Capacitance-Coupled Intermediate-Frequency Amplifiers*

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Summary—**This paper discusses the performance characteristics of capacitance-coupled intermediate-frequency-amplifier circuits. Double-ended loading is preferred to single-ended loading in order to satisfy practical tolerance requirements.**

An approximate method is treated for the design of capacitance-coupled attenuating traps for a television intermediate-frequency amplifier. Performance specifications for such an amplifier are considered. Performance characteristics of an amplifier built to conform to the specifications as outlined are shown.

INTRODUCTION

THIS PAPER deals exclusively with the design and performance of the capacitance-coupled system, with particular reference to the application at frequencies above 20 megacycles. No special effort is made to compare the capacitance-coupled circuit with mutual-inductance-coupled circuits[1] or others which may function equally well. Even though a coupling capacitor is used, the capacitance-coupled circuit has constructional simplicity. The complete isolation of the coils made possible by capacitance coupling permits the use of slug tuning.

Although capacitance coupling has been used, it has not had as extensive application to wide-band amplifiers as inductive coupling. Consequently there is little literature specifically pertaining to it.[2–4] Fig. 1 shows the circuit diagram with its alternating-current equivalent for a typical television intermediate-frequency-amplifier stage. The capacitance-coupled trap attenuates either the adjacent or the desired-channel sound signal. A desired band-pass response may be obtained by loading either the grid or the plate (single-ended loading), or by loading both the grid and plate (double-ended loading). The results of an experiment made to compare the two methods of loading are discussed.

SINGLE-ENDED LOADING

For the same bandwidth, single-ended loading yields more gain than double-ended loading. With single-ended loading, however, the response in the pass region is badly disturbed by a small change in either coil inductance or tube capacitance. Experiment (see Appendix A), representative of a typical television intermediate-frequency-amplifier application indicates that a change of only 5 per cent in the inductance or capacitance associated with either coil produces an unbalance in the peaks of approximately 15 per cent, considering one stage only. A change in tubes alone might often cause more than a 5 per cent capacitance change.

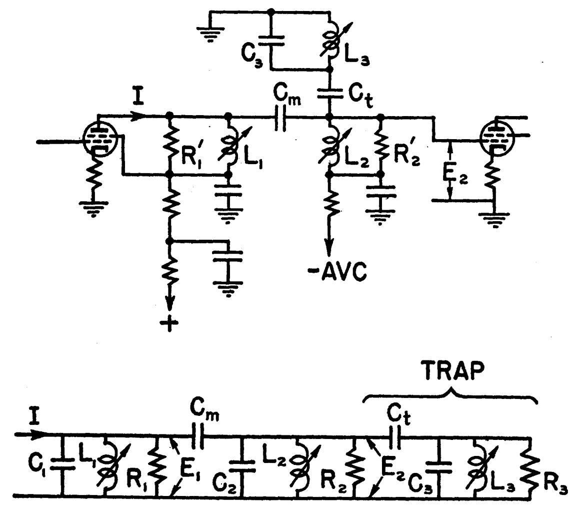

Fig. 1—Circuit diagram of a typical capacitance-coupled intermediate-frequency stage with its alternating-current equivalent.

It is concluded, therefore, that single-ended tuning is poor practice because component tolerance requirements are strained.

DOUBLE-ENDED LOADING

With double-ended loading, the shape of the response is only moderately vulnerable to alteration by minor component change. Damping resistors are selected which give a flat response, or a response with a slight center dip, when both coils are tuned to the same frequency. (In the case of capacitance coupling, the tuning frequency is at the extreme of the high-frequency end of the pass region. The coupling capacitor spreads the band toward the low-frequency end, leaving the other end relatively fixed.) When the damping resistors are selected in this manner, a moderate change in either inductance or capacitance shifts the band and amplitude somewhat, but does not unbalance the peaks appreciably. Quantitative data are tabulated in Appendix A. The experimental results given on loading are consistent with the trends indicated by Aiken.[5]

It appears evident that for practical application where it is desirable to maintain a uniformity of response, double-ended loading is essential.

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[1] G. Mountjoy, "Simplified television i-f systems," *RCA Rev.*, vol. 4, pp. 299–309; January, 1940.

[2] F. E. Terman, "Radio Engineers' Handbook," McGraw-Hill Book Company, New York, N. Y., 1943; sec. 3, pp. 164–172.

