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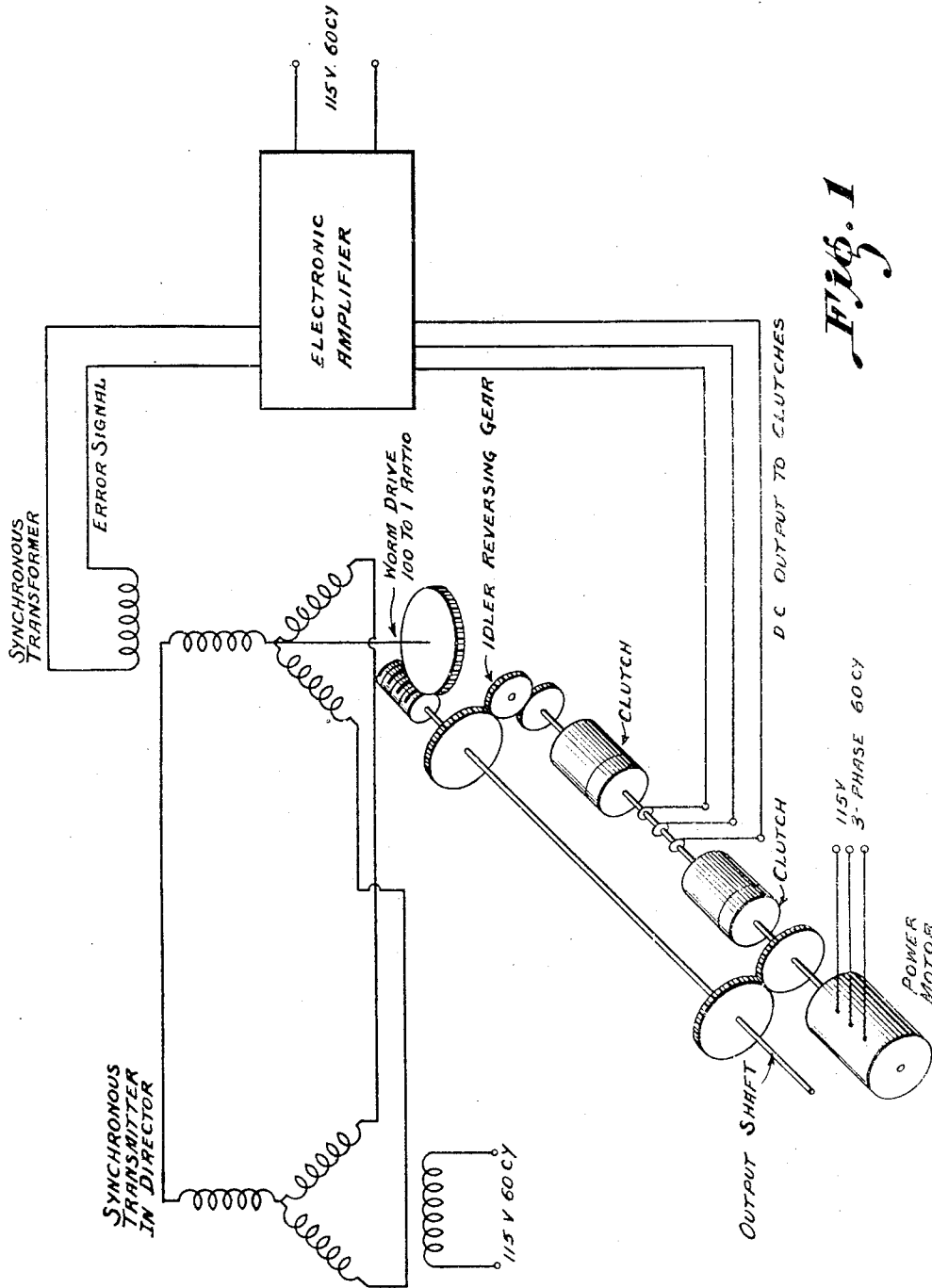
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2,455,618

