17.1. Fixed Attenuators. Networks which introduce a fixed amount of attenuation independent of frequency have extensive use. They can be designed to have

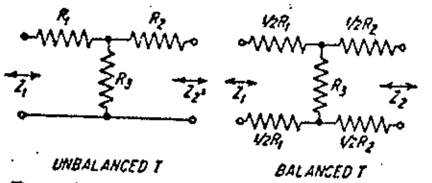


FIG. 17.1. T and H attenuator networks.

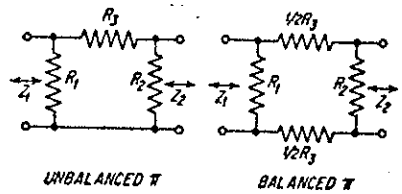


FIG. 17.2. π and O attenuator networks.

equal or unequal input and output impedances and to provide different amounts of attenuation.

Unbalanced and balanced T and π networks are shown in Figs. 17.1 and 17.2. For every ratio Z_1/Z_2 of the values of terminating impedances there is an associated minimum value of the ratio of input power to the attenuator to output power from the attenuator which can be realized.

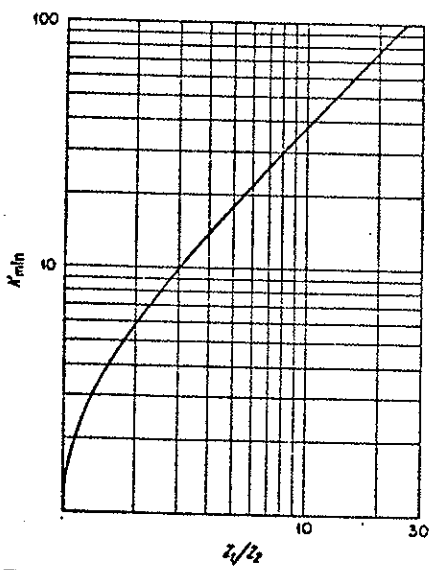


FIG. 17.3. Plot of the minimum possible values of K as a function of Z_1/Z_2 (refer to Figs. 17.1 and 17.2). If $K = K_{min}$, $R_1 = 0$ in Fig. 17.1 and $R_1 = \infty$ in Fig. 17.2.

$$K = \frac{\text{power into network}}{\text{power out of network}}$$

$$K_{min} = \frac{2Z_1}{Z_2} - 1 + 2\sqrt{\frac{Z_1}{Z_2}\left(\frac{Z_1}{Z_2} - 1\right)} \qquad (17.1)$$

where K_{min} = minimum possible value of K for particular ratio of Z_1 to Z_2. The minimum possible values of the power ratio K as a function of Z_1/Z_2 are given in Fig. 17.3. There is no maximum value for the power ratio. It should be noted that Z_1 is always taken as the larger impedance and can be either the input or output impedance.

Since these networks can be made to have unequal input and output impedances, they are frequently used for impedance matching even though there is an associated power loss.

For the balanced and unbalanced T networks shown in Fig. 17.1 where $Z_1 \geq Z_2$, the values of R_1, R_2, and R_3 can be determined from Eqs. (17.2) to (17.6).

$$R_1 = \frac{Z_1(K+1) - 2\sqrt{KZ_1Z_2}}{K-1} \qquad (17.2)$$

$$R_2 = \frac{Z_2(K+1) - 2\sqrt{KZ_1Z_2}}{K-1} \qquad (17.3)$$

$$R_3 = \frac{2\sqrt{KZ_1Z_2}}{K-1} \qquad (17.4)$$

and if $Z_1 = Z_2$,

$$R_1 = R_2 = Z \ldots$$

$$R_3 = \frac{2Z_1\sqrt{\ldots}}{K - 1 \ldots}$$

For the balanced and unbalanced π ...
the values of R_1, R_2, and R_3 can be det...

$$R_1 = \frac{(K \ldots}{(K+1 \ldots}$$

$$R_2 = \frac{(K \ldots}{(K+1 \ldots}$$

$$R_3 = \frac{K-1}{2} \ldots$$

and if $Z_1 = Z_2$,

$$R_1 = R_2 = Z_1 \ldots$$

$$R_3 = \frac{Z_1(K - \ldots}{2\sqrt{K \ldots}}$$

Example 17.1

Design a network to match a 500-ohm g...
possible power loss.

Solution

1. Determine the ratio of Z_1 to Z_2 and th...
work input power to network output power...

$$\frac{Z_1}{Z_2} = \frac{5\ldots}{2\ldots}$$

From Eq. (17.1)

$$K_{min} = 2 \times 2.50 - 1 \ldots$$
$$= 7.87$$

2. Determine the type of network to be u...
Since the type of network was not specifie...
T. It was stated that the network loss shou...
In Fig. 17.3 it is stated that $R_2 = 0$ ohms wh...
it is only necessary to determine R_1 and R_3.
From Eqs. (17.2) and (17.3)

$$R_1 = \frac{500(7.87 + 1) - 2\sqrt{7.87 \times 500 \times 200}}{7.87 - 1}$$
$$= 387 \text{ ohms}$$

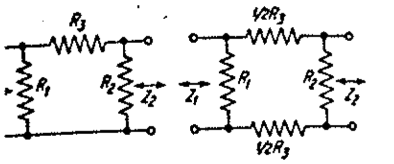
$$R_3 = \frac{2\sqrt{7.87 \times 500 \times 200}}{7.87 - 1}$$
$$= 258 \text{ ohms}$$

(Refer to Fig. 17.4.)

3. Determine the loss in the network.

$$\text{Loss} = 1 \ldots$$
$$= 8 \ldots$$

ıtroduce a fixed amount of attenua- use. They can be designed to have



o. 17.2. π and O attenuator networks.

ı and to provide different amounts of

ıre shown in Figs. 17.1 and 17.2. For npedances there is an associated mini- m value of the ratio of input power the attenuator to output power from : attenuator which can be realized.

$$K = \frac{\text{power into network}}{\text{power out of network}}$$

$$_{\min} = \frac{2Z_1}{Z_2} - 1 + 2\sqrt{\frac{Z_1}{Z_2}\left(\frac{Z_1}{Z_2} - 1\right)} \qquad (17.1)$$

ıere $K_{\min}$ = minimum possible value K for particular ratio of Z_1 to Z_2. ıe minimum possible values of the ·wer ratio K as a function of Z_1/Z_2 are ven in Fig. 17.3. There is no maximum ılue for the power ratio. It should be ıted that Z_1 is always taken as the rger impedance and can be either the put or output impedance.

Since these networks can be made to ıve unequal input and output imped- ıces, they are frequently used for im- edance matching even though there is n associated power loss.

For the balanced and unbalanced T net- rorks shown in Fig. 17.1 where $Z_1 \geq Z_2$, ed from Eqs. (17.2) to (17.6).

$$\frac{- 2\sqrt{KZ_1Z_2}}{- 1} \qquad (17.2)$$

$$\frac{- 2\sqrt{KZ_1Z_2}}{- 1} \qquad (17.3)$$

$$(17.4)$$

and if $Z_1 = Z_2$,

$$R_1 = R_2 = Z_1\left(\frac{\sqrt{K} - 1}{\sqrt{K} + 1}\right) \qquad (17.5)$$

$$R_3 = \frac{2Z_1\sqrt{K}}{K - 1} \qquad (17.6)$$

For the balanced and unbalanced π networks shown in Fig. 17.2 where $Z_1 \geq Z_2$, the values of R_1, R_2, and R_3 can be determined from Eqs. (17.7) to (17.11).

$$R_1 = \frac{(K - 1)Z_1\sqrt{Z_2}}{(K + 1)\sqrt{Z_2} - 2\sqrt{KZ_1}} \qquad (17.7)$$

$$R_2 = \frac{(K - 1)Z_2\sqrt{Z_1}}{(K + 1)\sqrt{Z_1} - 2\sqrt{KZ_2}} \qquad (17.8)$$

$$R_3 = \frac{K - 1}{2}\sqrt{\frac{Z_1Z_2}{K}} \qquad (17.9)$$

and if $Z_1 = Z_2$,

$$R_1 = R_2 = Z_1\left(\frac{\sqrt{K} + 1}{\sqrt{K} - 1}\right) \qquad (17.10)$$

$$R_3 = \frac{Z_1(K - 1)}{2\sqrt{K}} \qquad (17.11)$$

Example 17.1

Design a network to match a 500-ohm generator to a 200-ohm load with the minimum possible power loss.

Solution

1. Determine the ratio of Z_1 to Z_2 and the minimum possible value of the ratio of network input power to network output power.

$$\frac{Z_1}{Z_2} = \frac{500}{200} = 2.50$$

From Eq. (17.1)

$$K_{\min} = 2 \times 2.50 - 1 + 2\sqrt{2.50(2.50 - 1)}$$
$$= 7.87$$

2. Determine the type of network to be used and the network values.

Since the type of network was not specified, an arbitrary choice might be an unbalanced T. It was stated that the network loss should be a minimum, therefore K must equal 7.87. In Fig. 17.3 it is stated that $R_2 = 0$ ohms when K is equal to its minimum value; therefore, it is only necessary to determine R_1 and R_3.