[3] K. R. Sturley, "Radio Receiver Design, Part I," John Wiley and Sons, New York, N. Y., 1939; pp. 289–295.

[4] N. Marchand, M. Dishal, S. Frankel, "Wide Amplifier Design Nomograph," Federal Telephone and Radio Corporation, Newark, N. J., 1945. (Distributed at the 1945 I.R.E. Winter Technical Meeting.)

[5] C. B. Aiken, "Two-Mesh tuned coupled circuit filters," PROC. I.R.E., vol. 25, pp. 230–272; February, 1937.

Trap Design

In addition to the trap frequency, three other factors enter to determine the choice of trap-circuit parameters: first, the degree of attenuation desired (or obtainable); second, the effect of the trap on the response throughout the pass region; third, the shape of the response curve in the immediate vicinity of the trapping frequency.

Considering the capacitance-coupled circuit as shown in Fig. 2, the ratio of output voltage at trapping fre-

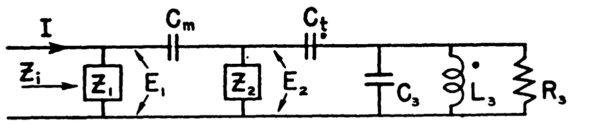

Fig. 2—Schematic diagram of capacitance-coupled circuit with trap.

quency to the output voltage in the pass band may be expressed approximately

$$\frac{E_{2t}}{E_{2p}} \doteq \frac{Z_{ip}C_m}{Z_{it}}\left[\left(\frac{C_3}{C_t}\right)\left(\frac{1}{Q_3C_t}\right)\right] \qquad (1)$$

where

Z_{ip} = input impedance at a frequency within the pass band
Z_{it} = input impedance at the trap frequency
C_m = main coupling capacitance
C_t = trap coupling capacitance
C_3 = trap tuning capacitance
Q_3 = Q of trap coil.

While (1) gives the approximate attenuation for a given set of circuit parameters, it does not dictate automatically the optimum values to use. More information is needed. It has been found by experiment that, with the trapping frequency on the low side of the band-pass region, C_3 and L_3 should resonate at some frequency f_2 close to the trapping frequency f_t. The position indicated in Fig. 3 is representative for

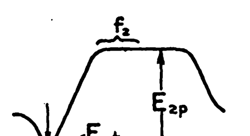

Fig. 3—Response showing approximate location of trap parallel-resonance frequency f_2.

trapping the television sound signal of the desired channel. As the ratio C_3/C_t is related to the ratio f_2/f_t in the following manner

$$C_3/C_t = 1/[(f_2/f_t)^2 - 1], \qquad (2)$$

a choice of f_2 determines the ratio C_3/C_t.

Assuming that the ratio C_3/C_t is established from (2), it is clear from (1) that the attenuation increases with C_t. Increasing the trap coupling capacitance indefinitely places excessive capacitive loading across Z_2 and reduces the gain in the pass region. Thus C_t will be a compromise value allowing sufficient attenuation without seriously reducing the pass-band gain.

The greater the Q of the trap coil Q_3, the greater the attenuation and the sharper the dip. If the shape of the trap response is too narrow, a slight amount of oscil-

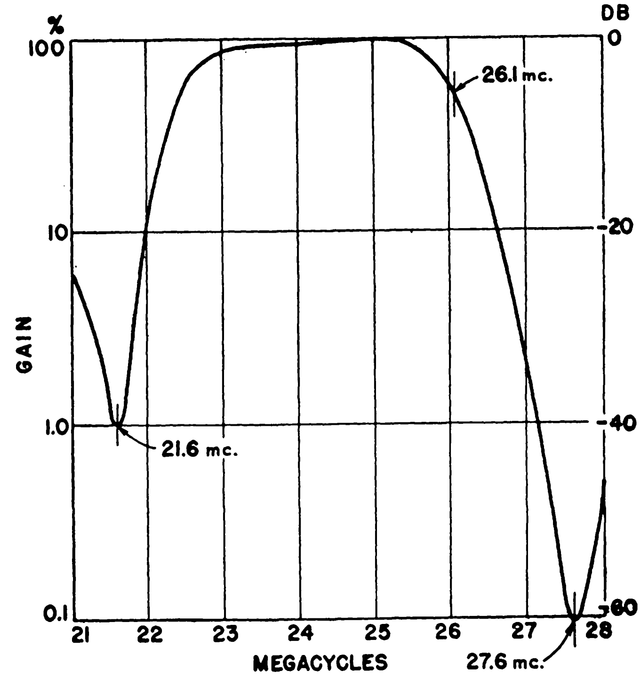

Fig. 4—Response curve of four-stage intermediate-frequency amplifier.

lator drift throws the signal to one of the steep sides. On the steep slope the discriminator action on the frequency-modulated sound carrier causes spurious amplitude modulation in the picture.

