FILTERING

Even when a system has been well designed and incorporates proper shielding and grounding considerations, undesired energy can still be conducted through the system to degrade performance or cause malfunction. Filters can reduce this unwanted conducted energy to levels at which the system can function satisfactorily. Because of this role, filters are important in contributing to electro-magnetic compatibility.

An electrical filter can be defined as a network of lumped or distributed constant resistors, inductors, and capacitors or their equivalent, or any combination thereof; that offers comparatively little opposition to certain frequencies or to direct current while blocking the passage of other frequencies. The design of filters is an art as well as a science since much depends on the judgment and techniques used by the filter design engineer.

The purpose of this article is to provide the EMC design engineer with general filter design information that can be useful in the development of compatible equipment. However, some overall comments on EMI filtering are first considered appropriate.

First of all, it is important to point out that filters are often used only as stop-gap measures to problems that might have been resolved in a different way earlier in system design. For example, improved circuit linearity requirements might have obviated the need for a harmonic filter. Similarly, improved isolation of a relay circuit could have resolved a problem that later had to be attacked with transient suppression filters. An initial engineering effort should be made to design circuits that are inherently free of EMI. As part of this engineering effort filters should be considered to limit the magnitude of EMI currents and to confine the currents to the smallest practical physical area, but the decision to use a filter should be made at a stage of development that provides maximum choice in alternative EMC approaches.

The impetus to the establishment of equipment filtering requirements (or shielding or grounding requirements for that matter) are the formal and informal specifications imposed on the designer. Thus, formal interference specifications such as MIL-STD-461A limit the amount of conducted interference that may be introduced on a power line. Tolerable interference levels on critical internal equipment leads must be defined during an early stage of EMC design so that circuit designers know the conditions their subassemblies must meet. The ability to comply with these specification limits can then be continuously assessed in the bread-board stage, at the points when subassemblies are interfaced, in the prototype stage, etc. Discrepencies between design objectives and actual EMI levels can often be most easily resolved by adding or modifying filters, particularly as portions of the design are frozen.

While filters are necessary and should be placed where needed, care should be taken to avoid redundant filtering caused by uncoordinated efforts of separate design groups. Redundancy usually occurs when each "black box" is required to meet an interference control specification regardless of final location. Although trade-offs must be made, there is no substitute for a well thought-out system EMC control plan. If formulated well ahead of the system design, filter duplication can be avoided.

The effectiveness of any EMI filter is greatly influenced by the impedance of its source and load terminations. Manufacturers of EMI suppression filters normally specify the filter characteristics with fixed source and load impedances, usually 50 ohms. The actual characteristics may be different when used in a circuit that requires other terminations, or when used in circuits whose impedances are not fixed. This aspect must be taken into consideration when designing, specifying or using EMI filters.

Certain guidelines are helpful in deciding what type of filter circuit to apply in any given instance. For example, if it is known that the filter will connect to relatively low impedances in both directions, then a circuit containing more series filter elements is indicated (a T-circuit, for instance). Conversely, a high-impedance system calls for a π-filter. If the filter is connected between two severely mismatched impedances, then an asymmetric filter circuit such as two L-section elements can be used. The series element faces the low-impedance side of the system.

The basic characteristic used to describe filter performance is its insertion loss. *Insertion loss* is defined as the ratio of voltages appearing across the system terminals immediately beyond the point of insertion of a filter, before and after insertion. It is represented as the ratio of input voltage required to obtain constant output voltage, with and without filter in the system. This ratio is expressed in decibels (dB) as follows:

$$\text{Insertion loss} = 20 \log \frac{E_1}{E_2}$$

where:

E_1 = the output voltage of the signal source with the filter in the circuit.

E_2 = the output voltage of the signal source with the filter not in the circuit.

A number of other filter characteristics are important. The input and output impedance requirements have already been cited. Others include the attenuation in the pass-band, the skirt falloff characteristic (rate at which the filter insertion loss changes as a function of frequency), steady-state and transient voltage ratings, etc.

FILTER DESIGN*

As indicated previously, filters are designed to attenuate at certain frequencies while permitting energy at other frequencies to pass unchanged. Reflective filters do this by using combinations of capacitances and inductances to set up a high series impedance or a low shunt impedance for the interfering currents. Lossy filters do this by absorbing the interference energy.

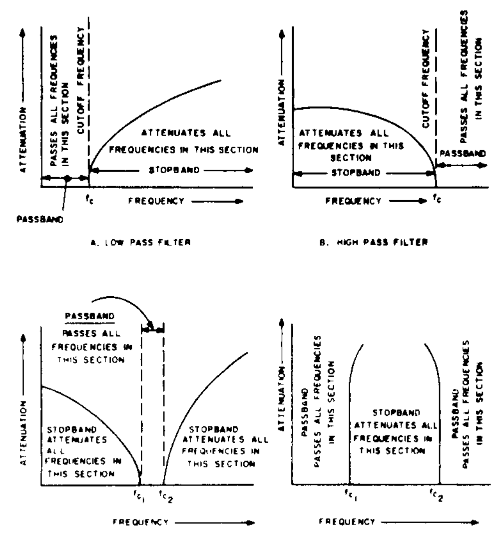

Figure 1. The Four Basic Classes of Filters

*Only lumped constant filters are considered in this design guide.

The *passband* of a filter is the frequency range in which there is little or no attenuation. The *stopband* is the frequency range in which attenuation is desired. The attenuation may vary in the stopband and is usually least near the *cutoff frequency* (the frequency at which a 3 dB insertion loss is obtained), rising to high values of attenuation at frequencies considerably removed from the cutoff frequency.

Filters can be grossly classified according to the relative positions of the passband and stopband in the frequency spectrum. There are four classes: low-pass, high-pass, band-pass, and band-reject, and the discussions to follow will deal with these classes. Attenuation as a function of frequency for each of the classes is shown in Figure 1.

2.1 Low-Pass Filters

EMI control usually requires filters of the low-pass type. Power line filters are low-pass filters that pass DC or power frequency currents without significant power loss, while attenuating signals above these frequencies. Filters incorporated in amplifier circuits and transmitter output circuits are usually of the low-pass type so that the fundamental signal frequency can be passed while harmonics and other spurious signals are attenuated.

2.1.1 Shunt Capacitive Filters, and General Capacitor Characteristics

The simplest low-pass EMI filter is a shunt capacitor connected from the interference-carrying conductor to ground. It serves to bypass high-frequency energy, as indicated in the ideal representation of Figure 2. Under these circumstances the insertion loss of a shunt capacitor filter is defined by the relationship:

$$IL(dB) = 10 \log (1 + F^2) \qquad (2)$$

where
$F = \pi fRC$
f = frequency, in Hertz
R = driving or termination resistance, in ohms
C = filter capacitance, in farads

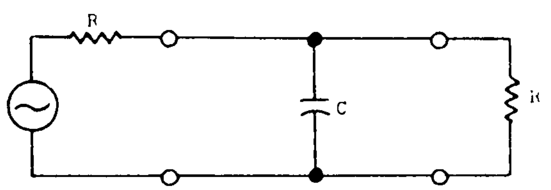

Figure 2. Capacitor Low-Pass Filter

An actual capacitor incorporates both resistance and inductance. These effects are due to such factors as the foil inductance of the capacitor plates, lead inductance, foil resistance, and lead-to-foil contact resistance.

The variations in these inductive and resistive effects depend upon the type of capacitor. Metalized paper capacitors, while small in physical size, offer poor RF bypass capabilities because of high resistance contact between the leads and the capacitor metal film. They are also a source of radio noise as the dielectric punctures and self-heals by burning away the metal film. This effect is indicated by the switch in the equivalent circuit shown in Figure 3. The standard wound aluminum foil capacitor may be employed as a radio frequency bypass in the frequency range up to 20 MHz. Its useful frequency range of operation is a function of capacitance and lead length. Its equivalent circuit is the same as that of the metallized paper capacitor, but R_S and S of Figure 3 are not in the circuit.