From Eqs. (17.2) and (17.3)

$$R_1 = \frac{500(7.87 + 1) - 2\sqrt{7.87 \times 500 \times 200}}{7.87 - 1}$$
$$= 387 \text{ ohms}$$

$$R_3 = \frac{2\sqrt{7.87 \times 500 \times 200}}{7.87 - 1}$$
$$= 258 \text{ ohms}$$

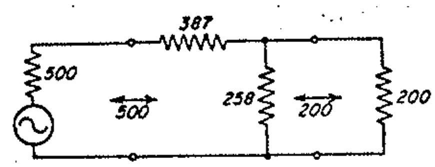


FIG. 17.4. Circuit for Example 17.1.

(Refer to Fig. 17.4.)

3. Determine the loss in the network.

$$\text{Loss} = 10 \log_{10} K$$
$$= 8.96 \text{ db}$$

Example 17.2

Design an unbalanced π attenuator with a loss of 20 db ($K = 100$) to operate between a 200-ohm line and a 500-ohm line.

Solution

1. Determine the ratio of Z_1 to Z_2 and the minimum possible value of K.

$$\frac{Z_1}{Z_2} = \frac{500}{200} = 2.50$$

From Example 17.1, K must be equal to or greater than 7.87.

2. Determine the network values.

Network was specified as an unbalanced π (see Fig. 17.2), and K is equal to 100.

From Eqs. (17.7) to (17.9)

$$R_1 = \frac{(100 - 1)500\sqrt{200}}{(100 + 1)\sqrt{200} - 2\sqrt{100 \times 500}} = 714 \text{ ohms}$$

$$R_2 = \frac{(100 - 1)200\sqrt{500}}{(100 + 1)\sqrt{500} - 2\sqrt{100 \times 200}} = 224 \text{ ohms}$$

$$R_3 = \frac{(100 - 1)}{2}\sqrt{\frac{200 \times 500}{100}} = 1{,}567 \text{ ohms}$$

(See Fig. 17.5.)

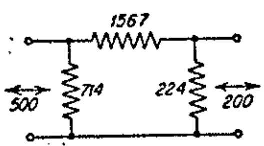


FIG. 17.5. Circuit for Example 17.2.

17.2. Amplitude Equalizers. Amplitude equalizers have an insertion loss which varies as some desired function of frequency, and consequently they are employed in electronic circuitry as a means of establishing or correcting the circuit gain characteristics.

In "Motion Picture Sound Engineering," Kimball[1] has provided an excellent treatment of amplitude equalizers, and the material in this section is based on his work.

On the assumption that an amplitude equalizer operates from a source impedance R_o and into a load impedance R_o, it is possible to design several equalizers having different configurations but which provide exactly the same attenuation characteristics as a function of frequency. The seven specific configurations for which design information is presented are:

1. Series-impedance type
2. Shunt-impedance type
3. Full-series type
4. Full-shunt type
5. T type
6. Bridged-T type
7. Lattice type

Shown in Fig. 17.6 are the required variations in these seven basic configurations for obtaining the type of attenuation characteristics indicated by the insertion loss curves in each column. The configurations in the last three rows have constant input and output impedances as a function of frequency, and the types in rows 3 and 4 have a constant input impedance.

Although two examples are given to aid in the use of the design data, the following suggestions are included to further help in the design of the different types of equalizers.

[1] Harry Kimball, "Motion Picture Sound Engineering," Chap. 16. D. Van Nostrand Company, Inc., Princeton, N.J., 1938.

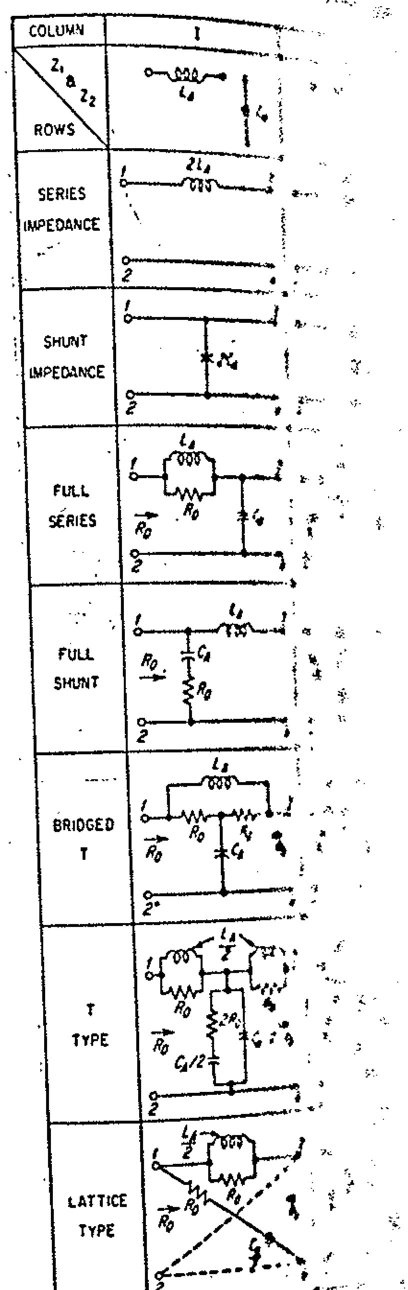


FIG. 17.6. Network con... Picture Sound Engine... Sciences, copyright 193...

anced π attenuator with a loss of 20 db ($K = 100$) to operate b
500-ohm line.

ratio of Z_1 to Z_2 and the minimum possible value of K.

$$\frac{Z_1}{Z_2} = \frac{500}{200} = 2.50$$

must be equal to or greater than 7.87.
work values.
d as an unbalanced π (see Fig. 17.2), and K is equal to 100.
17.9)

$$R_1 = \frac{(100 - 1)500\sqrt{200}}{(100 + 1)\sqrt{200} - 2\sqrt{100 \times 500}} = 714 \text{ ohms}$$

$$R_2 = \frac{(100 - 1)200\sqrt{500}}{(100 + 1)\sqrt{500} - 2\sqrt{100 \times 200}} = 224 \text{ ohms}$$

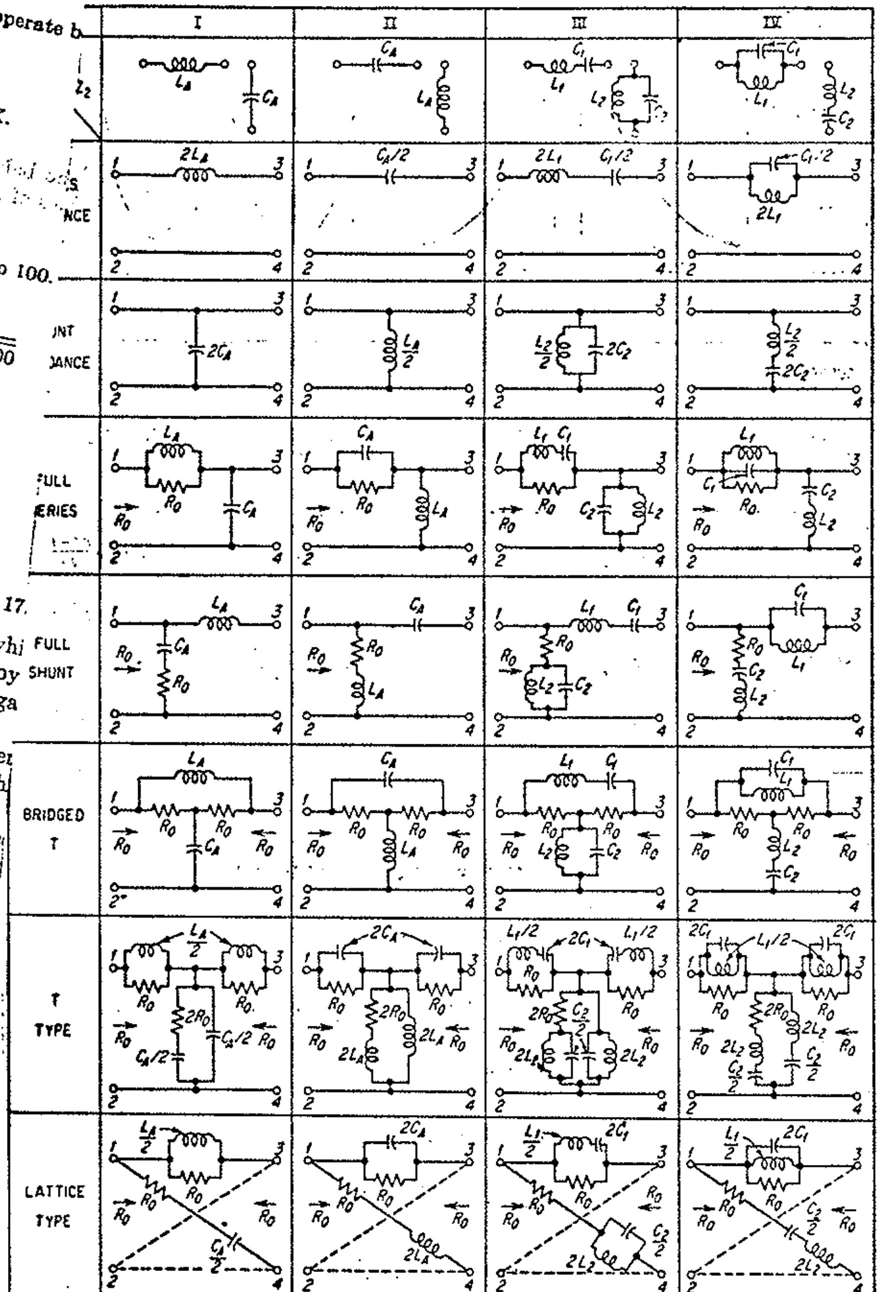
$$R_3 = \frac{(100 - 1)}{2}\sqrt{\frac{200 \times 500}{100}} = 1{,}567 \text{ ohms}$$