Performance Specifications for Television Picture Intermediate-Frequency Amplifier

A frequency of 21.6 megacycles is used for the sound carrier of the amplifier to be discussed. This frequency was advocated by Newlon[6] in a report presented to the Radio Manufacturers Association committee on Television Receivers. The sound carrier selected lies midway in the 21.25- to 21.9-megacycle region formulated as a standards proposal by the executive committee of the receiver section of the RMA engineering department. With the sound carrier at 21.6 megacycles, the picture carrier is 26.1 megacycles.

The desired-channel sound should be attenuated at least 35 decibels, provided the bottom of the trap response is flat enough to limit the envelope caused by discriminator action to −50 decibels.[7] The bottom of the trap response should be broad enough to allow for oscillator drift.

The adjacent-channel sound signal will be on the threshold of discernibility at approximately −50 decibels from the level of the received television signal.

[6] A. E. Newlon, "Selection of television sound and picture intermediate frequencies," Report to Radio Manufacturers Association Committee on Television Receivers, August, 1945.

[7] M. J. Larsen, "Minimum Acceptable Trappage Performance," Report to Subcommittee on Standards of Good Engineering Practice of Radio Manufacturers Association Committee on Television Receivers, October, 1945.

How much attenuation is needed, however, depends on ultimate station allocations as well as on how much protection the manufacturer wishes to give to those using receivers in unfavorable locations.

The response curve of Fig. 4 fulfills the specifications outlined above. The desired-channel sound trap attenuates 40 decibels at 21.6 megacycles. The adjacent-channel sound attenuates 60 decibels at 27.6 megacycles. The picture carrier is 6 decibels down at 26.1 megacycles to meet the vestigial-sideband-transmission requirements. The response shown permits a video response of over 3.5 megacycles before the high-frequency end tapers rapidly.

Selection of Circuit Parameters

The picture intermediate-frequency amplifier constructed to produce the response of Fig. 4 has four stages of amplification. Including the mixer output, there are five sets of coupled circuits with traps of the type shown in Fig. 1. The only capacitances involved are the tube output and input capacitances, including associated socket, wiring, and coil strays. The inductors are copper-slug tuned.

The first three sets of coils have the adjacent-channel 27.6-megacycle traps. The desired sound carrier is taken off the plate of the third intermediate-frequency tube via a small ($\frac{1}{2}$-micromicrofarad) capacitor. The third and fourth stages have the desired-channel sound traps.

Automatic gain control is applied to the first three stages. Unby-passed cathode resistors are necessary in order to stabilize the tube input capacitances as the bias is varied. Although this reduces the gain, it permits over 60 decibels variation in gain without perceptible change in the shape of the response curve.

The loading resistors and coupling capacitors for the band-pass circuit can be found readily by experiment with the aid of a sweep generator, oscilloscope, etc. In the alignment procedure the coils L_1 and L_2 are tuned with their respective capacitances to the same frequency near the high end of the band, say 26 megacycles. The resistors and capacitor C_m are adjusted to give the desired response, allowing a margin for "cutting in" of the traps. The traps are designed with the aid of (1) and (2) and tuned to attenuate at the appropriate frequency.

Typical approximate values for the various circuit parameters are listed below. For the band-pass circuit:

C_1—5 micromicrofarad
C_2—11 micromicrofarad
L_1—7.5 microhenry
L_2—3.4 microhenry
R_1'—10,000 ohms, $\frac{1}{2}$-watt direct-current nominal
R_2'—3700 ohms, $\frac{1}{2}$-watt direct-current nominal
C_m—2.0 micromicrofarad.

For the desired-channel sound trap, $f_t=21.6$ megacycles:

C_3—23 micromicrofarad
C_t—3 micromicrofarad
L_3—2.1 microhenry
Q_3—70.

For the adjacent-channel sound trap, $f_t=27.6$ megacycles:

C_3—12 micromicrofarad
C_t—2 micromicrofarad
L_3—2.3 microhenry.