DAMPING FOLLOW-UP MECHANISM BY DEGENERATIVE DERIVATIVE

Filed Jan. 10, 1945

3 Sheets-Sheet 1



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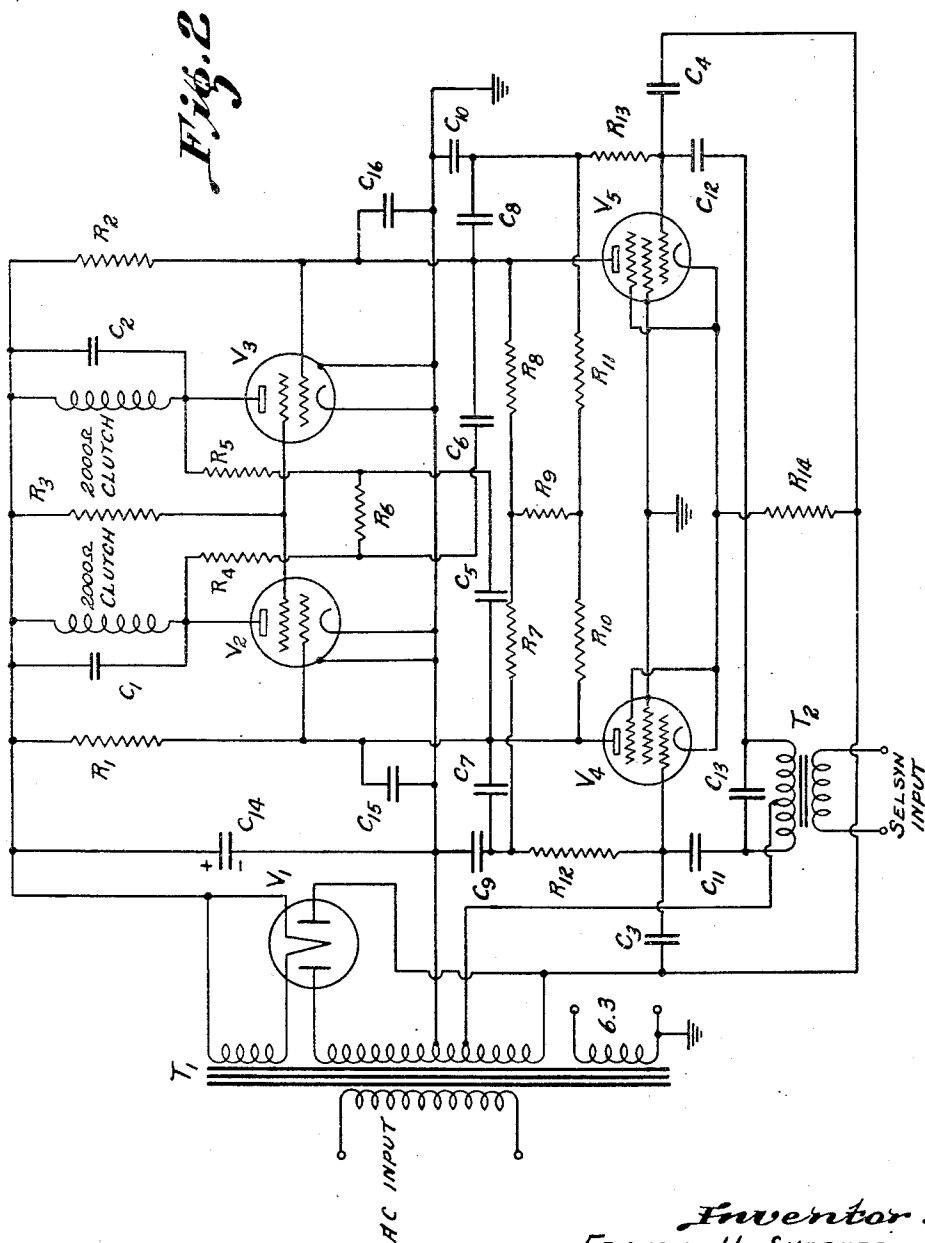
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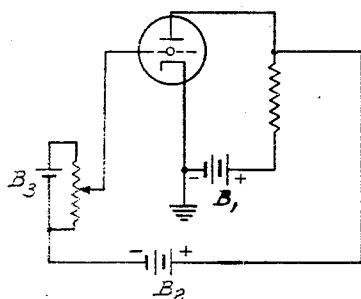
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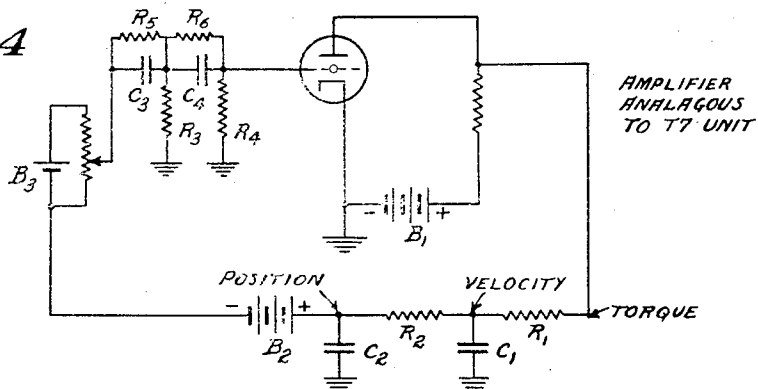
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Fig. 3