s. Amplitude equalizers have an insertion loss whi (See Fig. 17.
on of frequency, and consequently they are employ
means of establishing or correcting the circuit ga
"Engineering," Kimball[1] has provided an excelle
ers, and the material in this section is based on h
mplitude equalizer operates from a source impedanc
, it is possible to design several equalizers having
h provide exactly the same attenuation character
The seven specific configurations for which design

variations in these seven basic configurations
haracteristics indicated by the insertion loss
tions in the last three rows have constant
tion of frequency, and the types in rows 3

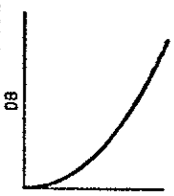
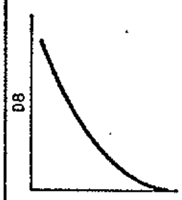
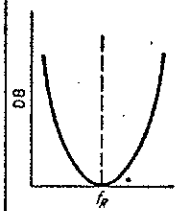
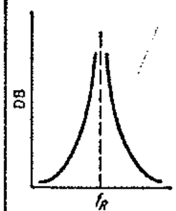
in the use of the design data, the following
he design of the different types of equalizers.

Engineering," Chap. 16. D. Van Nostrand



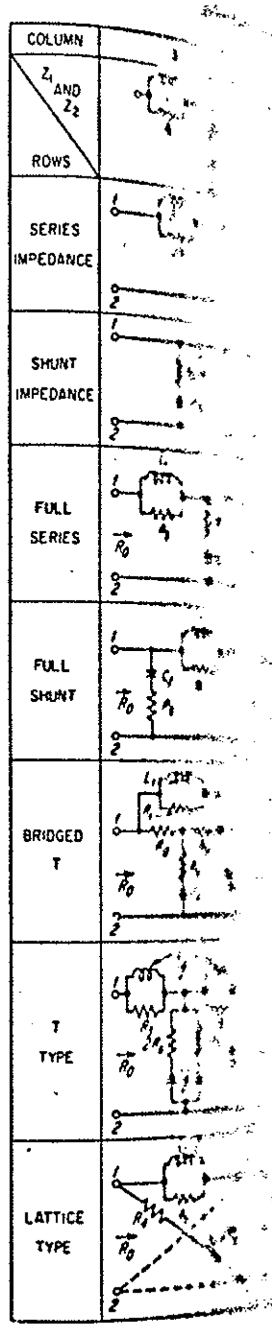
(a)

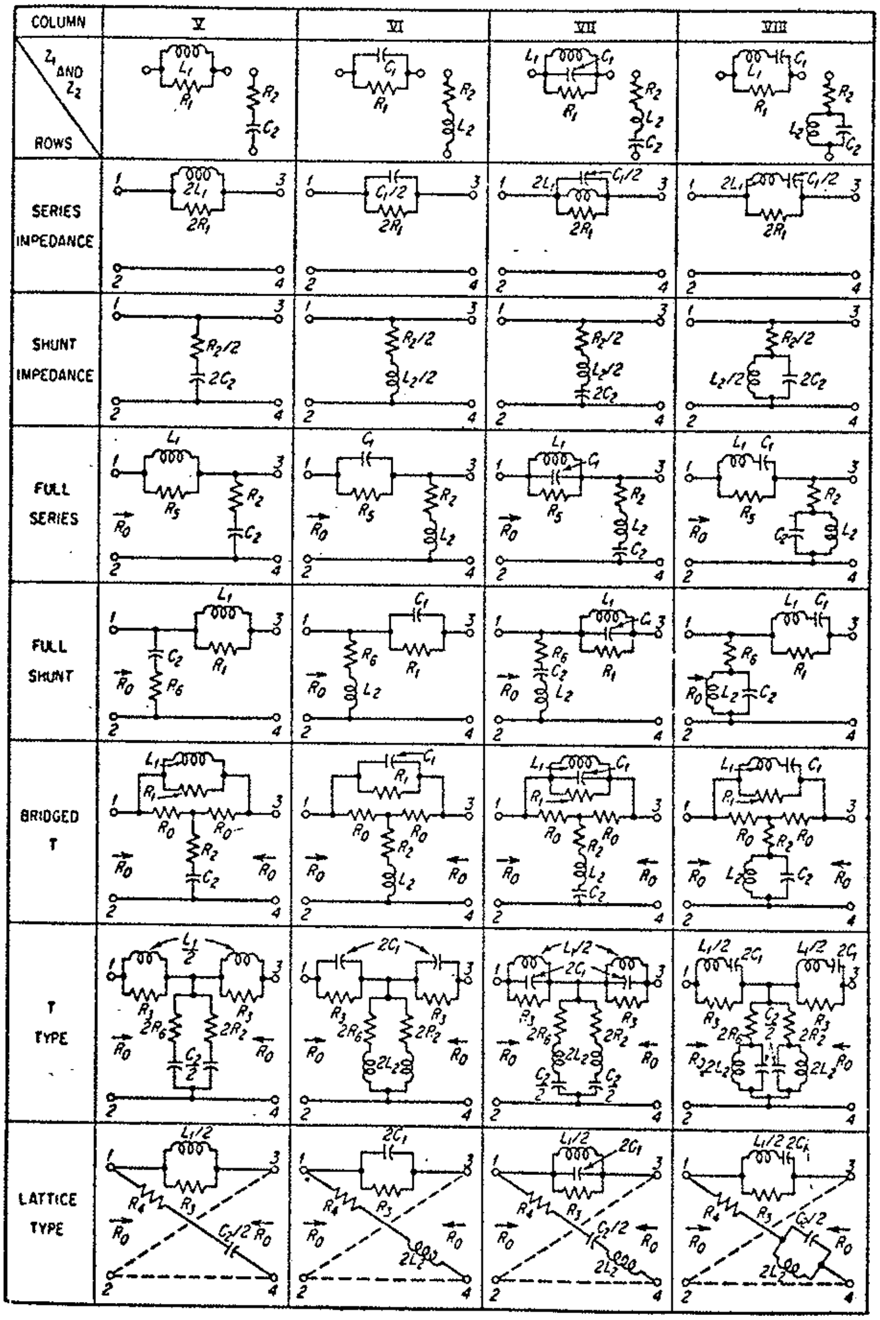
Fig. 17.6. Network configurations and formulas for attenuation equalizers. (*From "Motion Picture Sound Engineering," by Research Council of the Academy of Motion Picture Arts and Sciences, copyright 1938, D. Van Nostrand Company, Inc.*)

COLUMN	I	II	III	IV
INSERTION LOSS CHARACTERISTIC				
REFER TO	FIG. 17.7	FIG. 17.8	FIG. 17.9	FIG. 17.10
CURRENT RATIO $\left\lvert\left[\frac{I_L}{I_L'}\right]^2\right\rvert$	$1+\left[\frac{f}{f_0}\right]^2$	$1+\left[\frac{f_0}{f}\right]^2$	$1+\left[\frac{\frac{f}{f_R}-\frac{f_R}{f}}{a-\frac{1}{a}}\right]^2$	$1+\left[\frac{a-\frac{1}{a}}{\frac{f}{f_R}-\frac{f_R}{f}}\right]^2$
DESIGN FORMULAE	$L_A=\frac{R_0}{2\pi f_0}=\frac{R_0}{\omega_0}$ $C_A=\frac{1}{2\pi f_0 R_0}=\frac{1}{\omega_0 R_0}$ $f_0=\frac{1}{2\pi\sqrt{L_A C_A}}$ $R_0=\sqrt{\frac{L_A}{C_A}}$		$L_1=L_A\frac{1}{a^2-1}$ $L_2=L_A\frac{a^2-1}{a^2}$ $C_1=C_A\frac{a^2-1}{a^2}$ $C_2=C_A\frac{1}{a^2-1}$	$L_1=L_A\frac{a^2-1}{a^2}$ $L_2=L_A\frac{1}{a^2-1}$ $C_1=C_A\frac{1}{a^2-1}$ $C_2=C_A\frac{a^2-1}{a^2}$
NOTES	f_R = RESONANT FREQUENCY OF Z_1 AND Z_2 ARMS f_0 = FREQUENCY OF 3 DB INSERTION LOSS f = ANY FREQUENCY $a=\frac{f_R}{f_0}$ = DEFINED AS GREATER THAN UNITY R_0 = EQUALIZER RESISTANCE INSERTION LOSS = 10 LOG $\left\lvert\left[\frac{I_L}{I_L'}\right]^2\right\rvert$ L = INDUCTANCE IN HENRIES C = CAPACITANCE IN FARADS			