As a result of these inductive effects, a capacitor will exhibit a capacitive reactance at low frequencies, and this

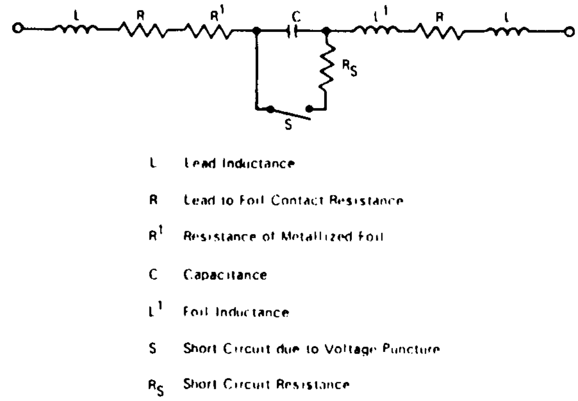

Figure 3. Metalized Capacitor Equivalent Circuit

situation will be maintained until its self-resonant frequency is reached. Above this frequency, the capacitor behaves like an inductive reactance. This effect is illustrated in Figure 4. Also note the effect of changing capacitor lead-length on this self-resonant frequency.

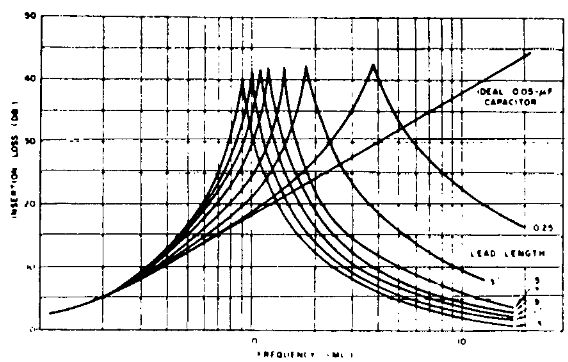

Figure 4. Insertion Loss of an 0.05-uf Aluminum Foil Capacitor

Mica and ceramic capacitors of small values are useful up to about 200 MHz. A capacitor of flat construction, if the capacitor plates are round as in a ceramic disc capacitor, will remain effective to higher frequencies than one of square or rectangular construction.

Other factors must be considered in selecting ceramic filter capacitors. A ceramic capacitor element is affected by operating voltage, current, frequency, age, and ambient temperature. The amount the capacity varies from its nominal value is determined by the composition of the ceramic dielectric. The dielectric composition can be adjusted to obtain a desired characteristic such as negative temperature or zero temperature coefficient, or minimum size. In obtaining one characteristic, othe characteristics may become undesirable for certain applications. For example, when the dielectric composition is adjusted to produce minimum size capacitors, the voltage characteristic may become negative to the extent that 50 percent capacity exists at full operating voltage, and full ambient temperature may cause an additional sizeable reduction in capacity. Also, from the time of firing of the ceramic, the dielectric constant of the materials used may decrease; after 1000 hours, the capacitance may be as low as 75 percent of the original value. The designer should make ceramic capacitor selection based on required capacity under the most adverse operating conditions, and taking into account aging effects.

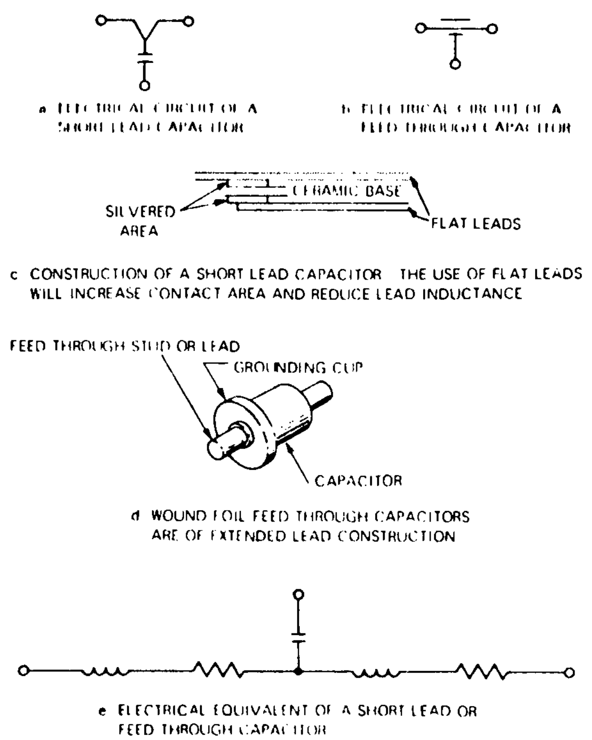

Figure 5. Three-Terminal Capacitor Construction

Capacitors of short-lead construction, and feed-through capacitors, are three-terminal capacitors designed to reduce inherent end lead inductances. Figure 5 shows the construction of these three-terminal types. In each case, the inductance of the lead is not included in the shunt circuit. The wound foil short-lead capacitor is made with an extended foil type construction so that each plate of the capacitor can be soldered to a washer-shaped terminal. One washer is, in turn, soldered to the center lead, while the other is soldered to the case that is the ground terminal.

Theoretical insertion loss of three-terminal capacitors is the same as for an ideal two-terminal capacitor. However, the insertion loss of a practical three-terminal capacitor follows the ideal curve much more closely than does a two-terminal capacitor. The useful frequency range of a feed-through capacitor is improved further by its case construction, enabling a bulkhead or shield to isolate the input and output terminals from each other.

While the short-lead construction capacitor is ideally suited for EMI suppression in the frequency range of 1 to 1000 MHz, feed-through capacitors are available with a resonant frequency well above 1 GHz. The feed-through current rating is determined by the stud diameter. Figure 6 shows the insertion loss characteristics of typical feed-through capacitors, while Figure 7 indicates the construction details of a feed-through unit.

Capacitor selection for shunt capacitive filters, or any other filter application, is determined in part by the voltage, temperature, and frequency range in which the filter must operate. For 28 VDC applications, capacitors rated at 100

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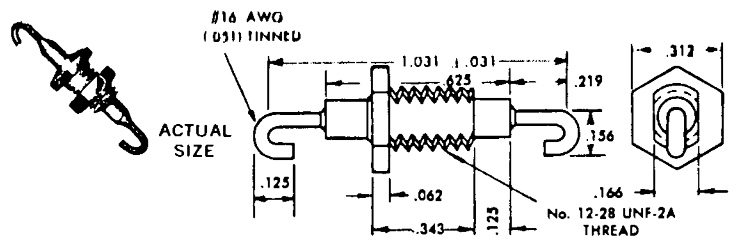
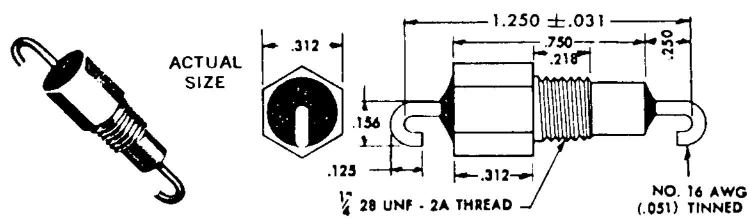
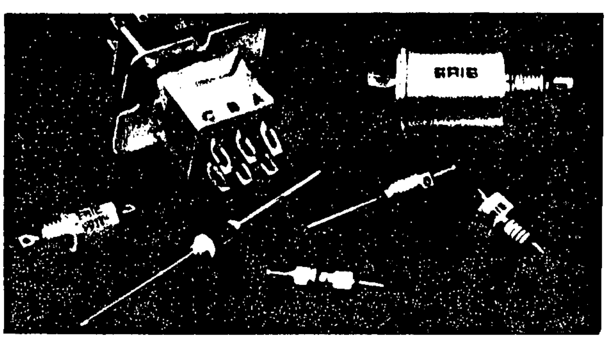