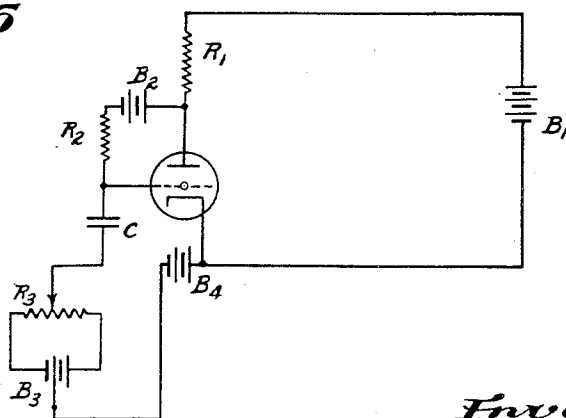
SIMPLE DEGENERATIVE
AMPLIFIER

Fig. 4



AMPLIFIER
ANALOGOUS
TO T7 UNIT

Fig. 5



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UNITED STATES PATENT OFFICE

2,455,618

DAMPING FOLLOW-UP MECHANISM BY
DEGENERATIVE DERIVATIVE

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Application January 10, 1945, Serial No. 572,209

4 Claims. (Cl. 250—27)

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In follow-up mechanisms where it is desired automatically to control the position of a mechanical device problems are encountered with the stability of location of the device. It is necessary to introduce derivative functions to anticipate the motion or change of balance in order to avoid hunting. This has been explained in my related copending applications Serial No. 499,774, filed August 24, 1943, entitled "Follow-up device" and Serial No. 563,566, filed November 15, 1944, entitled "Damping follow-up mechanisms by regenerative derivative."

The invention herein disclosed has been built into an operative device known as torque amplifier T7. The invention relates to the electronic amplifier used in the T7 unit and in particular to the circuits of the electronic amplifier which provide damping for the mechanism.

In the drawings,

Figure 1 is a schematic drawing illustrating the operation of the unit;

Figure 2 is a circuit diagram of the electronic amplifier employed in the unit; and

Figures 3, 4 and 5 are circuit diagrams illustrating the operation of the portion of the circuit of Figure 3 which provides the damping.

The principal components of torque amplifier T7 are the synchronous transformer, the electronic amplifier, the drive motor, and the magnetic clutches. The functioning of these components is illustrated schematically by Figure 1.

The synchronous transformer is electrically connected in the conventional manner to a synchronous transmitter mounted in the director. The shaft of the transmitter is driven in accordance with predicted fuze data by the A. A. director. When the synchronous transformer shaft is in the position called for by the director, the transformer has zero voltage output. If the transformer shaft is displaced from this position, the transformer has a 60-cycle output voltage, whose amplitude is approximately proportional to the sine of the displacement angle. It is convenient to call this displacement angle the error, and the resulting transformer output voltage the error signal.

The electronic amplifier is fundamentally a current amplifier whose input voltage is the error signal and whose D.-C. output current is supplied to the clutches. The circuit employs phase detection to determine direction of error, and includes damping circuits which prevent hunting.