(b)

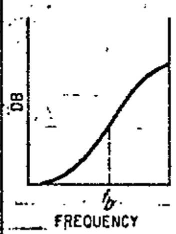
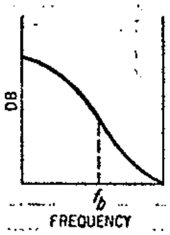
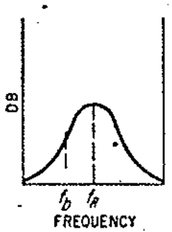
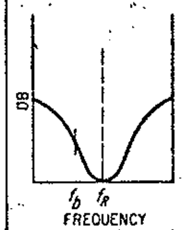
Fig. 17.6. (*Continued*)





(c)

Fig. 17.6. (*Continued*)

COLUMN	V	VI	VII	VIII
INSERTION LOSS CHARACTERISTIC				
REFER TO	FIG. 17.11	FIG. 17.12	FIG. 17.13	FIG. 17.14
CURRENT RATIO $\left\|\left[\frac{I_1}{I_L}\right]^2\right\|$	$1+\frac{K^2-1}{1+K\left(\frac{f_b}{f}\right)^2}$	$1+\frac{K^2-1}{1+K\left(\frac{f}{f_b}\right)^2}$	$1+\frac{K^2-1}{1+K\left[\frac{\frac{f}{f_R}-\frac{f_R}{f}}{b-\frac{1}{b}}\right]^2}$	$1+\frac{K^2-1}{1+K\left[\frac{b-\frac{1}{b}}{\frac{f}{f_R}-\frac{f_R}{f}}\right]^2}$
DESIGN FORMULAE	$L_1=L_B\frac{K-1}{\sqrt{K}}$ (V and VI)		$L_1=L_B\frac{K-1}{\sqrt{K}}\frac{b^2-1}{b^2}$	$L_1=L_B\frac{K-1}{\sqrt{K}}\frac{1}{b^2-1}$
	$L_2=L_B\frac{\sqrt{K}}{K-1}$ (V and VI)		$L_2=L_B\frac{\sqrt{K}}{K-1}\frac{1}{b^2-1}$	$L_2=L_B\frac{\sqrt{K}}{K-1}\frac{b^2-1}{b^2}$
	$C_1=C_B\frac{\sqrt{K}}{K-1}$ (V and VI)		$C_1=C_B\frac{\sqrt{K}}{K-1}\frac{1}{b^2-1}$	$C_1=C_B\frac{\sqrt{K}}{K-1}\frac{b^2-1}{b^2}$
	$C_2=C_B\frac{K-1}{\sqrt{K}}$ (V and VI)		$C_2=C_B\frac{K-1}{\sqrt{K}}\frac{b^2-1}{b^2}$	$C_2=C_B\frac{K-1}{\sqrt{K}}\frac{1}{b^2-1}$
	FOR ALL NETWORKS			
	$R_0=\sqrt{\frac{L_B}{C_B}}$	$R_1=R_0(K-1)$	$R_2=R_0\frac{1}{K-1}$	$R_6=R_0\frac{K}{K-1}$
	$R_3=R_0\frac{K-1}{K+1}$	$R_4=R_0\frac{K+1}{K-1}$	$R_5=R_0\frac{K-1}{K}$	
	$L_B=\frac{R_0}{2\pi f_b}=\frac{R_0}{\omega_b}$	$C_B=\frac{1}{2\pi f_b R_0}=\frac{1}{\omega_b R_0}$	$f_b=\frac{1}{2\pi\sqrt{L_B C_B}}$	
NOTES	f_R = RESONANT FREQUENCY OF Z_1 AND Z_2 ARMS		f = ANY FREQUENCY	
	INSERTION LOSS = 10 LOG $\left\|\left[\frac{I_1}{I_L}\right]^2\right\|$		PAD LOSS = MAXIMUM LOSS = 20 LOG K	
	$b=\frac{f_R}{f_b}$ = DEFINED AS GREATER THAN UNITY		L = INDUCTANCE IN HENRIES	
			C = CAPACITANCE IN FARADS	
	f_b = FREQUENCY OF ONE-HALF PAD LOSS		R_0 = EQUALIZER RESISTANCE	

(d)

Fig. 17.6. (*Continued*)

For the equal... loss at some fre... is applicable, th...

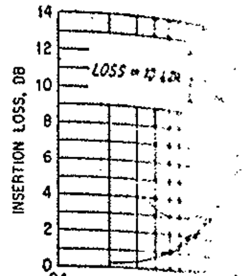


Fig. 17.7. Attenuat... works shown in ... (*From "Motion Pi... by Research Counc... Picture Arts and Sc... Van Nostrand Comp...*

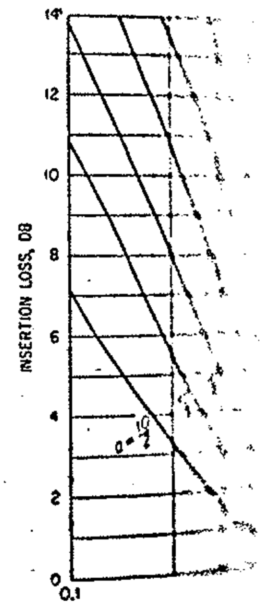


Fig. 17.9. Attenuat... (*From "Motion Pict... Picture Arts and Sc...*

The value of f_r [illegible] can then be determ...

When working ... 17.6, the frequency ... infinite insertion loss ... value of f/f_R must be ...

For the equalizers treated in columns I and II of Fig. 17.6, the desired insertion loss at some frequency f must be specified. From either Fig. 17.7 or 17.8, whichever is applicable, this insertion loss can then be associated with a specific value of f/f_a.

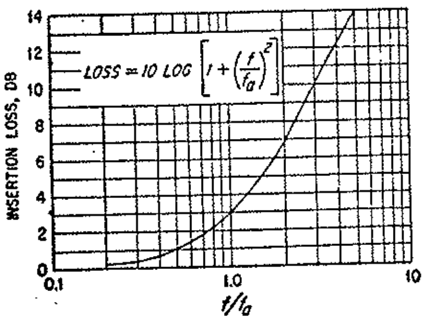


Fig. 17.7. Attenuation characteristics of networks shown in column I of Fig. 17.6. *(From "Motion Picture Sound Engineering," by Research Council of the Academy of Motion Picture Arts and Sciences, copyright 1938, D. Van Nostrand Company, Inc.)*

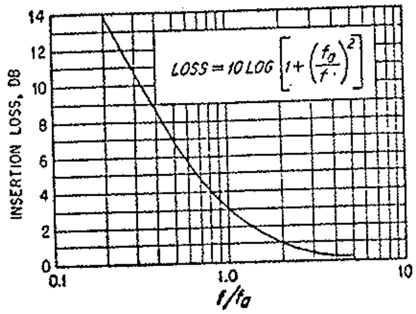


Fig. 17.8. Attenuation characteristics of networks shown in column II of Fig. 17.6. *(From "Motion Picture Sound Engineering," by Research Council of the Academy of Motion Picture Arts and Sciences, copyright 1938, D. Van Nostrand Company, Inc.)*

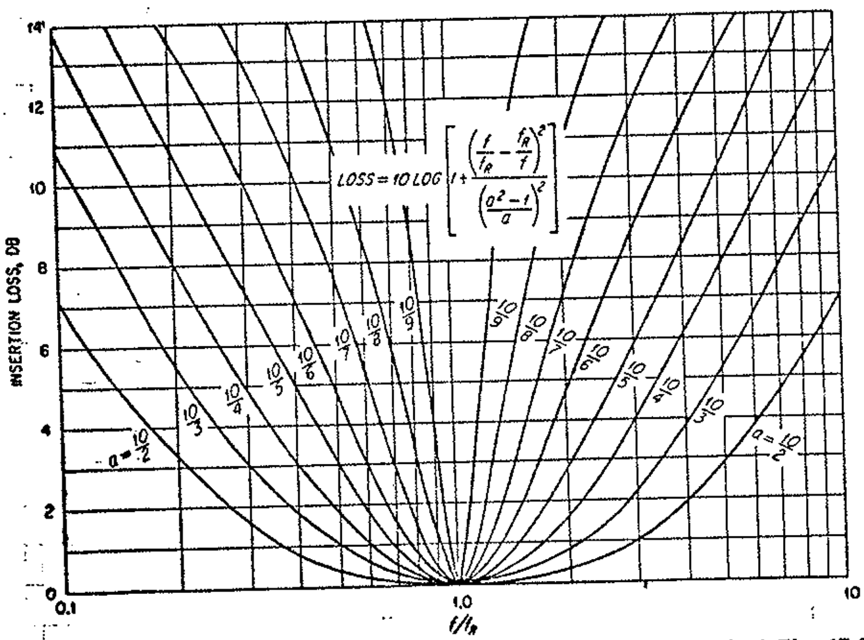


Fig. 17.9. Attenuation characteristics of networks shown in column III of Fig. 17.6. *(From "Motion Picture Sound Engineering," by Research Council of the Academy of Motion Picture Arts and Sciences, copyright 1938, D. Van Nostrand Company, Inc.)*

a = 1.5373 ⇒ 6 dB/octave

The value of f_a, which is required for the calculation of the equalizer circuit values, can then be determined since the values of f and f/f_a are known.