SPECIFICATIONS

Capacitance Range	— 10 pF through 6,000 pF
Capacitance Tolerance	— ±20%, or GMV
Power Factor	— 3% Maximum
Working Voltage D.C.	500 Vdc
Temperature Range	−55°C to +85°C (derate voltage 50% at 125°C)
Testing	— EIA RS 198 CLASS 2
Marking	— Color Code
Tolerance on Dim.	— ±.015 unless otherwise specified

● 10 pF through 10,000 pF CAPACITANCE RANGE





SPECIFICATIONS

Capacitance Range	— 10 pF through 10,000 pF
Capacitance Tolerance	— ±20%, or GMV
Power Factor	— 3% Maximum
Working Voltage D.C.	— 500 Vdc
Temperature Range	— −55°C to +85°C (derate voltage 50% at 125°C)
Testing	— EIA RS 198 CLASS 2
Marking	Stamp capacitance and tolerance on [illegible] Color Code on [illegible]
Tolerance on Dim	— ±.015 unless otherwise specified

Figure 6. Typical Feed-Through Capacitor Characteristics

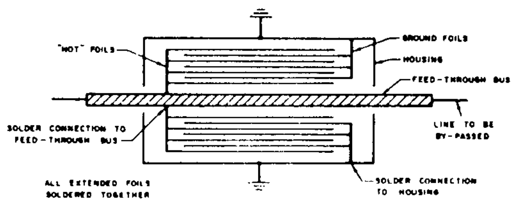


Figure 7. Construction of Feed-Through Capacitor

working volts DC (WVDC) are adequate. Metallized mylar capacitors offer the most compact design and good reliability. Their dissipation factor is very low, and lead length can generally be kept short to improve high frequency performance.

Wet-type electrolytic capacitors are used for dc filtering and sometimes used in EMI filters. They are single polarity devices, and their high dissipation factor or series resistance make them poor rf filters. An rf bypass capacitor should be placed across the output of DC supplies using electrolytics. The dissipation factors of electrolytic capacitors increase, and their capacitances decrease with age.

If a large value of capacitance is required in a small space, tantalum capacitors may be considered. Because tantalum capacitors are electrolytics, they are more sensitive to over-voltages, and are damaged by reverse polarity. The dissipation factor is considerably higher than for mylar or paper capacitors, and high frequency characteristics are poor. A large tantalum capacitor reaches its minimum impedance at 2 to 5 MHz or less, depending upon construction and capacitance value.

Capacitors for 120 VAC applications should be rated at 400 WVDC and be suitable for AC use. A unit of mylar and foil or of paper-mylar and foil is recommended. Dissipation factor is low and high frequency performance is good. For 240 VAC applications, an oil-impregnated paper and foil unit is recommended.

If good capacitor performance is to be expected above about 50 MHz, it is necessary to use designs incorporating feed-through techniques. As noted previously, lead inductance in a feed-through capacitor is not part of the shunt circuit, so that, compared to capacitors with leads, its insertion loss is not degraded as rapidly with increase in frequency.

2.1.2 Series Inductive Filters, and General Inductor Characteristics

Another simple form of low-pass filter is an inductor connected in series with the interference carrying conductor. It is ideally represented in Figure 8. In practice, its insertion loss can be defined by the relationship:

$$IL(dB) = 10 \log (1 + F^2) \qquad (3)$$

where

$$F = \pi f \frac{L}{R}$$

L = filter inductance, in henries

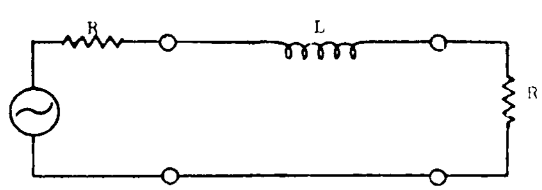


Figure 8. Inductor Low-Pass Filter

In practice, an inductor exhibits inductive reactance only until its self-resonant frequency is reached. Above self-resonance, it appears as a capacitive reactance, with the inter-winding capacitance becoming dominant.

Filter inductors are usually toroidal, wound on cores of powdered iron, molybdenum permalloy, or ferrite material. The size of the core is determined by required inductance and current rating. The magnetic flux (number of turns multiplied by the peak current) should not drive the core to more than 50 percent of magnetic saturation.

The choice of core materials is determined by operating frequency and current rating. Powdered iron cores can be used for all DC applications and for most 60 Hz applications. For high current 60 Hz devices, and for all 400 Hz applications, molybdenum permalloy cores should be used. For extremely low current applications of less than 0.1 ampere, ferrite materials can be considered.

Stray or distributed capacitance in a filter inductor has two detrimental effects: EMI may be coupled from input to output of the filter via the capacitance; and the capacitance may cause the filter to become self-resonant at one or more critical frequencies. Windings should be placed on the coil so that input and output turns are separated as much as possible to keep stray capacitance low. Distributed capacitance effects may be reduced by a careful arrangement of turns. In some cases, two or more coils wound on separate cores are connected in series to raise the self-resonant frequency.

Coil loss resistance is a measure of all power losses, hysteresis losses, and frequency-dependent absorption losses in the core. Loss resistance increases with frequency because of skin effect in the conductor, and due to changes in core loss with frequency. An increase in loss resistance represents an increase in attenuation in the filter passband. Losses in the core are not particularly detrimental, except that the insertion loss in the passband must be kept low.

2.1.3 Low-Pass "L" Section Filters

A primary disadvantage of single element filters is that their out-of-band falloff rate is only 6 dB per frequency octave (20 dB per decade). By combining both a shunt capacitor and a series inductance single element filter into an "configuration", a falloff rate of 12 dB/octave can be obtained.

The two possible representations of low-pass "L" section filters are shown in Figure 9. In one representation the capacitor shunts the source impedance, while in the other the capacitor shunts the load impedance. The insertion loss for the "L" section filter is independent of the direction of inserting the "L" section into the line, if source and load impedances are equal. When source and load impedance are not equal, the greatest insertion loss will usually be achieved when the capacitor shunts the higher impedance.

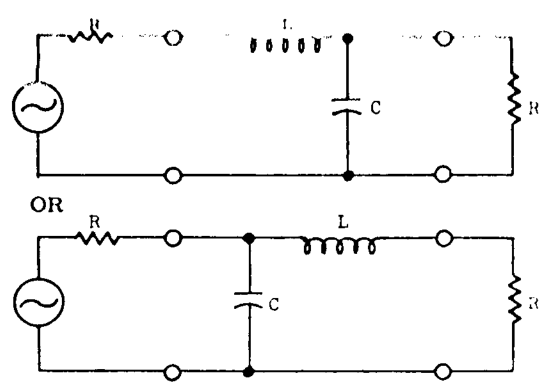


Figure 9. Low-Pass "L" Section Filter

The insertion loss of an "L" section lumped-constant network into 50 ohm resistance source and load impedances is:

$$IL(dB) = 10 \log (1 + F^2D^2/2 + F^4) \quad (4)$$

where

$$D = \frac{1 - d}{\sqrt{d}}$$

$$d = L/CR^2 = \text{damping ratio}$$

$$w_o = \sqrt{2}R/L = \sqrt{2}/RC \text{ (if } d = 1)$$

$$w_o = \sqrt{2/LC} \text{ (if } d \neq 1)$$

$$F = \frac{w}{w_o}$$

The "damping ratio", d, relates the magnitudes of the filter elements to the magnitude of the source and load impedance. It is defined so that setting d equal to one (ideal damping) results in the elimination of the squared frequency term from the insertion loss equation and produces an abrupt transition from the pass-band to the stop region. The equations for Butterworth filter designs are obtained when d is set equal to one.

Values of d less than one result in insertion loss curves identical to those obtained when d is greater than one. That is:

$$IL \text{ (for } d = n) = IL \text{ (for } d = 1/n) \quad (5)$$

for two element filters. The insertion loss of a two-element filter is not changed when it is "turned around" so that the source and load terminals are transposed, so long as the source and load impedances are equal.