The driving motor which supplies mechanical power to the system is a 110-volt 60-cycle 3-phase motor running at 1725 R. P. M. Although power is supplied to the synchronous transformer and amplifier when the cable system is energized, the motor does not receive power until the fuze setter rammer motor is started.

The driving portion of the magnetic clutch

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assembly is permanently coupled to the motor and rotates at constant speed. This portion of the assembly is made up of the clutch shaft, slip rings, two magnetic coils and two clutch bodies.

A pair of clutch keepers are also mounted on the clutch shaft adjacent to the clutch bodies. When current is passed through either coil, the corresponding clutch body and keeper are brought into engagement, thus causing the keeper to accelerate in the direction of rotation of the body. The keepers are geared to an auxiliary shaft, one directly and the other through an idler gear for reversing the direction of movement. The auxiliary shaft is in turn geared to the output shaft and to the synchronous transformer shaft. When the synchronous transformer develops an error signal, the amplifier supplies current to the proper clutch for driving the output and the transformer shafts in the direction to reduce the error signal to zero.

The circuit diagram of the electronic amplifier is shown in Figure 2. The principal components of this circuit are; the power supply, employing transformer T₁ and rectifier tube V₁; the push-pull input stage, employing tubes V₄ and V₅; the push-pull output stage, employing tubes V₂ and V₃; and three resistor-condenser networks. Two of these networks prevent hunting. The third gives the amplifier a sensitivity which, except for transient conditions, is infinite. This infinite sensitivity network enables the amplifier to correct any persistent error, no matter how small. This is described in my copending application Serial No. 499,774 referred to above. The various components of the circuit of Figure 3 and their values for the particular piece of apparatus referred to above are as follows:

V ₁	5W4
V ₂ , V ₃	SV6
V ₄ , V ₅	6SJ7
T ₁ power transformer	
T ₂ input transformer	
C ₁ , C ₂ , C ₉ , C ₁₀	.05 mfd., 600 volt, paper
C ₃ , C ₄	.001 mfd., 600 volt, paper
C ₅ , C ₈	.002 mfd., 600 volt, paper
C ₇ , C ₆ , C ₁₃	.02 mfd., 600 volt, paper
C ₁₁ , C ₁₂ , C ₁₅ , C ₁₆ ..	.01 mfd., 600 volt, paper
C ₁₄	4 mfd., 350 volt, electrolytic
R ₁ , R ₂	3 meg., ½ watt
R ₃	1000 ohms, ½ watt
R ₄ , R ₅	1 meg., ½ watt
R ₆	0.15 meg., ½ watt
R ₇ , R ₈ , R ₁₀ , R ₁₁ , R ₁₂ ,	
R ₁₃	5 meg., ½ watt
R ₉	0.1 meg., ½ watt
R ₁₄	0.2 meg., ½ watt

The amplifier is able to select the proper direction in which to drive the output shaft because

the phase of error signal depends on the direction of error. That is, when the error is in one direction, the error signal is in phase with the A.-C. line voltage supplied to power transformer T₁. When the error is in the opposite direction, the error signal is 180° out of phase with this voltage. The amplifier makes use of this phase reversal to determine which clutch should be excited in order to drive the synchronous transformer to the position of zero error signal.

It can be seen from Figure 2 that A.-C. voltage is applied to the cathodes of the input tubes through bias-resistor R₁₄ from the high-voltage winding of transformer T₁. Further, the center-tap of this winding and the screens of the input tubes are grounded. Under this condition, the transformer voltage causes the screen to be alternately positive and negative with respect to the cathodes. It is only during the positive half cycles of screen voltage that the input tubes can conduct plate current. The tubes cannot conduct plate current during the other half cycles because the screens are then negative with respect to the cathodes.

The error signal is applied in push-pull through condensers C₁₁ and C₁₂ to the input grids by the center-tapped secondary of transformer T₂. When the error is in one direction, the error voltage on the grid of V₄ is out of phase with the 60-cycle voltage applied to the screen of V₄. Under this condition, the error signal reduces the D.-C. plate current of V₄ because the signal swings the grid negative during the tube's conducting half cycles. At the same time, the error signal applied to the grid of V₅, being in opposite phase, swings the grid of V₅ in the positive direction during the conducting half cycles, and thus increases the D.-C. plate current of V₅.

