The Design of an Intermediate-Frequency System for Frequency-Modulated Receivers*

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Summary—**With a possibility that the present frequency-modulation wave band may be increased in width it has become imperative that an intermediate-frequency amplifier operating at a frequency higher than that most commonly in use at present, 4.3 megacycles, be developed. Stability both as to performance and permanence of adjustment govern the choice of frequency and restrict this choice to a definite maximum value. Design data are given in this paper for an amplifier operating on 8.25 megacycles which satisfies the stability conditions, and gives the required performance.**

INTRODUCTION

RADIO receivers designed for the reception of frequency-modulation broadcasts are usually of the superheterodyne type employing a stage of radio-frequency amplification followed by a frequency converter and with two stages of intermediate-frequency amplification preceding the limiter and frequency discriminator. The band of frequencies assigned to these transmissions, namely, 42 to 50 megacycles, dictates a value of receiver intermediate frequency somewhat greater than 4 megacycles in order to avoid image interference from other frequency-modulation transmissions. With a view to the possibility that the frequency-modulation band may be extended beyond 50 megacycles, and also with an idea of standardizing with television receiver practice, an intermediate-frequency value of 8.25 megacycles in superheterodyne receivers seems in order. This discussion is limited to the problems arising in the design of the intermediate-frequency amplifier when two stages are employed using a frequency of 8.25 megacycles, and to the transformer design problems involved in coupling a limiter to a frequency discriminator.

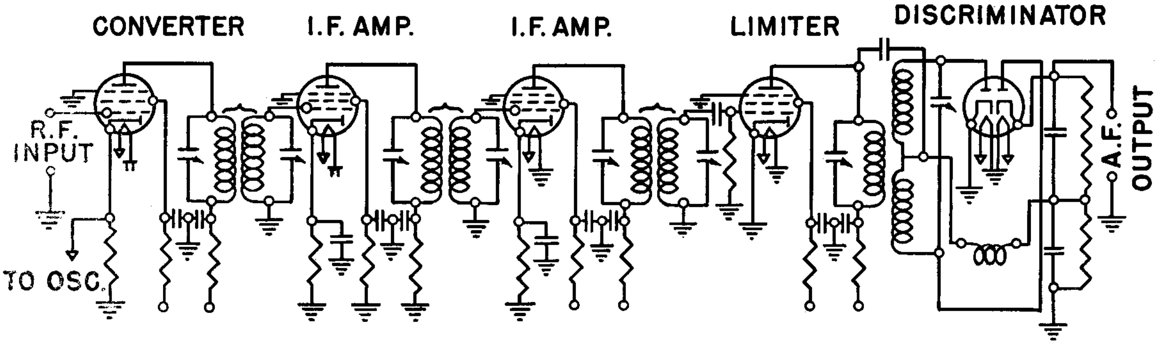

Fig. 1—Schematic for frequency-modulation—intermediate-frequency amplification.

THE INTERMEDIATE-FREQUENCY AMPLIFIER

The gain required in the intermediate-frequency amplifier is expressed by the ratio of the voltage needed at the limiter for effective operation (approximately 2 volts) to the voltage appearing at the input to the converter tube from an assumed 5 microvolts at the antenna terminals. The gain is of the order of 40,000 times assuming a total radio-frequency gain of 10.

As a selectivity requirement, the amplifier must allow passage of modulation frequencies to ±100 kilocycles, from the carrier with a minimum of attenuation and then must attenuate as rapidly as possible thereafter. Previous experience with 4.3 megacycles has indicated that an attenuation of 6 decibels, 75 kilocycles removed from the carrier, will result in no observable output distortion. Under this condition, an attenuation of 30 decibels at 200 kilocycles removed from tune can be achieved in design and will result, from a field standpoint, in a practical degree of selectivity. These conditions dictate the requirements for an intermediate-frequency amplifier operating at 8.25 megacycles.

Several factors govern the gain and the selectivity of the intermediate-frequency amplifier when the value of the intermediate frequency is established. These are principally (a) the mutual conductance of the amplifier tube and its interelectrode capacitance, (b) the number and Q of the tuned circuits, and (c) the ratio of inductance to capacitance in the tuned circuits.

The mutual conductance of the amplifier tube enters into the gain as a first-order effect. The interelectrode capacitance (i.e., between control grid and plate) acts to limit the maximum gain by introducing regeneration effects.[1]

The gain factor of an amplifier tube may thus be considered as directly proportional to g_m, and inversely proportional to C_{gp}. Three types of tubes have been proposed for amplifier service. A comparison of their

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[1] J. A. Worcester, Jr., "Double superheterodyne for FM receivers," *FM Magazine*, vol. 4, pp. 15–18, 58–60; March, 1944.

properties may be of interest. The superior properties of the type 6SG7 tubes are obvious and this type was accordingly selected for use in the amplifier.