The physical size of an "L" section filter depends upon insertion loss requirement, current rating, and voltage rating, with the first two usually predominant. The "L" section type of filter may give poor high frequency attenuation because of stray inter-turn capacitance. In some cases, the "L" type may resonate and oscillate when excited by transients.

Figure 10 provides an example of a commercially available "L"-section low-pass filter. This type of configuration enables a unit to be manufactured that can maintain an adequate rejection level to 1 GHz.

2.1.4 π-Section Filters

The "pi" section filter is the most common type of radio frequency interference suppression network. Figure 11 shows the circuit of the "pi" section filter. Advantages are ease of manufacture, high insertion loss over a wide frequency range, and moderate space requirements. Although voltage rating must be considered, current rating and attenuation are the most important factors in determining the size of the filter.

The insertion loss of a lossless "pi" section network operating with 50 ohm source and load impedances is:

$$IL \text{ (dB)} = 10 \log (1 + F^2D^2 - 2F^4D + F^6) \quad (6)$$

where

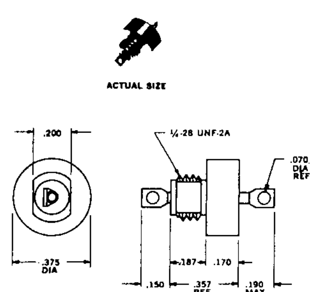
$$D = \frac{1 - d}{\sqrt[3]{d}}$$

$$d = L/2CR^2 = \text{damping factor}$$

BUTTON FILTERS

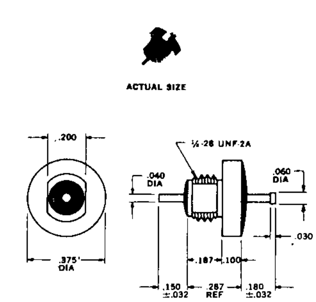
Courtesy of USCC/Centralab, Electronics Div. Globe-Union, Inc.

1020-000 HERMETICALLY SEALED UNIT



TOLERANCES: ±.010 unless otherwise noted

1021-000 EPOXY SEALED UNIT



TOLERANCES: ±.010 unless otherwise noted

SPECIFICATIONS — Meet or exceed all applicable requirements of MIL-F-15733

Working Voltage — 50 VDC (−55°C to +125°C)

Current — 15 amps DC maximum

Dielectric Withstanding Voltage — 2 times rated voltage, with 50 ma maximum charging current

Insulation Resistance — 100 megohms minimum with 50 VDC, 50 ma maximum charging current

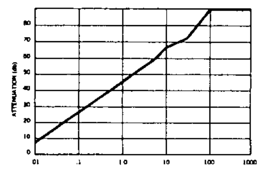
DC Resistance — .006 ohms maximum

Housing — Tin plated brass (standard)

Insertion Loss per MIL-STD-220, full load —

Frequency	db
30 kHz	15
150 kHz	28
300 kHz	33
1 MHz	44
10 MHz	60
1 GHz	70

TYPICAL INSERTION LOSS



Schematic —

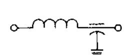


Figure 10. Example of Commercial "L" Section Filter

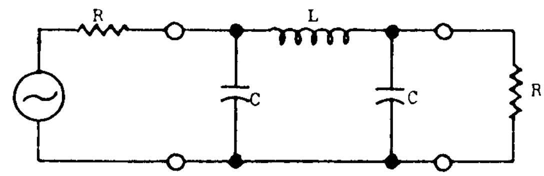
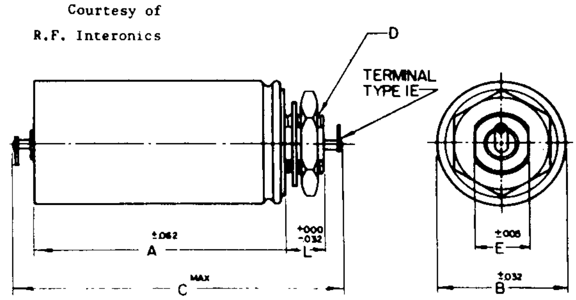


Figure 11. Low-Pass π Filter

Courtesy of R.F. Interonics



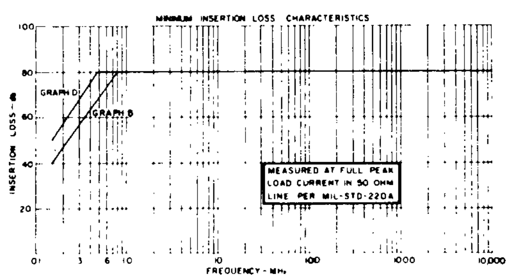


Figure 12. Representative π-Section Filter Characteristics

$$w_o = \sqrt{2/LC} = 2R/L = \frac{1}{RC} \text{(if d = 1)}$$

$$w_o = \sqrt[3]{2/RLC^2} \text{(if d} \neq 1)$$

$$F = \frac{w}{w_o}$$

Unlike the "L" section filter case, overdamping or underdamping of π-section (and T-section) filters result in entirely different affects. This is discussed further in Section 2.1.6 of this article.

A typical attenuation curve of a "pi" section filter has a slope of approximately 18 dB per octave; the high frequency performance can be improved by internal shielding within the filter case. However, the "pi" circuit is very susceptible to oscallatory ringing when excited by a transient. Representative data on a series of commercial low-pass "π" filters are shown in Figure 12.

The multiple "pi" section filter (cascaded π-sections) has characteristics identical to those of the multiple "L" section filter. The attenuation curve of the theoretical multiple "pi" section filter rises at a rate of 20 dB more per decade of frequency than does a multiple "L" filter of the same number of sections. Although this may not be a significant factor when three or more sections are used, it does provide a capacitive input at both ends of the filter that is sometimes advantageous. An extensive use for this type of network is as a power-line filter in large installations, and for shielded enclosures where high attenuation is needed at very low frequencies.

2.1.5 "T" Section Filters

The "L" type low-pass filter can also be improved by the introduction of another series inductor. This addition forms a "T" section filter, which consists of two inductors in series with a shunt capacitor connected from the junction of the two inductors to ground (see Figure 13). Insertion loss is given by:

$$IL\,(dB) = 10 \log (1 + F^2D^2 - F^4D + F^6) \quad (7)$$

where

$$D = \frac{1 - d}{\sqrt[3]{d}}$$

$$d = R^2C/2L = \text{damping factor}$$

$$w_o = \sqrt{\frac{2}{LC}} = \frac{R}{L} = \frac{2}{RC} \text{(if d = 1)}$$

$$w_o = \sqrt[3]{2R/L^2C} \text{(if d} \neq 1)$$

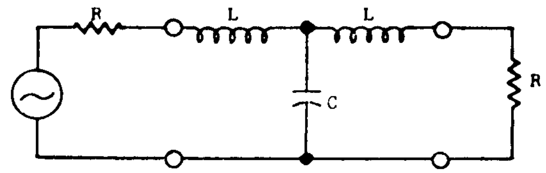


Figure 13. Low-Pass "T" Filter

The "T" type of filter is a very effective form of the lumped-constant type of filter for reducing transient interference. Its major disadvantage is the requirement for two inductors, which under some circumstances may present a size penalty. It provides the same out-of-band falloff rate as the π-section filter, that is, 18 dB/octave (60 dB/decade) for a single section.

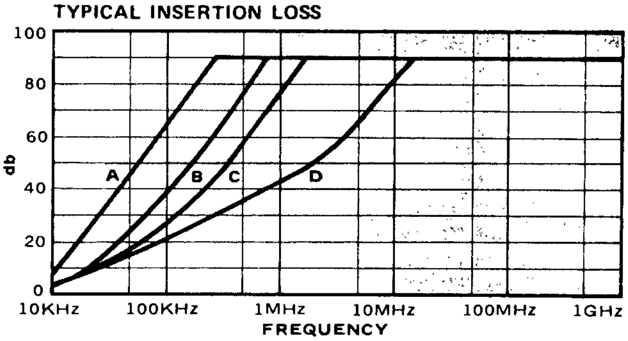
Figure 14 provides representative information on commercially available T-section low-pass filters.