When working with equalizers of the types shown in columns III and IV of Fig. 17.6, the frequency of resonance f_R within the equalizer (associated with zero and infinite insertion losses, respectively) and the desired insertion loss at some specific value of f/f_R must be specified so that the proper attenuation curve and the asso-

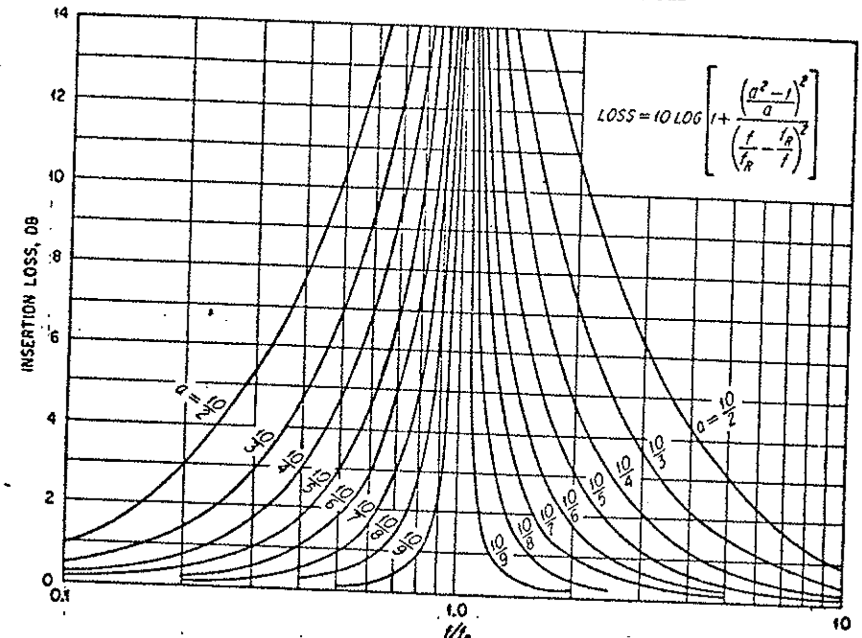


Fig. 17.10. Attenuation characteristics of networks shown in column IV of Fig. 17.6. *(From "Motion Picture Sound Engineering," by Research Council of the Academy of Motion Picture Arts and Sciences, copyright 1938, D. Van Nostrand Company, Inc.)*

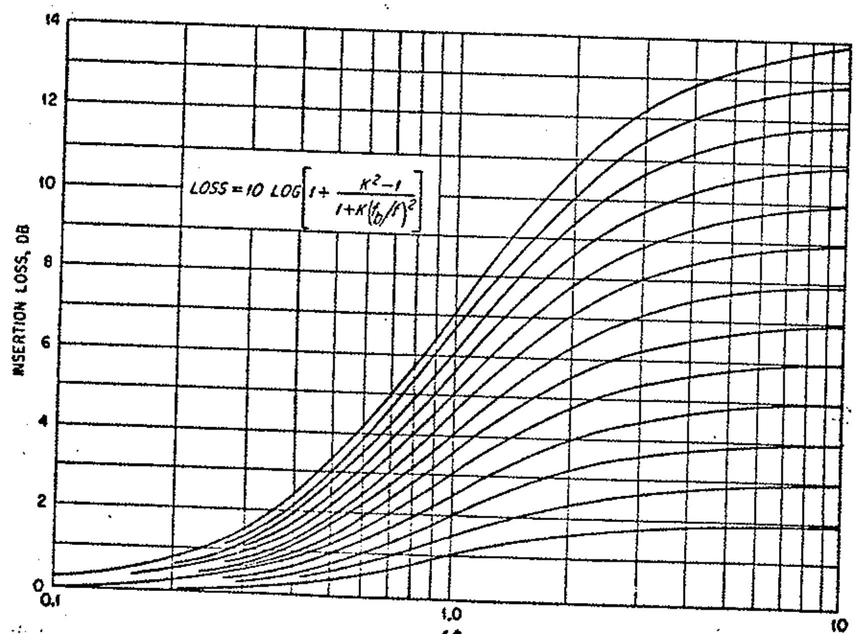


Fig. 17.11. Attenuation characteristics of networks shown in column V of Fig. 17.6. *(From "Motion Picture Sound Engineering," by Research Council of the Academy of Motion Picture Arts and Sciences, copyright 1938, D. Van Nostrand Company, Inc.)*

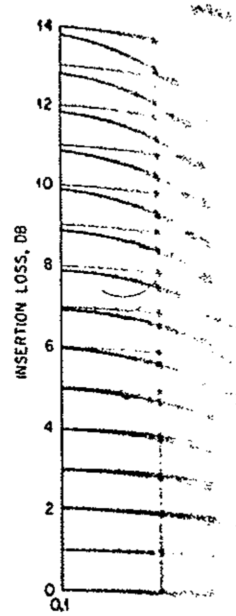


Fig. 17.12. Atte... *(Figs. 17.12, 17.1... of the Academy of ... pany, Inc.)*

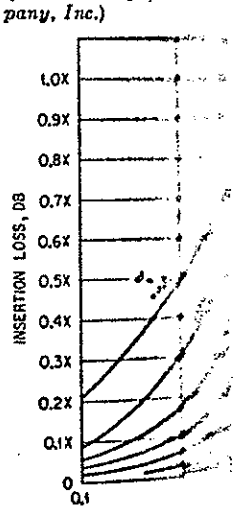


Fig. 17.13. Atte...

ciated value of ... applicable. The ... circuit values, can ...

The first step ... specify the max... at f can then be ... maximum loss in ...

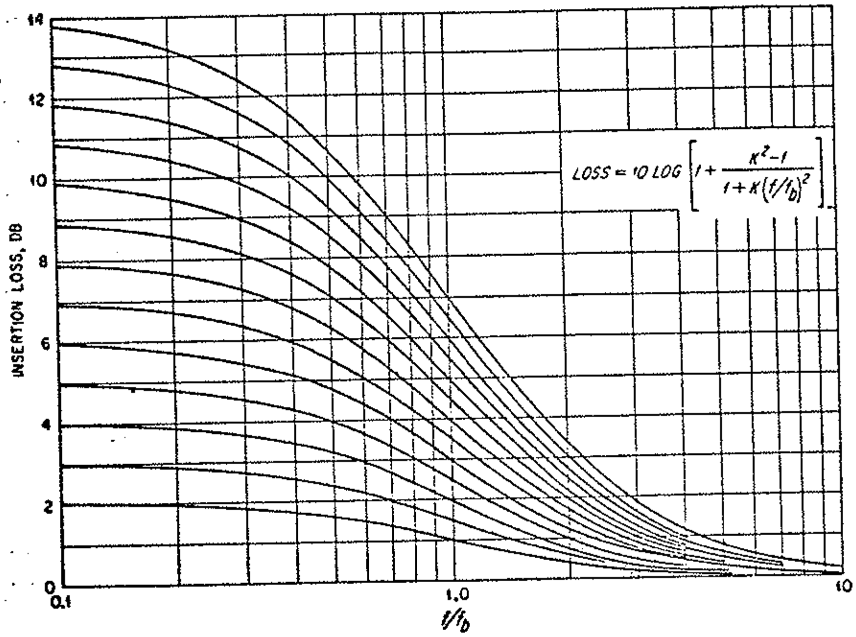


Fig. 17.12. Attenuation characteristics of networks shown in column VI of Fig. 17.6. (*Figs. 17.12, 17.13, and 17.14 from "Motion Picture Sound Engineering," by Research Council of the Academy of Motion Picture Arts and Sciences, copyright 1938, D. Van Nostrand Company, Inc.*)

