line capacities and the output capacity of the preceding or input tube. To be sure, from the viewpoint of the frequency-response curve of the gain it is important only that the sum total of these capacities should be as low as possible or even slightly negative. In the light of all previous experience this effect is obtained, better than with one-grid tubes (triodes), with tubes in which a control action upon the electrons is exercised after they have been accelerated to a positive potential impressed upon an auxiliary grid (distribution control). In other words, according to this invention, types of tube such as space-charge grid tubes, baxtode tubes, heodepots, octodes, etc., are particularly well suited, the alternating potential to be amplified being impressed upon the control grid nearer the plate. What is favorable from the viewpoint of utilization of the effect is the fact that the capacity variation due to influence action is fairly independent of frequency.

In Fig. 6 is shown an exemplified embodiment of such a circuit arrangement. Included in the plate circuit of the input tube \( R_a \), upon the grid of which the potential to be amplified is impressed across terminals \( a, b \), is the resistance \( R_b \), and in shunt relation to the latter is the capacity \( C_b \) which exercises an unfavorable effect upon the frequency response. The succeeding tube \( R_b \) is predicated for its operation upon the principle of current-distribution control; this tube contains the four grids \( G_1-G_4 \), in addition to the cathode \( K \) and the anode \( A \), the amplified potentials being taken off the plate circuit across the output terminals \( c, d \). The third grid \( G_3 \) is impressed with the output potential of the preceding tube or input tube. Grids \( G_2 \) and \( G_4 \) are impressed with constant positive potentials, grid \( G_1 \) is impressed with a constant negative or a feebly positive potential. The adjustment of the discharge conditions occurs according to the above described prescriptions, so that the input capacitance \( C_p \) prevailing between the control grid \( G_2 \) and the filament will be less than the cold capacitance between the said two electrodes, and preferably negative in value so that the harmful parallel capacitance \( C_p \) is wholly or partly compensated. As pointed out on page 2, the grid bias is so chosen that the operating point of the tube is at a part of the plate current-grid voltage characteristic which is concave downwards. The grid bias source \( U_a \) supplies the bias to grid \( G_3 \) through the usual grid leak resistor. It is at the part of the characteristic which is concave downwards that the exponent \( n \) is less than unity. The grid \( G_3 \) is shielded by \( G_4 \) and \( G_5 \) from the influence of varying potentials of other electrodes. The grid \( G_3 \) and \( G_4 \) are maintained at an unvarying positive potential since no load is inserted in circuit therewith.

In addition to the application of this effect for the purpose of improving the frequency-response curve of resistance-coupled amplifiers, there may be mentioned still another channel for using the same. The damping \( d \) of a parallel oscillation circuit is given by:

\[
d = \frac{r}{\sqrt{L/C}}
\]

where \( r \) is the series loss resistance, \( C \) the capacitance, and \( L \) the inductance of the oscillation circuit. Inasmuch as the damping is proportional to \( C \), reduction of \( C \) will imply also a reduction of damping, in other words, this leads to a raise of resonance resistance and the selectivity of the fly-wheel circuit. Now, according to the invention the effect of capacity reduction due to influence effects is to be utilized for the regeneration (deattenuation) of oscillatory circuits. From a technical angle, such regeneration of oscillation circuits is useful and desirable in a great many circuit organizations used in radio-frequency work. As concerns the choice of the tubes and of the operating conditions which will be most suited to obtain the said effect of regeneration, reference is had here to what has been pointed out above, for the preceding remarks and explanation apply also to this case.

While we have indicated and described various systems for carrying our invention into effect, it will be apparent to one skilled in the art that our invention is by no means limited to the particular organizations shown and described, but that many modifications may be made without departing from the scope of our invention as set forth in the appended claims.

What is claimed is:

1. In an electronic network adapted to produce a negative capacity effect, a positive mutual capacitance tube having a cathode, a plate and at least two control grids arranged in succession therebetween, the one of said grids adjacent the cathode being maintained at an invariable positive potential, means maintaining said plate at a positive potential, means establishing the second one of said grids at a negative potential with respect to the cathode, the magnitude of the said negative potential being so chosen that the operating point of the tube is on that portion of the plate current-second grid potential characteristic which is concave downwards, said negative capacity effect existing between said second grid and said cathode.

2. In an electronic network adapted to produce a negative capacity effect, a positive mutual capacitance tube having a cathode, a plate and at least two control grids arranged in succession therebetween, the one of said grids adjacent the cathode being maintained at an invariable positive potential, means maintaining said plate at a positive potential, means establishing the second one of said grids at a negative potential.
with respect to the cathode, and the magnitude of the said negative potential being so chosen that the operating point of the tube is on that portion of the plate current-second grid potential characteristic which is concave downwards, said negative capacity effect existing between said second grid and said cathode, and a third control grid located between the plate and the second grid, said third grid being maintained at an invariable positive potential.

HORST ROTHE.
WERNER KLEEN.