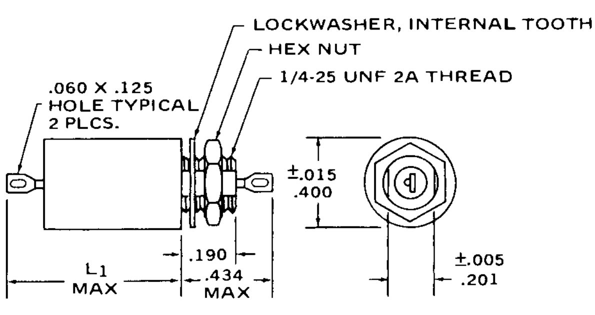
2.1.6 Insertion Loss Calculations for "π" and "T" Section Filters

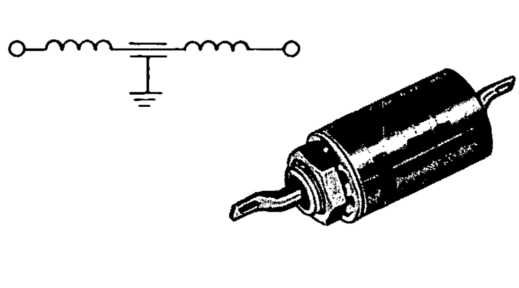
INDUCTIVE INPUT TYPE WITH EXCELLENT REJECTION CHARACTERISTICS

RATINGS

PART NO.	CURRENT AMPS	DCR AT 25°C OHMS	INSERTION LOSS CURVE	L1 MAX INCHES	L2 MAX INCHES
GF51F3A	0.10	3.20	A	.99	.94
GF51F3B	0.50	.66	B	.99	.94
GF51F3C	1	.36	C	.99	.94
GF51F3D	5	.022	D	.99	.94







1. Tolerance: ±0.010 unless otherwise specified.
2. Case material and finish: steel, gold plated (optional).
3. Case marked with Genisco G and part number.
4. Typical weight: 5 to 12 grams.
5. Recommended torque during installation: 40 in. oz.
6. Each filter is supplied complete with lock washer and nut.

Courtesy of Genisco Technology Corp.

Figure 14. Representative Commercial Low-Pass T-Section Filter Characteristics

The equations for the insertion loss of a T-circuit and a pi-circuit as given by Equations (6) and (7) are seen to be identical. The equation has three modes of response. When d equals one, the response is optimally damped and is the ideal (Butterworth) response curve. When d is greater than one, the response is in an overdamped mode. When d is less than one, the response is in an underdamped mode. In the underdamped case, the curve has a maximum in band loss of:

$$IL = 10\log\left(1 + \frac{4D^3}{27}\right) \qquad (8)$$

at the frequency where F = D/3. A minimum loss point will also occur at the frequency where F = D.

2.1.7 Lossy Line Filters

While the input and output impedances of some filters can be expected to match their intended source and load impedances over a fairly broad frequency range, it is more often the case that such matches will not occur. For example, the input impedance of a powerline filter almost never achieves a match with the impedance of its associated power line. As another example, a transmitter harmonic filter is generally designed to match the transmitter output stage over the fundamental frequency range, but not necessarily at its harmonic frequencies.

Because of such mismatch situations, there have been many cases when the insertion of a filter into a line carrying interference has actually resulted in more, rather than less, interference voltage appearing on the line beyond the point of its application. This deficiency in all filters composed of low loss elements has led to the development of dissipative filters that take advantage of the loss-versus-frequency characteristics of magnetic materials such as ferrites.

One form of dissipative filter uses a short length of ferrite tube with conducting silver coatings deposited on the inner and outer surfaces to form the conductors of a coaxial transmission line. The line becomes extremely lossy at radio frequencies, that is, it has high attenuation per unit length in the frequency range where either electric or magnetic losses, or both, become large. An example of the performance of a lossy line filter of this type is shown in Figure 15.

Dissipative filters of this type are necessarily low-pass. One of the large uses of such filters is in general-purpose power-line filtering, in which the dissipative filter is combined with conventional low loss elements to obtain the necessary low cutoff frequency.

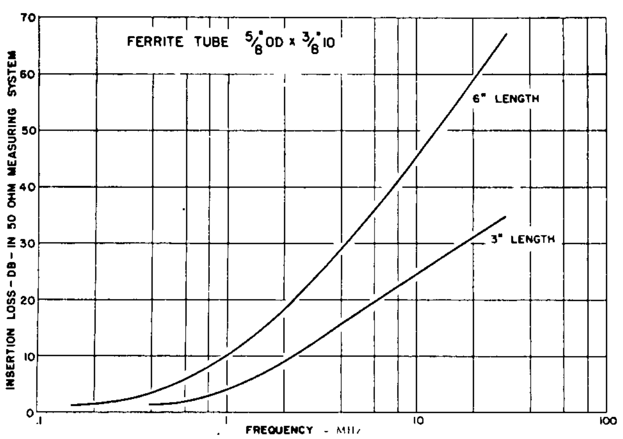
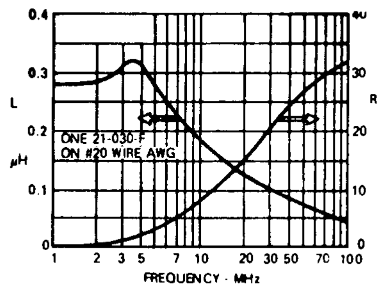


Figure 15. Insertion Loss of a Ferrite Tube Low-Pass EMI Filter



Typical values of equivalent series resistance and inductance attributable to ferrite beads.

TYPICAL PROPERTIES	
Flux Density (B) at 5 O_e	2400 G
Coercive Force (Hc)	0.56 O_e
Hysteresis Factor (h/μ^2)	22×10^{-6}
Initial Permeability (μo)	450
Permeability (μ) at 250G	900
Resistivity - Ohm - cm	$\geq 10^7$
Curie Temperature	$\geq 155\,^\circ C$

Figure 16. Filter Characteristics of Ferrite Beads

SIZES AVAILABLE

Lundy Part No.	Inside Diameter (Inches)	Outside Diameter (Inches)	Tolerance on I.D. & O.D. (Inches)
LST-060	060	150	±.004
LST-080	080	170	±.005
LST-100	100	200	±.006
LST-125	125	.225	± 006
LST-150	150	.250	± 007
LST-175	175	.300	±.008
LST-200	200	325	±.008
LST-225	.225	350	±.010
LST-250	.250	375	± 010
LST-275	275	400	± 010
LST-300	300	450	± 010
LST-325	325	475	± 010
LST-350	350	500	± 010
LST-375	375	525	± 010
LST-400	400	550	± 010
LST-425	425	575	± 010
LST-450	450	600	± 010
LST-475	470	650	± 010
LST-500	500	700	± 010

ATTENUATION CURVES

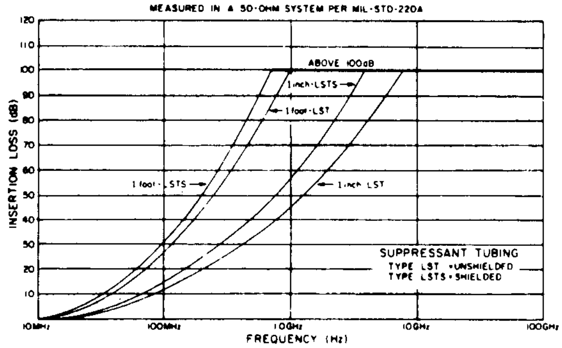


Figure 17. Typical Characteristics of Lossy Line Suppressant Tubing

Another method of achieving a dissipative filter is by use of lossy beads. Tubular ferrite toroids offer a simple, economical method for attenuating unwanted high frequency noise or oscillations. One bead slipped over a wire produces a single-turn RF choke that possesses low impedance at low frequencies and moderately high impedance over a wide high frequency band.