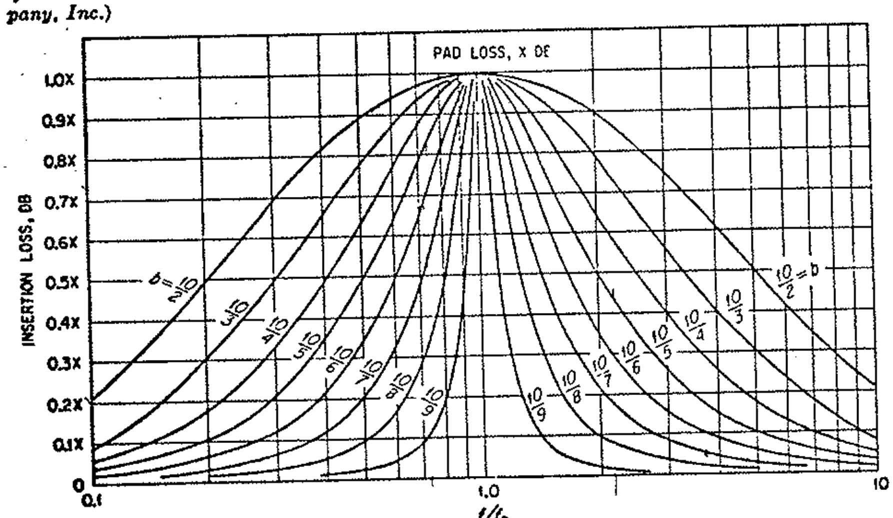


Fig. 17.13. Attenuation characteristics of networks shown in column VII of Fig. 17.6.

ciated value of a can be determined from either Fig. 17.9 or 17.10, whichever is applicable. The value of f_a, which is also required for the calculation of the equalizer circuit values, can be determined by dividing f_R by a.

The first step in the design of equalizers in columns V and VI of Fig. 17.6 is to specify the maximum desired loss and the loss at some specific frequency f. The loss at f can then be associated with a specific value of f/f_b on the curve having the desired maximum loss in either Fig. 17.11 or 17.12, whichever is applicable. The value of f_b, which is required for the calculation of the equalizer circuit values, can then be determined since the values of f and f/f_b are known.

To design equalizers shown in columns VII and VIII of Fig. 17.6, the maximum insertion loss, the frequency of resonance f_R within the equalizer (associated with the

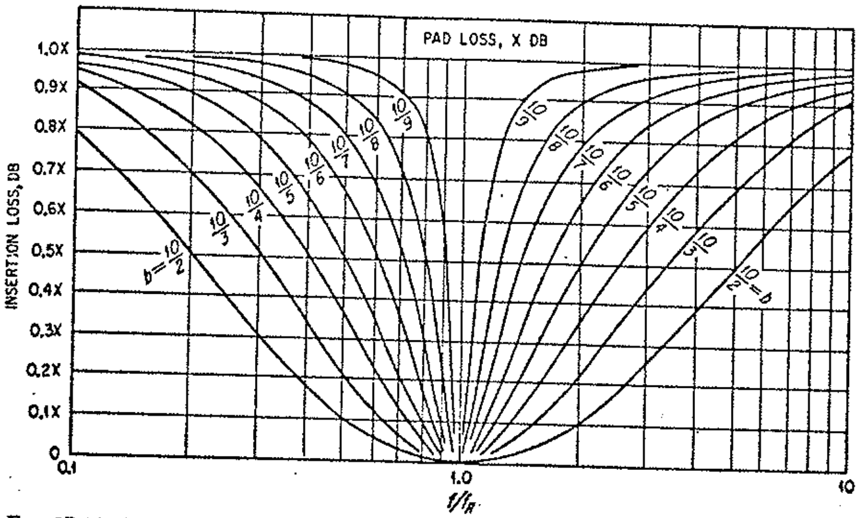


FIG. 17.14. Attenuation characteristics of networks shown in column VIII of Fig. 17.6.

maximum and zero insertion losses, respectively), and the desired insertion loss at some value of f/f_R must be specified. It is then possible to establish the proper curve and the associated value of b from either Fig. 17.13 or 17.14, whichever is applicable. The value of f_b which is also required for the calculation of the equalizer circuit values can be determined by dividing f_R by b.

When working in columns V to VIII, the frequency f_b is the frequency at which the pad loss in decibels is one-half the maximum loss in decibels, e.g., if the maximum loss is 8 db, f_b is the frequency at which the loss is 4 db.

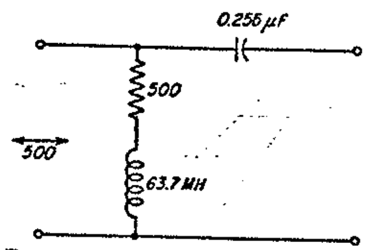


FIG. 17.15. Full shunt equalizer for Example 17.3.

Example 17.3

Design a full-shunt equalizer of the type shown in column II of Fig. 17.6 which has an insertion loss of 4 db at 1 kc and an input impedance of 500 ohms.

Solution

From Fig. 17.8 $f/f_a = 0.8$ for an insertion loss of 4 db. Therefore,

$$f_a = \frac{f}{0.8}$$

$$= \frac{1{,}000}{0.8} = 1{,}250 \text{ cycles}$$

$R_a = 500$ ohms (from statement of problem)

$$L_a = \frac{500}{2 \times 3.14 \times 1{,}250} = 63.7 \times 10^{-3} \text{ henry, or } 63.7 \text{ mh}$$

$$C_A = \frac{1}{2 \times 3.14 \times 1{,}250 \times 500} = 0.255 \times 10^{-6} \text{ farad, or } 0.255\ \mu f$$

(See Figs. 17.15 and 17.16.)

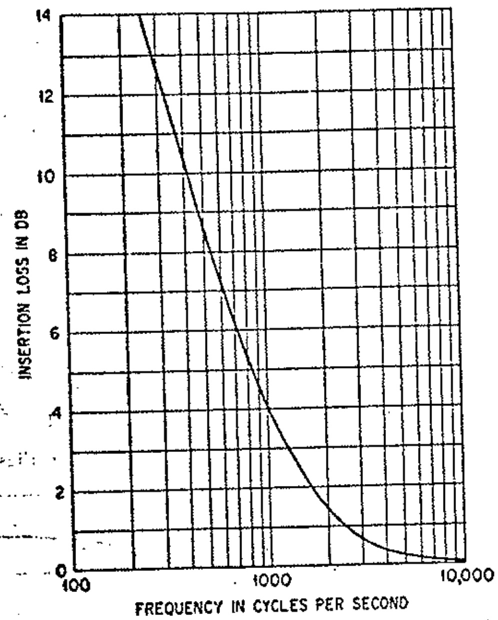


Fig. 17.16. Insertion-loss characteristics of network shown in Fig. 17.15.

Example 17.4

Design an amplitude equalizer with attenuation characteristics as indicated in column VIII of Fig. 17.6 and of the bridged-T type which will introduce zero attenuation at 5 kc (frequency of equalizer resonance), 14-db attenuation at 3.5 kc, and 20-db attenuation at frequencies far above and far below 5 kc. The equalizer should have a characteristic impedance of 200 ohms.

Solution

1. Determine f_R, b, f_b, and K.

$$f_R = 5{,}000 \text{ cycles (frequency of resonance and no attenuation)}$$

At 3,500 cps, $f/f_R = 3{,}500/5{,}000 = 0.7$. The maximum attenuation has been specified as being equal to 20 db; therefore, $X = 20$ db in Fig. 17.14, and the desired attenuation of 14 db at 3,500 cps is equal to $0.7X$. The curve for $b = 1\frac{2}{8}$ satisfies these conditions. The values of f_b and K are determined as follows:

$$b = \frac{f_R}{f_b}$$

$$f_b = \frac{5{,}000}{1.25} = 4{,}000 \text{ cycles}$$

$$20 \log_{10} K = \text{maximum pad loss} = 20$$

$$K = 10$$

2. Determine the values of the elements in the bridged T. Refer to Fig. 17.6.

$$R_o = 200 \text{ ohms} \quad \text{(specified in statement of problem)}$$

$$L_B = \frac{200}{2 \times 3.14 \times 4{,}000} = 7.96 \times 10^{-3} \text{ henry, or } 7.96 \text{ mh}$$

$$C_B = \frac{1}{2 \times 3.14 \times 4{,}000 \times 200} = 0.199 \times 10^{-6} \text{ farad, or } 0.199\ \mu f$$

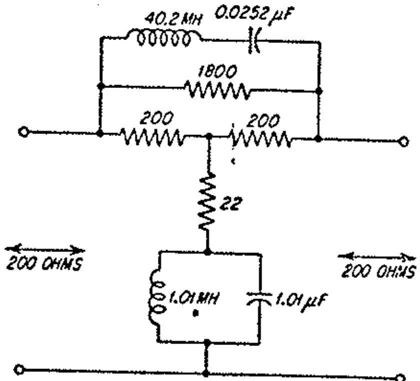


FIG. 17.17. Bridged-T equalizer for Example 17.4.

$$L_1 = 7.96 \times \frac{10 - 1}{\sqrt{10}} \times \frac{1}{1.25^2 - 1} = 40.2 \text{ mh}$$

$$L_2 = 7.96 \times \frac{\sqrt{10}}{10 - 1} \times \frac{1.25^2 - 1}{1.25^2} = 1.01 \text{ mh}$$

$$C_1 = 0.199 \times \frac{\sqrt{10}}{10 - 1} \times \frac{1.25^2 - 1}{1.25^2} = 0.0252\ \mu f$$

$$C_2 = 0.199 \times \frac{10 - 1}{\sqrt{10}} \times \frac{1}{1.25^2 - 1} = 1.01\ \mu f$$

$$R_1 = 200(10 - 1) = 1{,}800 \text{ ohms}$$

$$R_2 = 200 \times \frac{1}{10 - 1} = 22.2 \text{ ohms}$$

(Refer to Figs. 17.17 and 17.18.)