TABLE I

Tube Type	g_m	C_{gp}	Gain Factor
6SK7	2000	0.003	667
6SG7	4000	0.003	1334
6AC7	9000	0.015	600

The intermediate-frequency amplifier comprises three amplifying tubes, including the converter, and three interstage transformers of double-tuned-circuit design. The schematic is shown in Fig. 1. The individual stage gain is expressed by the relation, when the coupling coefficient k is at the critical value[2]

$$\text{stage gain} = g_m(w\sqrt{L_1L_2}\sqrt{Q_1Q_2})/2$$

g_m = mutual conductance of the amplifying tube
w = angular value of the intermediate frequency
L_1 = inductance of the primary circuit
L_2 = inductance of the secondary circuit
Q_1 = figure of merit of primary circuit
Q_2 = figure of merit of secondary circuit

By design considerations L_1 is made equal to L_2, and Q_1 is made equal to Q_2, which reduces the expression to stage gain $= g_m(wLQ/2)$.

The individual stage selectivity is a function of the circuit Q, and the over-all selectivity requirement previously stated is attained by using appropriate pairs of selective circuits in individual transformers. It then becomes necessary to balance the influence of Q in stage gain against its effect on selectivity. The maximum antenuation requirement of 30 decibels at 200 kilocycles removed from tune resolves to an individual stage attenuation of 10 decibels. By reference to convenient data based on the attenuation as a function of the number and Q of the circuits and deviation from mid-frequency, the required value of Q is found[3,4] to be 45.

The ratio of inductance to capacitance chosen for the tuned circuit is a compromise between amplifier stage gain and stability. The tuning inductance should be high so as to provide adequate stage gain, but on the other hand, the tuning capacitance should be high in order to minimize the effects of changes in capacitance with temperature in the tube, the socket, and the associated wiring. Experience has indicated that not less than 35 micromicrofarads should be included in the total shunt capacitance to allow stable operation and optimum gain. At 8.25 megacycles, the circuit inductance is thus 10.5 microhenries.

The total gain requirement of 40,000 results in an individual stage-gain requirement of slightly more than 34, assuming equal gain in all stages. This is only approximately the case, since the gain in the converter and the gain in the stage preceding the limiter are less than in the normal intermediate-frequency stage. The load conditions in the converter and limiter stages are not the same as in a normal intermediate-frequency amplifier and thus a different adjustment in coupling is required in order that the desired selectivity and gain be realized. Referring to the expression for stage gain, and inserting established circuit constants, a gain of 49 is calculated for the interstage intermediate-frequency amplifier. This result was experimentally verified. By suitable adjustment of coupling, a conversion gain of 27 was realized, and in the stage preceding the limiter a gain of nearly 30 was obtained. The net over-all gain is thus computed to be 39,800 which is in close agreement with the specification.

The Intermediate-Frequency Transformer

Experimental work led to the development of intermediate-frequency transformers embodying the circuit constants enumerated. The data are tabulated as follows:

Coil form diameter	$\frac{5}{16}$ inch
Wire size	no. 36 B&S gauge enamel
Type of winding	solenoid, single layer
Number of turns (primary)	32
Number of turns (secondary)	32
Distance between inside turns of windings	23/64 inch
Shield container	$1\frac{3}{8}$ inches square on sides
Q of windings, in air	75

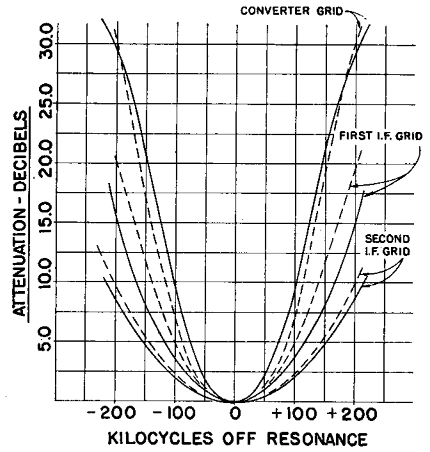

Fig. 2—Selectivity characteristic 8.25-megacycle intermediate-frequency amplifier.

The measured gain of the first intermediate-frequency stage with the transformer described was 55, and that of the second stage (operating into the limiter) was 31. The selectivity characteristics of one, two, and three stages, both calculated and measured are shown in Fig. 2. The selectivity is measured between the second intermediate-frequency-amplifier grid and the limiter input, between the first intermediate-frequency-amplifier grid and the limiter input, and between the converter grid and the limiter input as indicated.

A word might be said as to the need for electrostatic shielding between transformer windings. In the absence of a shield, the capacitive coupling in the design

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[2] F. E. Terman, "Radio Engineers' Handbook," McGraw-Hill Book Company, New York 18, N. Y., 1943, section 5, paragraph 19.
[3] See section 3, paragraph 5, of footnote reference 2.
[4] "Radiotron Designer's Handbook" (third edition) edited by F. Langford Smith, published by Wireless Press for Amalgamated Wireless Valve Company, Sydney, Australia, 1942, p. 128.

described is approximately the same order of magnitude as the inductive coupling. Capacitive coupling makes difficult the attainment of a symmetrical selectivity curve. Also effective coupling between the windings changes rapidly with spacing and the desired coupling is difficult to obtain and to maintain in production. The simple expedient of a brass screw inserted axially in the coil and connected to a frame proved a satisfactory means of minimizing the disturbing electrostatic coupling. A typical transformer construction is shown in Fig. 3.