Ferrites are inert ceramics containing granulated iron compounds. They are free of any organic substances, and are not degraded by most environments. Generally, their inductance is small. Because of the high resistivity of ferrite beads, they may be considered insulators for most applications.

The presence of a ferrite bead on the wire causes a local increase of series impedance (largely resistive) presented to currents in the wire. Figure 16 illustrates the effects of one ferrite bead on a length of wire. Adding more or longer beads provides additional units of series inductance and resistance in direct proportion. Extra turns of wire can be passed through the bead, increasing both resistance and inductance in proportion to the square of the number of turns. Because of distributed winding capacitance, this technique is most effective at the lower frequencies.

High amplitude signals below 50 MHz may cause some reduction in the suppression effect due to ferrite saturation. However, as long as only one turn links the core, fairly high currents can be tolerated using representative materials before saturation is approached. At saturation, inductance and resistance will be low, but will return to normal values upon removal of the high field.

Lossy line suppressant tubing also provides an efficient means for suppressing undesired EMI and other spurious signals. The tubing can be slipped over standard wire and cable and suppresses both radiated and conducted energy. It can be used in environments from −55° to +250° C without electrical or mechanical degradation. The tubing will provide shielding from low frequency electrostatic interference and magnetic fields, and will not cause dc or low frequency ac losses. RF power handling capability is in excess of 10 watts/inch of tubing. Representative data on this type of tubing is shown in Figure 17.

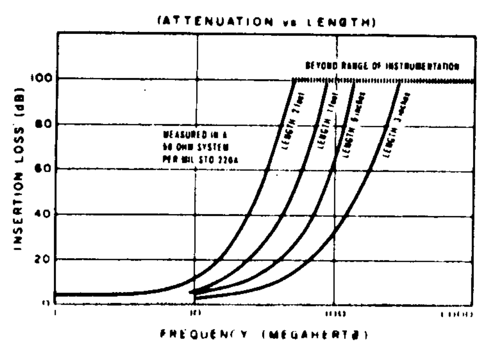
Lossy line coaxial cable can also serve as a dissipative low pass filter. Data on such cables are provided in Figure 18. The lossy media have high rf attenuation and low Q. Short lengths of this cable (perhaps only a few inches long) may be adequate for achieving the desired suppression.

Still another form of ferrite filter that extends the ferrite bead concept is the filtering connector. Lossy filters are built directly into a male connector assembly, and offer low-pass filter performance as shown in Figure 19.

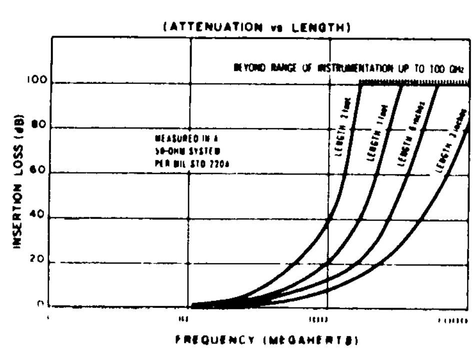
Improvement of high frequency rejection characteristics of a conventional low-pass filter may be obtained by employing a conventional reactive filter in cascade with a lossy line section. This arrangement can provide an overall characteristic having both a rapid cutoff slope and a high-stop band attenuation. An example of the improvement in stop-band attenuation that can be gained by preceding a reactive filter with a lossy line section is illustrated in Figure 20.

Typical Attenuation Curves

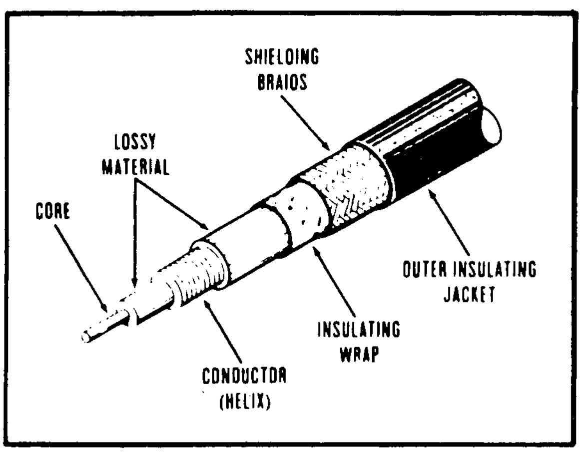
HELIX WOUND CONDUCTOR



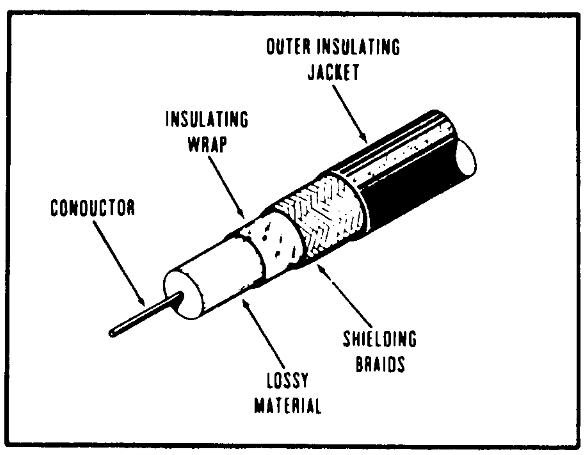
STRAIGHT CONDUCTOR



* Note: Attenuation characteristics vary slightly with different voltage ratings and shielding.



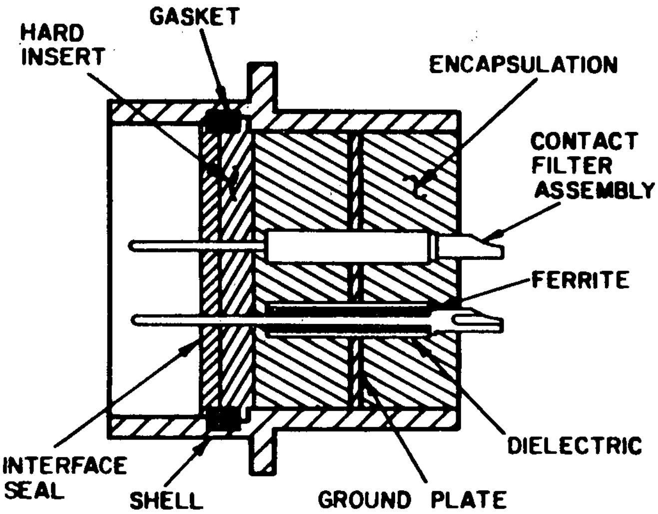
Basic Construction Features of Helix Conductor Flexible Filter



Basic Construction Features of Single Conductor Flexible Filter

Courtesy of Lundy Electronics & Systems

Figure 18. Typical Characteristics of Lossy Coaxial Cable



Minimum Attenuation from −55°C to +125°C and 100 MHz to 10 GHz	50 db
D.C. Working Voltage (includes summation of the D.C. and low level A.C. superimposed peak voltages)	200 VDC @ +125°C
Dielectric Strength (for 5 sec. with charging current of 50 milliamperes maximum)	500 VDC
Feed Through Current (Nominal) D.C. and/or audio frequency RMS	7.5 Amperes
Insulation Resistance	5 Gigaohms
R.F. Current	0.25 Amperes
Operating Temperature Range	−55°C to +125°C
Capacitance (pf)	6500 pf Nominal