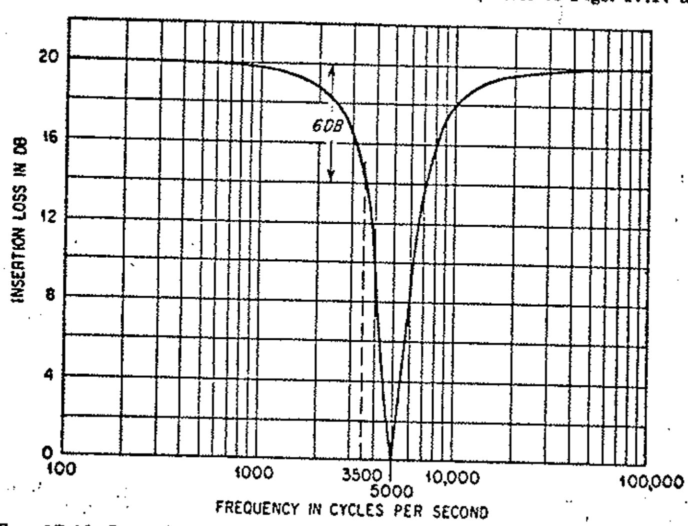


FIG. 17.18. Insertion-loss characteristics of network shown in Fig. 17.17.

17.3. Phase Equalizers. The types of phase equalizers treated are those which theoretically introduce either zero or a fixed amount of attenuation at all frequencies. They can therefore be added to existing circuits for phase correction without distorting the gain characteristics.

The shape of electrical impulses which contain many frequency components can be distorted in passing through an electrical circuit even though the circuit has the same gain for the different frequency components. If such is the case, the distortion is due to unequal transmission delays for the different frequency components. This type of distortion is called *phase distortion* and can be corrected by adding a network which will cause the total transmission period for all frequencies to be identical. The added network must, therefore, be a network in which the phase characteristics can be controlled.

Equal transmission periods for different frequency components through a circuit stipulates that the circuit must introduce either no phase shift or an amount of phase shift which is directly proportional to frequency. This is identical to stating that the transmission period must be either zero or a constant amount at all frequencies.

Four different configurations of phase equalizers[1] are shown in Figs. 17.19 to 17.21. It should be noted that the four-terminal networks can be used in only those applications in which the input and output circuits are either both balanced or are in no way connected to each other.

The circuit in Fig. 17.19 introduces an insertion loss of 6 db and does not have constant input and output impedances as a function of frequency. In addition, the

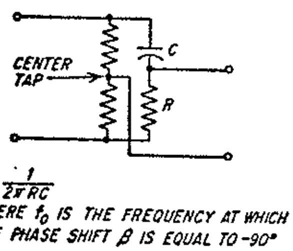


Fig. 17.19. Phase equalizer with a fixed insertion loss of 6 db. The phase characteristics are exactly the same as for the lattice network shown in Fig. 17.20, provided the output is not loaded.

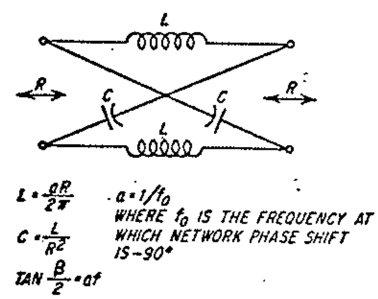


Fig. 17.20. Phase-shift network with zero attenuation. Refer to Fig. 17.22 for phase characteristics.

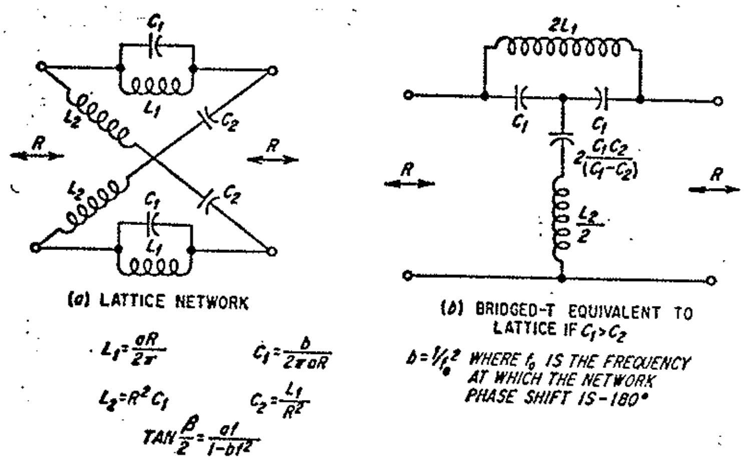


Fig. 17.21. Phase-shift network with zero attenuation. Refer to Fig. 17.23 for phase characteristics.

phase-shift curve for the circuit, Fig. 17.22, is based on there being no terminating impedance.

A center-tapped transformer secondary winding could be substituted for the resistor in Fig. 17.19, provided the amplitude and phase characteristics of the transformer were acceptable.

The networks shown in Figs. 17.20 and 17.21 have constant input and output characteristic impedances as a function of frequency and provide phase shift without attenuation. Figures 17.22 and 17.23 indicate the phase characteristics which can be obtained.

The phase equalizers shown in Figs. 17.19 to 17.21 introduce a lagging phase shift.

[1] These networks are also referred to as *all-pass* filters.

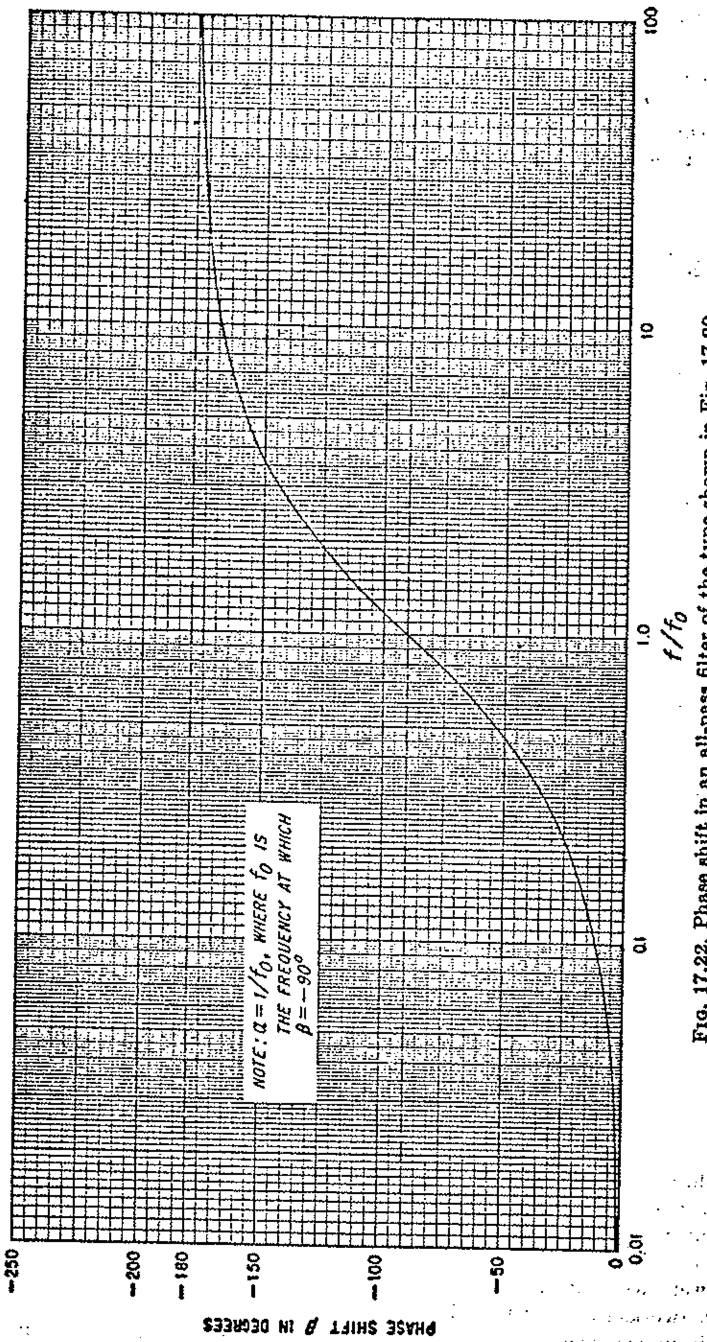
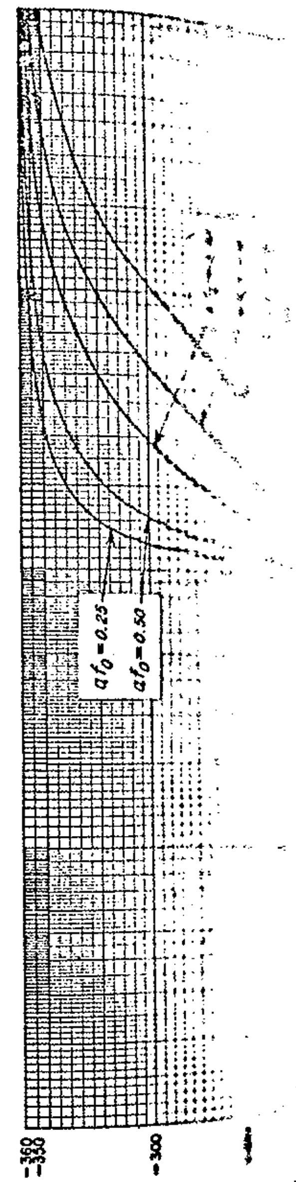


FIG. 17.22. Phase shift in an all-pass filter of the type shown in Fig. 17.20.