The decrease in D.-C. plate current of V₄ decreases the D.-C. voltage drop across resistor R₁ and thus changes the grid potential of tube V₂ in the positive direction. This change increases the plate current drawn by this tube through one of the clutches and causes the clutch to apply torque to the output shaft. If the error had been in the direction opposite to that assumed above, the other clutch would have been excited and torque would have been applied to the output shaft in the opposite direction. The direction of the applied torque is always such as to drive the control transformer to the correct zero-signal position.

Strong harmonics of 60 cycles in the error signal supplied to the input grids could cause one of the input tubes to have much lower gain than the other. These harmonics are suppressed by condenser C₁₃ which tunes the secondary of transformer T₂ to 60 cycles.

The output stage can be thought of as operating as a class B amplifier. When error signal is static at zero, the D.-C. plate current of both output tubes is small, about 4 ma. each. Hence, there is no appreciable heating of the clutches when the called-for position is static. When error signal causes the plate current in one tube to rise appreciably, it causes the plate current in the other tube to be cut off. The maximum D.-C. plate current drawn by an output tube is approximately 30-40 ma.

To understand the problem of preventing hunting suppose the director requires the amplifier to turn the output shaft from one angular position to another in a given period of time. During the first portion of this period considerable torque must be applied in order to accelerate the

mass of the gears and the control transformer driven by the shaft. During the second portion of the period, velocity is constant, no acceleration is required, and the only torque necessary is that required to overcome friction. Because friction is small compared to the mass load, the required torque during the second portion of the period is comparatively small.

During the last portion of the period the mass of the system must be decelerated to zero velocity, and because considerable momentum has been built up, considerable negative torque must be applied. If decelerating torque were not applied at this time, momentum would carry the shaft past the called-for position. The resultant error signal would produce a restoring torque which would eventually drive the shaft back toward the called-for position. But, if again no decelerating torque were applied before the position was attained, the shaft would overshoot again and severe oscillation or hunting would result.

Hunting is prevented by making the amplifier developed torque proportional to the rates of change of the error signal amplitude. During the first portion of the period referred to above, the director accelerates rapidly and gets ahead of the control transformer. The error signal, therefore, rises to a positive peak during this period. During the second portion of the period, the torque required for producing the desired motion is small and, therefore, the error signal during this period is small. During the third portion of the period the director decelerates rapidly and the control transformer runs ahead of the director. The error signal, therefore, goes to a negative peak during this portion.

For stable operation, the amplifier must develop much more torque during the first and third portions of the periods (negative torque during the third portion) even though the error signal is no greater than during the middle portion. In other words, the torque output of the amplifier must be determined not only by the error signal amplitude but also by rates of change of amplitude. To meet this requirement the amplifier must include means for differentiating error signal amplitude.

Differentiation of error signal amplitude in the input stage is performed by plate-to-grid feedback through condensers C₇ and C₈, resistor R₁₂, and condenser C₁₁ in the circuit of tube V₄ and the corresponding parts in the circuit of V₅. Differentiation in the output stage is provided by cross-coupling the plate of V₂ to the grid of V₃ through R₄ and C₆, and similar cross coupling from the plate of V₃ to the grid of V₂. The differentiating action of these networks will be explained later.

In Figure 2, the plate of V₄ is coupled to the grid of V₅ through resistors R₁₀, R₁₁, and R₁₃. The plate of V₅ is similarly coupled to the grid of V₄. The feedback due to this cross-coupling, is highly regenerative. Hence, a very small amount of positive voltage applied to either input grid can cause the regeneration to drive this grid all the way to zero bias and the other grid all the way to cut-off. The regenerative effect occurs comparatively slowly because it takes time for the coupling resistors to charge condensers C₇, C₈, C₃, C₁₁ and the corresponding condensers associated with V₅. The condensers which mainly determine the time constant of the network are C₉ and C₁₀. This has been described in my copending application Serial No. 499,774 referred to above.