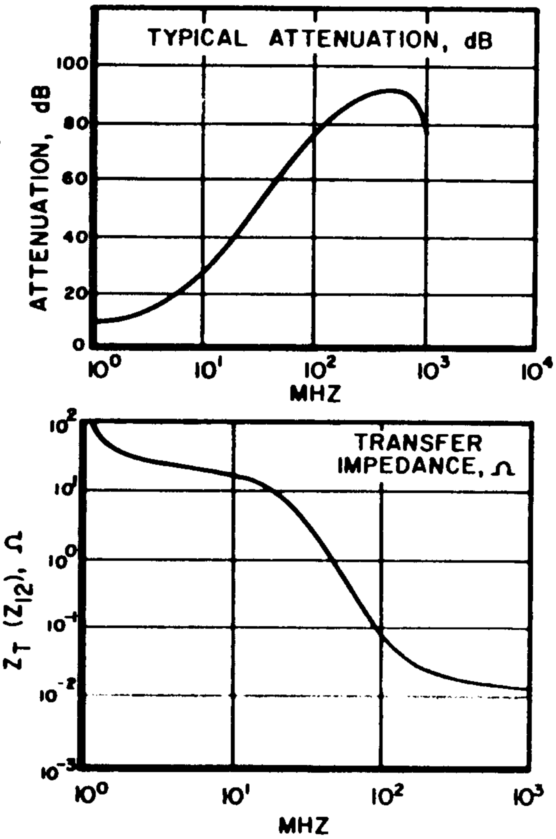


Figure 19. Typical Characteristics of Lossy Connector

Figure 20a shows the performance of a reactive low-pass filter constructed with lumped constant elements. The rapid cutoff at 400 MHz is followed by a high attenuation region between 400 MHz and 3 GHz, but at frequencies above 3 GHz the attenuation is greatly reduced. If the same low-pass filter is preceded by a section of coaxial line whose dielectric space is filled with a 6:1 ratio of iron-to-epoxy dielectric material, the attenuation characteristic is altered to that shown in Figure 20b. The addition of the lossy section has increased the passband attenuation only slightly, but the stop band attenuation has been increased to greater than 60 dB.

When a lossy line section is used in cascade with a conventional low-pass filter, the passband insertion loss can be minimized by the proper choice of the dielectric material. However, there is always some passband loss introduced by the lossy dielectric. Such passband losses can be reduced by designing the reactive filter to have as wide a region as possible between the low-pass cutoff frequency and the first spurious passband, so that a minimum of lossy material is needed to provide the required stopband attenuation.

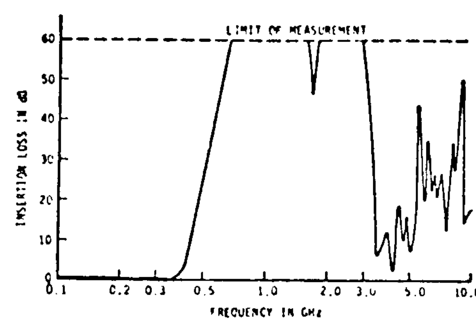


Figure 20a. Typical Low-Pass Filter Loss Characteristics, Low-Pass Filter Only

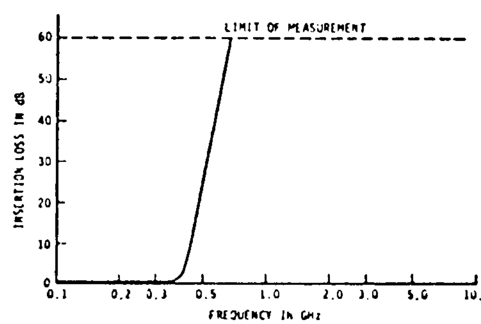


Figure 20b. Typical Low-Pass Filter Plus Lossy Filter Section

2.2 High Pass Filters

Although not as common as the low-pass type, high-pass filters also have an application in EMI reduction. In particular, such filters have been used to remove ac power line frequencies from signal channels and to reject particular lower frequency environmental signals.

Highpass filters can be designed by inverting the high pass filter response requirements, so that they become requirements on a low-pass filter. Low-pass filters meeting this new requirement can be readily transformed back into the highpass filter of interest.

The low-pass filter transforms into a highpass filter by replacing each coil with a capacitor, and vice versa, and by replacing the element values by their reciprocals. Thus, 2 henries become 0.5 Farad, 10 Farads become 0.1 Henry, etc. The attenuation given by the low-pass filter at w, is now given by the highpass filter at 1/w.

For example, a Butterworth low-pass, π-section has the element values shown in Figure 21. The cutoff frequency is 10 kHz. The filter is shown transformed into a highpass filter. A similar transform relative to a T-section filter is also provided.

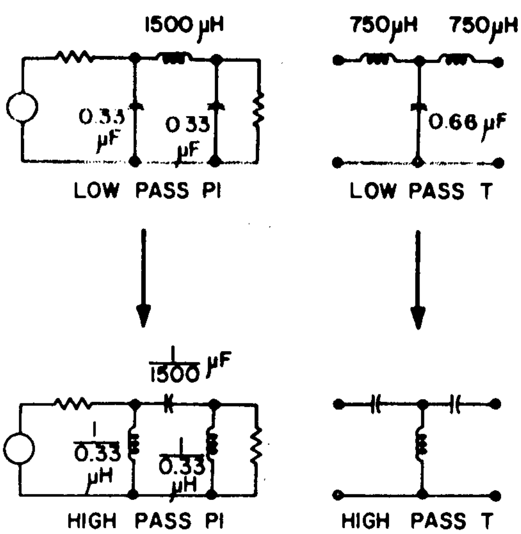


Figure 21. Lowpass to Highpass Transforms

2.3 Bandpass Filters

Each low-pass filter can also be the basis for defining a unique family of symmetrical bandpass filters with known characteristics, and vice versa. Thus, the requirements of a bandpass filter (a filter designed to pass an arbitrary frequency band and reject signals outside that band) can be readily established by use of the following transformation procedure:

a. Convert the desired bandpass filter requirements into low-pass filter requirements. The low-pass prototype has the same 3 dB bandwidth and insertion loss as the bandpass filter.
b. In the case of single section L, T and π filters having 50 ohm input and output impedances, select a low-pass filter with the required attenuation using the two and three element filter design equations discussed.
c. Establish the filter element values in the manner previously described using the rf 3 dB bandwidth value.
d. Resonate each L and C at the required bandpass center frequency.

As an example of this procedure, consider a bandpass filter requirement of a center-tuned frequency at 1.0 MHz, and a skirt roll-off rate of at least 15 dB/octave. The required impedance level is 50 ohms input and output. There is to be no ripple in the pass-band; that is, response should at all points be monotonic. Bandwidth is to be 100 kHz between the -3 dB points.

A three element, Butterworth, low-pass pi-network is selected as the prototype low-pass filter. From Equation (6), it is found that the L and C values for such a filter are 160 μH and 0.03 μF, using a cutoff frequency of 100 kHz and a damping factor of unity.

Each of the above components are next resonated at 1.0 MHz using the relationship

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{9}$$

The result is a 150 pF capacitor in parallel with L, and a 0.8 μH inductor in series with C. The final filter configuration is shown in Figure 22.

Note that the rf filter response is log-frequency symmetrical. That means that the response on a logarithmic frequency axis at some displacement above f_0 is a mirror image of the equivalent displacement below f_0. Alternatively if the attenuation at a frequency xf_0, is N dB, then the attenuation will be the same at f_0/x. For the example above, the band-pass filter cutoff frequencies are shown in Figure 22 as 0.95 and 1.05 MHz, since the logarithmic effect is not evident at frequencies close to the tuned frequency of the filter.

Transformation is thus the essential principle in the design of bandpass filters. It reduces the design to a procedure of specifying the element values of a low-pass filter section and transforming this section into a bandpass filter. In this transformation, a capacitor is added across each coil of a size to resonate the coil at f_0. A coil is added in series with each capacitor of the low-pass filter of a size to resonate the capacitor at f_0.