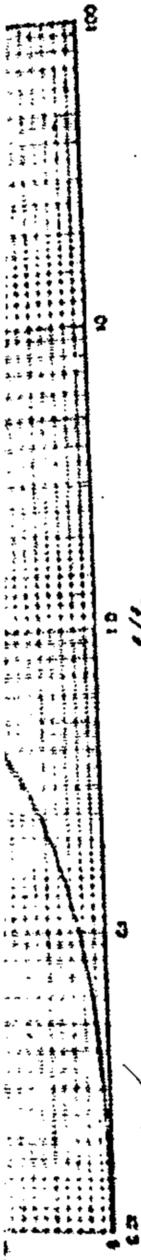


Fig. 17.22. Phase shift in an all-pass filter of the type shown in Fig. 17.20.

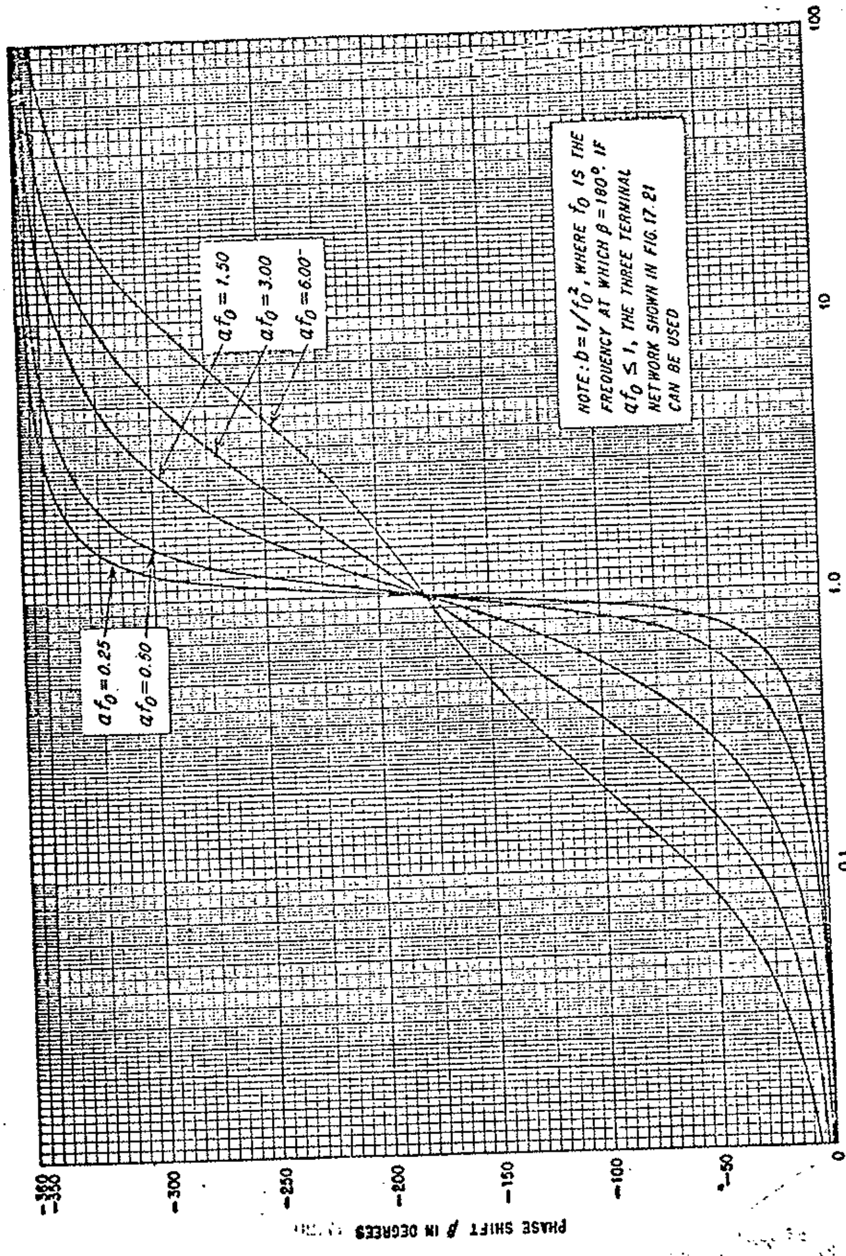


Fig. 17.23. Phase shift in an all-pass filter of the type shown in Fig. 17.21.

Example 17.5

Assume that intelligence must be transmitted in the 10- to 20-kc frequency band and that the circuit employed introduces phase shift in accordance with the following tabulation.

Phase Shift	*Frequency*
−27°	10 kc
−43.5°	15 kc
−63°	20 kc

Design a phase equalizer of the lattice type with a characteristic impedance of 1,000 ohms for use with this circuit.

Solution

1. Determine the required phase characteristics of the phase equalizer.

The departure from linear phase shift as a function of frequency for the existing circuit must first be determined. Since the phase shift at 20 kc is −63°, the phase shift at 10 kc should be $\frac{1}{2} \times -63$, or −31.5°, and the phase shift at 15 kc should be $\frac{3}{4} \times -63$, or −47.25°. The existing network therefore introduces a phase error of +4.5° at 10 kc and +3.75° at 15 kc.

Phase Error	*Frequency*
+4.5°	10 kc
+3.75°	15 kc
0°	20 kc

The phase equalizer must therefore exhibit the inverse characteristics, i.e.,

Phase Error	*Frequency*
−4.5°	10 kc
−3.75°	15 kc
0°	20 kc

2. Determine from Figs. 17.22 and 17.23 if the required conditions tabulated in step 1 can be satisfied with either of the networks shown in Figs. 17.20 or 17.21.

Since the network shown in Fig. 17.20 is simpler, the curve shown in Fig. 17.22 should first be examined.

The procedure is to determine if the phase shift in the equalizer at any three values of f/f_o, which are related in the same proportions as are 10, 15, and 20 kc, will depart from linear phase shift as a function of frequency by the desired amount. A few experimental groups of values of f/f_o reveal that the phase shifts for f/f_o equal to 0.4, 0.6, and 0.8 are equal to −43, −61.5, and −77°, respectively, and satisfy the specified requirements. This is true since a phase shift of −77° at $f/f_o = 0.8$ requires that the phase shift be −38.5 and −57.75° at f/f_o equal to 0.4 and 0.6, respectively, for linear phase characteristics. The phase equalizer therefore introduces phase errors of −4.5 and −3.75° when f/f_o is equal to 0.4 and 0.6, respectively. It should be apparent that the three values of f/f_o, that is, 0.4, 0.6, and 0.8, correspond to f being equal to 10, 15, and 20 kc, respectively.

3. Determine f_o and the values for the lattice elements.

$$\frac{f}{f_o} = 0.8 \text{ (at } f = 20 \text{ kc)}$$

$$f_o = 25 \text{ kc}$$

From Fig. 17.22

$$a = \frac{1}{25{,}000} = 4 \times 10^{-5}$$

From Fig. 17.20

$$L = \frac{4 \times 10^{-5} \times 10^3}{2 \times 3.14}$$

$$= 6.37 \times 10^{-3} \text{ henry, or } 6.37 \text{ mh}$$

$$C = \frac{6.37 \times 10^{-3}}{10^6}$$

$$= 6{,}370 \times 10^{-12} \text{ farad, or } 6{,}370\ \mu\mu f$$

The lattice network is shown in Fig. 17.24.

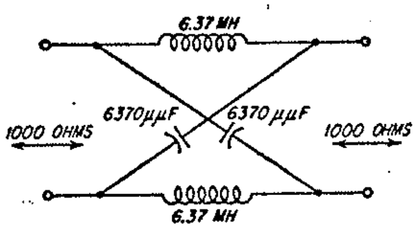


FIG. 17.24. Lattice network for Example 17.5.

Principle