For an explanation of how the network contributes to accuracy, suppose the director has called for a new value of fuze-timing and the control transformer is approaching its new zero-error position. As the error signal becomes smaller and smaller, the torque developed by simple amplification of the signal becomes too small to overcome friction. If there were no other source of torque, the output shaft would stop turning when still a small distance short of the correct position. The resulting residual error would be too large for the accuracy required for fuze-setting.

The regenerative network eliminates this residual error because the feedback causes the residual error signal to build up a slowly increasing voltage on the input grids. This slow building-up takes place no matter how small the residual error signal is. The increasing voltage on the grids produces a slowly increasing torque on the output shaft. This torque becomes large enough to overcome friction, and reduces the residual error to zero. The time constants of the network are adjusted so that there is a smooth transition from direct-amplification torque to regenerative-amplification torque. The differentiating action discussed above prevents the regenerative torque from causing overshoot and hunting.

For another illustration, suppose there is a heavy friction load on the output shaft, and that the director calls for a constant-velocity motion over a period of time. When the unit starts to reproduce this motion, there will be considerable momentary error because it takes comparatively large error signal to develop enough torque to overcome the friction. However, the regenerative feedback between the input tubes builds up differential D.-C. voltage on the input grids. These voltages produce more torque which reduces the error. The process continues, the regenerative voltage gradually supplanting the error signal as a cause of torque, until the control shaft performs the required motion with zero error.

For a third illustration, suppose there is a heavy mass load on the output shaft with negligible friction load, and the director calls for a constant-acceleration motion over a length of time. Just as before, the regenerative network, after a short time, develops the required torque with zero error signal and enables the output shaft to perform the required motion with zero error.

These illustrations show how the regenerative network enables the T7 unit to perform with high accuracy under many different conditions of load and acceleration.

The operation of my invention may perhaps be explained most lucidly by analogy. A useful analogy for the T7 unit is an amplifier with degenerative feedback. A simple amplifier of this kind is shown in Figure 3. The variable voltage obtainable from battery B_3 corresponds to the signal from the director. When this voltage changes, the plate voltage changes and is fed back so as to reduce the change in grid-cathode voltage. The battery B_2 is introduced merely to provide negative grid bias. The degenerative feedback of Figure 3 is similar to the T7 unit's degenerative electromechanical feedback through the clutches and output shaft. The advantage of the analogy is that it represents both mechanical and electrical functions in electrical terms.

However, the analogy of Figure 3 is not entirely accurate. It implies that the output current of the T7 amplifier directly determines the angular

position of the control transformer shaft. Actually, of course, the output current determines the torque applied to the shaft. This torque produces angular acceleration of the shaft. At any instant, the shaft's angular velocity is proportional to the time integral of the acceleration, and its angular position is determined by the time integral of the velocity. The position of the shaft is, therefore, determined not directly by the amplifier's output current but by the second time integral of this current. The more accurate analogy of Figure 4 represents the double integration by two R. C. networks, R_1C_1 and R_2C_2 .

In order for this representation to be valid, it must be considered that time constants C_1R_1 and C_2R_2 are long compared with frequencies of interest, that R_2 and C_2 have negligible shunting effect on C_1 , and that both R. C. networks have negligible shunting effect on the tube's plate resistor. Under these conditions, the voltage across C_2 is proportional to the second time integral of the tube's plate voltage which, in turn, is proportional to plate current. The voltage across C_2 is therefore analogous to the position of the output shaft of the T7 because this position is determined by the second time integral of output plate current.

The important point immediately apparent from Figure 4 is that, for an A.-C. voltage originating at the plate, the two integrations each introduce a 90° phase lag in the feedback path. The total lag is 180° and, if the voltage across C_2 were applied directly to the grid without further phase shift, any random A.-C. plate voltage would be fed back regeneratively and the circuit would oscillate. This oscillation corresponds to hunting in the electro-mechanical system being represented.