The gain averaged over the four stages, using type 6AG5 tubes, measured 8 per stage.

APPENDIX A

Experimental Measurement of Coupled-Circuit Performance

For the coupled circuit of the type shown in the schematic of Fig. 1, but minus the trap, the equation of the output voltage E_2 may be expressed in the form

$$E_2=\frac{I}{2\pi f_0\sqrt{C_1C_2}}\left[\frac{f/f_0}{\sqrt{\frac{C_2}{C_1}}\left[\frac{1}{Q_2}-j\alpha\right]+\sqrt{\frac{C_1}{C_2}}\left[\frac{1}{Q_1}-j\alpha\right]-j\left(\frac{f_0}{f}\right)^2\frac{\sqrt{C_1C_2}}{C_n}\left[\frac{1}{Q_1}-j\alpha\right]\left[\frac{1}{Q_2}-j\alpha\right]}\right]. \quad (3)$$

In (3) both coils are tuned to the same frequency f_0. Constant input current I is assumed. $Q_1=R_1/wL_1$, $Q_2=R_2/wL_2$, $\alpha=1-(f/f_0)^2$.

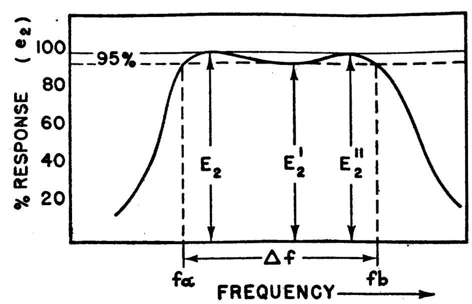

Fig. 5—Response curve used as reference in determining response deviations with changes in circuit inductances.

It is noted that the portion of (3) in the brackets is a function of frequency ratio, capacitance ratio, and Q. These three are simultaneously related to produce a given response shape. The relative shape will be the same, therefore, at any frequency, provided the frequency ratio, capacitance ratio, and Q's remain the same. The amplitude may vary, however, depending on the value $I/2\pi f_0\sqrt{C_1C_2}$.

It is convenient, then, to write (3) as

$$E_2=\frac{I}{2\pi f_0\sqrt{C_1C_2}}B_{a,b} \quad (4)$$

where $B_{a,b}$ indicates that the values in the brackets of (3) are selected to give a curve of some reference characteristic (see Fig. 5) having a frequency ratio of f_a/f_b, where f_a and f_b are the band-pass limits, and having specified ratios of E_2, E_2', and E_2''.

The above analysis shows the manner in which it is valid to extend from one frequency to another. Regard must, of course, be taken for any change with frequency of any of the circuit components.

An audio-frequency coupled circuit was used to measure the effect of component changes on the shape of the response curve. Audio frequencies were used to facilitate taking quantitative data. The circuit employed was made approximately equivalent to the television intermediate-frequency-amplifier circuit, without trap, as discussed herein, so that the results would have practical significance. In the tests only the inductance was varied, it being apparent that similar changes in capacitance would have comparable results.

Table I shows the case with double-ended loading. The loading was adjusted to yield symmetrical response, after both coils were tuned to the same frequency f_0. The inductances were varied 5 per cent from their reference values. The symbols used in the table are indicated on the reference curve shown in Fig. 5.

TABLE I

Double-Ended Loading, Showing Effect on Response Shape of 5 Per Cent Changes in Inductance

Condition	Per cent of f_0		Per cent $\Delta f/f_0$	Per cent of L_0		Per cent of E_0		
	f_a	f_b		L_1	L_2	E_2	E_2'	E_2''
Response balanced $L_1C_1=L_2C_2$	86	100	14	100	50	100	95	100
L_1 decreased 5 per cent	87	100	13	95	50	105	102	106
L_1 increased 5 per cent	84	99	15	105	50	95	90	95
L_2 decreased 5 per cent	86	101	15	100	47.5	94	88	94
L_2 increased 5 per cent	85	99	14	100	52.5	105	101	106

Under balanced-response conditions of operation as shown in the first row: $Q_1=8.8$, $Q_2=7.2$, $f_0=5000$ cycles, $L_0=0.615h$, $C_2/C_1=2$ (L_0 and C_1 resonate at f_0), $B_{a,b}=3.3$. (See (4) for computing gain at any other frequency, using $\Delta f/f_0=14$ per cent, 5 per cent dip, $C_2/C_1=2$).