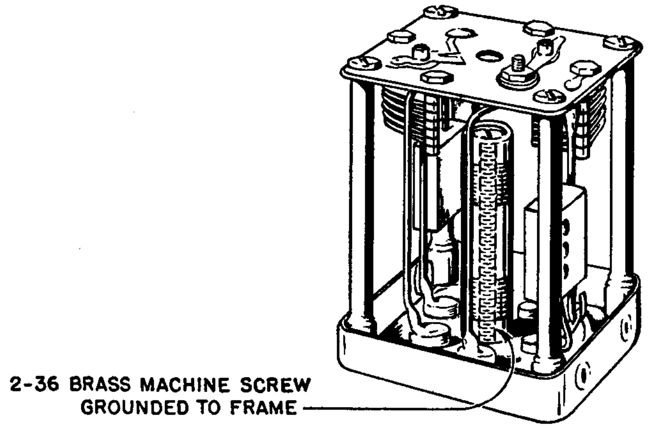

Fig. 3—Intermediate-frequency transformer, 8.25 megacycles.

The Discriminator Transformer

Derivation of the audio voltage from the frequency-modulated signal is accomplished in the discriminator network following the limiter. Due to its simplicity and ease of adjustment, the well-known Foster-Seeley circuit is used. A transformer for this service was designed. Its specifications follow:

Coil-form diameter	$\frac{1}{4}$ inch
Wire size (primary and secondary)	no. 38 B&S gauge single silk-enamel
Type winding (primary)	universal (64/66 gears)
Type winding (secondary)	solenoid, single layer
Number of turns (primary)	35
Number of turns (secondary)	58
Shield container	$1\frac{3}{8}$ inches square on sides
Q of primary in air	35
Q of secondary in air	65

The voltage-input versus output-frequency change is shown in Fig. 4. These data were obtained by introducing a frequency-modulated source at the limiter grid and observing the direct-current change in the discriminator output as the modulation index was changed. A carrier level of 2 volts input was used. The characteristic is observed to be linear to ±75 kilocycles from the center frequency, with some departure from linearity between ±75 to 100 kilocycles from the center frequency.

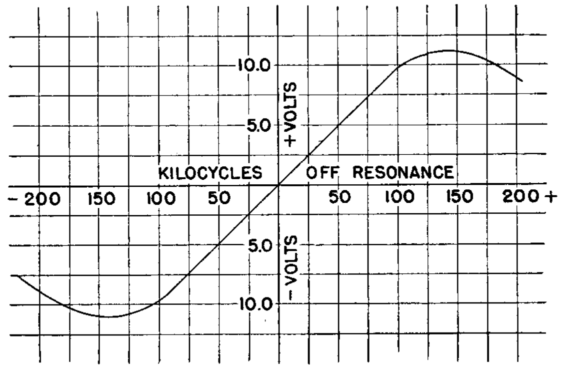

Fig. 4—Discriminator characteristic, 8.25 megacycles.

Conclusion

The intermediate-frequency amplifier of the design described was installed in several experimental receivers previously designed for 4.3-megacycle operation. Satisfactory results were obtained. The receivers were uniform in performance, and indications are that no difficulties due to instability will arise when the receivers are built in production.

Triode Linear Saw-Tooth-Current Oscillator*

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Summary—**It is shown that a triode may be used for generating a linear saw-tooth current when coupled to a suitably designed transformer. The triode is operated on a hitherto unused portion of the E_p/I_p characteristics, notably the positive-grid region where the E_p/I_p characteristic is a straight line of slope $R=E_p/I_p$. While the over-all efficiency of the oscillator is low, it is shown to be inherently more efficient than conventional scanning systems operating in the negative-grid region. Improved operating conditions and circuit efficiency may be obtained by the use of an inverted diode. The losses in a typical triode-scanning oscillator are analyzed and individually computed for a given design. Attention to these individual circuit losses should enable designs to be made of considerably higher efficiency.**

Many diverse methods are used for the generation of saw-tooth currents for sweeping cathode-ray tubes. It is not generally realized, however, that a triode vacuum tube using a suitably designed magnetic and electric circuit is capable of producing a linear sweep with a high degree of efficiency and simplicity of circuit design. Like the triode sine-wave oscillator, the frequency and wave-form characteristics are almost completely determined by the feedback transformer design. The use of the triode oscillator for magnetic scanning was first proposed by Philo T. Farnsworth,[1] modifications being made later by other workers in the field, notably G. R. Tingley and A. H. Gilbert.

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[1] U. S. Patent No. 2,059,683, November 3, 1936.