The way to prevent hunting in the circuit of Figure 4 is to introduce differentiating networks C_3R_3 and C_4R_4 in the feedback path. The phase advance produced by these networks compensate for the phase lag of the integrating networks. By proper adjustment of time constants, the net phase shift of the feedback path can be made practically zero for all frequencies of interest and oscillation can be eliminated. To make the analogy more complete, the D.-C. blocking effect of C_3 and C_4 can be circumvented by means of resistors R_5 and R_6 which are made large enough to have negligible A.-C. shunting effect on the condensers. The final result is that the amplifier is stabilized against regenerative feedback of A.-C. plate voltage and is also able to degenerate D.-C. voltage changes from B_3 .

Reasoning by analogy from Figure 4, the way to stabilize the T7 unit is to introduce in the amplifier means for differentiating the error-signal amplitude twice. This reasoning shows why the two differentiating networks are used, and how they are able to eliminate from the unit all tendency to hunt.

In the T7 unit, it is necessary to differentiate, not just a simple D.-C. voltage as in Figure 4, but the amplitude of the A.-C. error signal. The differentiating means should be able to differentiate comparatively rapid changes of this amplitude. The reason for this is based on a characteristic property of clutches.

Clutches, as used in the T7 unit, can apply a comparatively large torque to the output shaft but load the shaft with a comparatively small mass. In other words, to any force which tries to displace the shaft from its called-for position, the shaft presents high stiffness but compara-

tively little mass. If the shaft were driven directly from a motor, the ratio of stiffness to mass would be much less.

Because of the high stiffness-to-mass ratio provided by the clutches, the natural period of the mechanical system is comparatively high. That is, if the system were to hunt it would hunt at a comparatively high frequency, 20 or 30 cycles. Any differentiating means which is to prevent hunting should be able to differentiate variations of signal amplitude at this frequency. Because this frequency is appreciable compared with the 60-cycle frequency of the error signal, it is not feasible to differentiate by means of the conventional diode rectifier, ripple filter and differentiating network.

The method used in the T7 unit for differentiating the amplitude of the A.-C. error signal can be explained by reference to the simplified circuit of Figure 5. In this circuit, the tube is to be considered as having very high voltage gain from grid to plate, and the condenser as having no leakage. Negative grid bias is provided by battery B₂ and this bias is adjusted so that the tube operates in the high-gain middle portion of its characteristic. The contact on R₃ and the voltage of battery B₄ are initially adjusted so that there is no voltage across the condenser.

Now, suppose the contact on R₃ is moved in the positive direction. Let us call the voltage of the contact, the error voltage. The increasing positive error voltage resulting from the motion of the contact causes a positive change in grid voltage and, consequently, a negative change in plate voltage. This negative plate-voltage change charges the condenser C in the negative direction and thus feeds back on to the grid a negative voltage opposing the positive error voltage. With very high voltage gain from grid to plate, the feedback holds the grid very close to its initial potential. In other words, the feedback voltage built up across the condenser is, at any instant, approximately equal to the error voltage at that instant.

Because the feedback voltage is built up by the plate charging the condenser through resistor R₂, the feedback voltage is proportional to the time integral of the change in plate voltage from its steady-state value. Conversely, the change in plate voltage is the time derivative of the feedback voltage. Since the feedback voltage is approximately equal to the error voltage, it follows that: When the error voltage changes, the plate voltage changes from its steady-state value by an amount which, at any instant, is approximately proportional to the time derivative of the error voltage at that instant.

The method used in the T7 unit for differentiating the amplitude of error signal can now be explained by reference to the circuit of tube V₄ in Figure 2. For illustration, suppose that transformer T₂ applies to the grid of V₄ an increasing error signal of positive phase. By positive phase it is meant that the signal increases D.-C. plate current because the signal swings the grid in the positive direction during the conducting half-cycles when the power transformer swings the cathode of V₄ negative. The increase in D.-C. plate current causes the D.-C. plate voltage to become more negative. A portion of this change in plate voltage is fed back to the grid from the capacitive voltage divider constituted by C₇ and C₈ in series. Because the changes in plate voltage that are important are fast enough so that D.-C. leakage in C₇ and C₈ is negligible, the con-

densers can be thought of as forming a simple D.-C. voltage divider. The negative D.-C. voltage fed back to the grid biases the grid back and thus counteracts the positive-phase error signal on the grid. Since C₃, C₁₁ and R₁₂ form an integrating network, it follows, as before, that: When the amplitude of error signal changes, the D.-C. plate voltage changes from its steady-state value by an amount which, at any instant, is approximately proportional to the time derivative of error-signal amplitude at that instant.