·Table II shows the results with the loading pre dominantly on the secondary side. Values of L_1, L_2, and the loading resistor on the secondary were adjusted to yield the same reference curve as under the double-loaded, balanced condition of Table I. It was necessary to increase the coupling capacitance 20 per cent over that used for the results of Table I. Experiments show that, where both coils are tuned to the same frequency, one set of Q's only will give symmetrical response for a specified per cent center dip. If the loading is predominantly on one side, then the coils must be detuned relative to each other in order to produce the symmetrical response. Measurements for this particular case showed a gain increase of 30 per cent over the case of double-ended loading.

TABLE II

Single-Ended Loading, Showing Effect on Response Shape of 5 Per Cent Changes in Inductance

Condition	Per cent of f_0		Per cent $\Delta f/f_0$	Per cent of L_0		Per cent of E_0		
	f_a	f_b		L_1	L_2	E_2	E_2'	E_2''
Balanced response but $L_1C_1=0.89L_2C_2$	86	100	14	92	51.5	100	95	100
L_1 decreased 5 per cent	90	103	13	87	51.5	94	93	109
L_1 increased 5 per cent	83.5	97	13.5	97	51.5	109	93	94
L_2 decreased 5 per cent	86	100	14	92	49	105	90	91
L_2 increased 5 per cent	86	100	14	92	54	94	93	109

Under balanced response conditions: $Q_1=27$, $Q_2=5.1$, $f_0=5000$ cycles, $L_0=0.615h$, $C_2/C_1=2$ (L_0 and C_1 resonate at f_0), $B_{a,b}=4.3$. (See equation (4) for computing gain at other frequencies, using $\Delta f/f_0=14$ per cent, 5 per cent dip, $C_2/C_1=2$).

APPENDIX B

Derivation of Trap Design Formula

The following is an approximate method for designing capacitance-coupled traps yielding results close enough for practical use at the higher frequencies.

Considering the capacitance-coupled circuit shown in Fig. 2, the approximate expression for the output voltage across Z_2, neglecting voltage drop across C_m, is

$$E_{2p} \doteq IZ_{ip} \tag{5}$$

where subscript p denotes calculation at a frequency in the pass region. Also

$$E_{1t} = IZ_{it} \tag{6}$$

where subscript t denotes calculation at the trapping frequency.

The circuit of Fig. 6 is an approximation of the circuit of Fig. 2 operating at the trapping frequency at

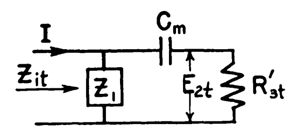

Fig. 6—Approximate representation of capacitance-coupled circuit with trap when considered at the trapping frequency.

which frequency Z_2 is effectively shunted out by the lower trap impedance. Resistance R_3 (see Fig. 2) is chargeable to the losses in coil L_3. As Q_3 of coil L_3 is moderately high, say over 50, R_{3t}', representing the series resistance of the trap when the capacitive reactance of C_t is equal in magnitude to the inductive reactance of the combination C_3 and L_3, may be written

$$R_{3t}' = X_{C_t}^2/Q_3X_3. \tag{7}$$

Also, at the trap frequency, from Fig. 6,

$$E_{2t} = E_{1t}R_{3t}'/X_{C_m}. \tag{8}$$

From the above four equations, the attenuation ratio follows:

$$E_{2t}/E_{2p} \doteq (Z_{ip}/Z_{it})(C_mC_3/Q_3C_t^2). \tag{9}$$

Fixing empirically the frequency f_2 at which L_3 and C_3 are in resonance, and knowing that f_t is the frequency of series resonance between C_m and L_3, C_3, it follows that

$$C_3/C_t = 1/[(f_2/f_t)^2 - 1]. \tag{10}$$

In equation (9) the ratio (Z_{ip}/Z_{it}) and C_m remain reasonably constant over a considerable range of trap parameters. The trapping is adjusted then by the quantity $C_3/Q_3C_t^2$ after giving consideration to selecting the value for f_2, as discussed in the body of the paper.

As an example of the application of (9) and (10), using the circuit components listed for the television intermediate frequency, the attenuation of the 21.6-megacycle desired-channel sound trap is approximately 18 decibels. The two traps in the complete amplifier, with the help of some "sloping off" of the response by the remaining three sets of coupled circuits, give a total attenuation of 40 decibels by test measurement.