The degeneration used in this circuit enables it to meet two conflicting requirements. These requirements can be explained on the basis of the circuit's gain-versus-frequency characteristic. In order for the circuit to differentiate so as to prevent hunting, its gain must increase with frequency up to and slightly beyond 30 cycles, the system's natural hunting frequency. However, the gain must be low at 60 cycles so that the 60-cycle plate voltage will not overload the output stage.

The differentiating circuit used in the T7 has the desired rising frequency characteristic because the plate-to-grid degeneration decreases as frequency increases. The circuit also has the desired low gain at 60 cycles, principally because of the plate-to-ground capacitance provided by C₇, C₉, and C₁₅. The degenerative action of the circuit makes it possible to design the circuit so that it has a sharp transition from the high gain at 30 cycles to the low gain at 60 cycles.

The second differentiation is performed by means of condensers C₅ and C₆. It can be seen that C₅ is connected from the grid to V₂ to a point on a resistive voltage divider between the plates of V₂ and V₃. Because this point is closer to the V₃ plate than to the V₂ plate, and because V₂ and V₃ are connected in push-pull, the feedback is regenerative. Hence, when error signal drives the grid side of C₅ in the positive direction, and the grid side of C₆ in the negative direction, the voltage divider drives the other side of C₅ still more positive. The condenser, therefore, acts as a negative capacitance. The positive change in voltage of the grid V₂ causes positive charge, not to flow into the condenser as it would into a positive capacitance, but to flow out of it. The rate of flow of this charge is, of course, proportional to the rate of change of voltage across C₅ which, in turn, is proportional to the rate of change of voltage at the grid of V₂ (plate of V₄). Hence, the voltage drop across R₁ due to the flow of charge from C₅ introduces a second derivative term in the error voltage on the grid of V₂.

It should be noted that the feedback through C₅ and C₆ is regenerative only for a signal applied in push-pull. For a signal applied in parallel to the grids of V₂ and V₃, the feedback through C₅ and C₆ is degenerative. Since the undesired ripple voltage output of V₄ is a signal applied in parallel with the ripple output of V₅, condensers C₅ and C₆ help to filter out this undesired ripple.

It will, of course, be understood that my invention is capable of various modifications which will be understood by those skilled in the art, and I do not desire to be restricted to the particular details of disclosure but only within the scope of the appended claims.

What is claimed is:

1. An electronic amplifier comprising an amplifier tube, an input circuit and an output circuit for said tube, whereby a signal applied to said input circuit produces an output proportional thereto, regenerative means for modifying said

output in proportion to time rate of change in amplitude of said signal, and degenerative means for modifying said output in proportion to the time rate of change of the time rate of change in amplitude of said signal.

2. An electronic amplifier comprising an amplifier tube, an input circuit and an output circuit for said tube, whereby a signal applied to its input circuit is amplified to produce an output proportional thereto, degenerative means for modifying said output in proportion to time rate of change in amplitude of said signal, and regenerative means for modifying said output in proportion to the time rate of change of the time rate of change in amplitude of said signal.

3. An electronic amplifier comprising an amplifier tube, an input circuit and an output circuit therefor a regenerative connection between said output and input circuits for amplifying a signal applied to said input circuit to produce an output proportional thereto, degenerative means for modifying said output in proportion to time rate of change in amplitude of said signal and regenerative means for modifying said output in proportion to the time rate of change of the rate of change in amplitude of said signal.

4. An electronic amplifier comprising a push-pull input stage with two tubes each having an anode and a grid, a push-pull output stage, a circuit connecting said stages, means for applying a signal to the input stage, means for amplifying said signal to produce an output proportional thereto, and means for modifying the output in proportion to the time rate of change of amplitude of said signal comprising an integrating network connecting the anode and grid of each of said tubes.

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