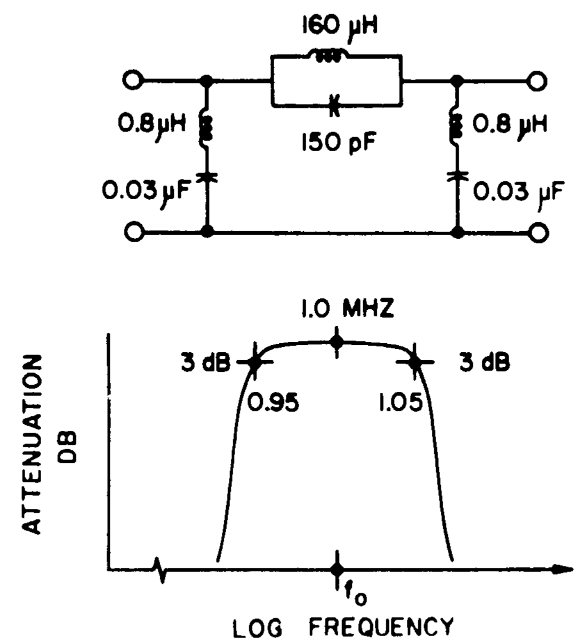


Figure 22. Example of Band-Pass Filter Design

The above approach is conceptually the same for multiple-section bandpass filters, or for filters whose input and output impedances differ, but the process becomes much more complicated. Tabular techniques are available to simplify the process under these circumstances. They are based on first converting the filter requirements to per-unit values (per cycle, per ohm of input impedance, etc.) designing the low-pass filter on that basis, and then converting back to the bandpass equivalent.

Butterworth filters have a maximally flat bandpass response. If some ripple within the pass-band can be tolerated, then a steeper descent into the attenuation band can be obtained. Tchebyscheff filters have a greater roll-off rate than do Butterworth filters for the same number of components, and are generally used in bandpass designs where bandpass ripple can be tolerated. Tabular approaches to the design of Tchebyscheff bandpass filters are also available.

2.4 Band-Rejection Filters

Band-rejection and notch filters are networks that, from an EMC standpoint, are designed to attenuate a specific narrow band of frequencies that may be causing interference problems. This type of device is normally used as a series rejection device between the interference source and the load. An alternative is to use a bandpass configuration that shunts the interference to ground.

Typical applications and locations of band-rejection notch filters include the following:

- At input terminals to reject strong out-of-band interference that would otherwise cause overload.
- At receiver input terminals to reject troublesome image frequencies.
- At receiver input terminals to reject IF-feedthrough signals.
- At transmitter output or interstage terminals to reject harmonics.
- In ac or dc power distribution leads to reject radar PRF, computer-clock surges, or rectifier ripple.
- At audio amplifier input or interstage terminals to reject IF or BFO feedthrough, unwanted heterodynes, signal tones, radar PRF.

A notch filter or wavetrap may take the form of a lumped-constant inductor-capacitor circuit, or it may be a shorted quarter wave coaxial or waveguide stub, or a crystal or ceramic filter lattice. The inductive characteristics of capacitor leads and foil can be planned so that the capacitor acts as a self-contained wavetrap. For frequencies below about 1 MHz, a twin-T resistor-capacitor filter is often found to be an acceptable configuration.

The simplest types of wavetrap are a parallel or series resonant circuit such as those shown in (a) and (b) of Figure 23. The configuration of Figure 23(a) will give a high impedance at the resonant frequency, while the configuration of Figure 23(b) provides a low impedance at resonance. The disadvantages of these circuits are that their skirt fall-off rates are low (6 dB/octave), and they do not present a good impedance match to either the source or load. Band reject performance can be improved by using parallel and series tuned elements in L, π or T configurations, as also illustrated in Figure 23.

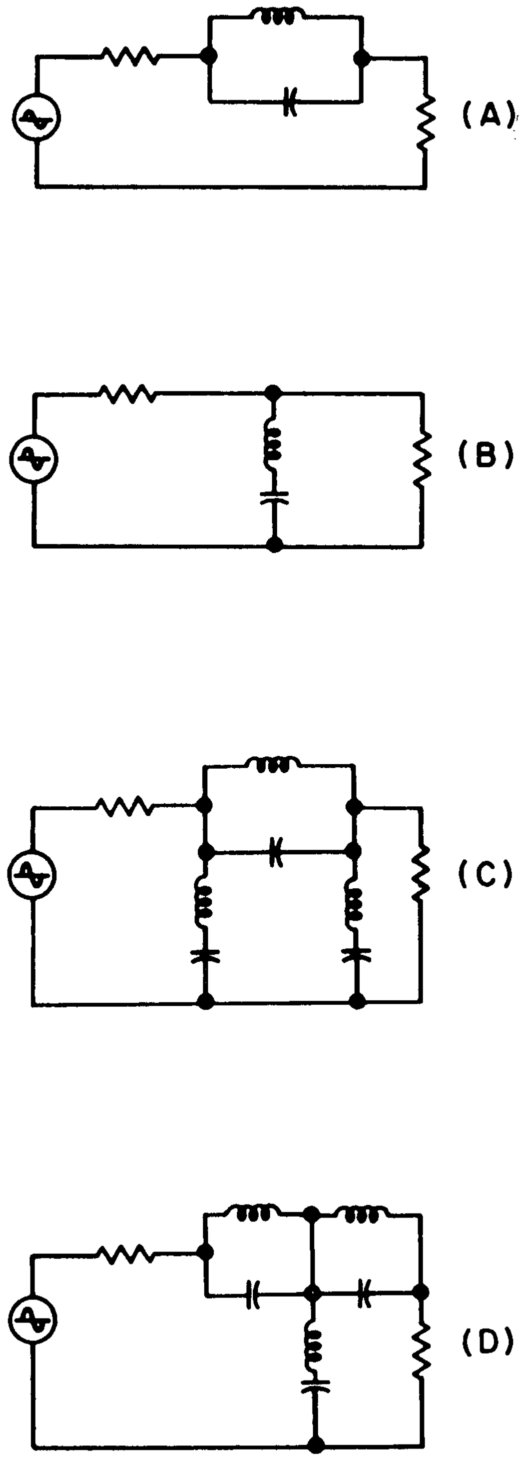


Figure 23. Band-Reject Filter Configurations

The details on the design of the above types of band-reject filters are available in many filter textbooks and handbooks, and will not be discussed here. However, some additional comments are considered appropriate on one particular type of notch filter, because of its wide use in this type of application.

The twin-T notch filter shown in Figure 24 is useful as a band-reject filter in the lower frequency ranges. At low frequencies, the twin-T filter can achieve a circuit Q on the order of 100, which would not be economically feasible for a wavetrap or inductance-capacitance type filter at the same frequency. Shunting effects reduce its usefulness at high frequencies. The notch frequency is determined by:

$$f_n = \frac{0.1592\,K}{(R_1R_2C_1C_2)} \qquad (10)$$

where

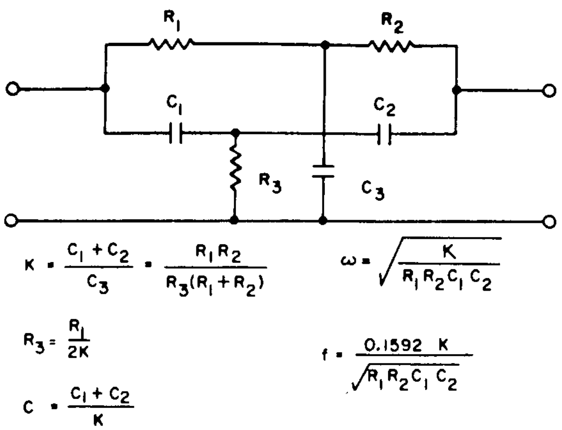


Figure 24. Twin-T Notch Filter

Three special cases are of interest. The case when K = 1 gives the symmetrical form of Figure 25. With K = 1/2, a circuit with three equal resistances as shown in Figure 26 is obtained. In Figure 27, with K = 2, three equal capacitances result.

It should be pointed out that the twin-T notch filter parameters must be accurately selected to obtain attenuation at the null frequency. Getting the best possible null requires careful balancing in network tuning; a convenient way to do this is by use of trim capacitors or potentiometers.

The above article was extracted from NAVAIR AD 115, Chapter 7.

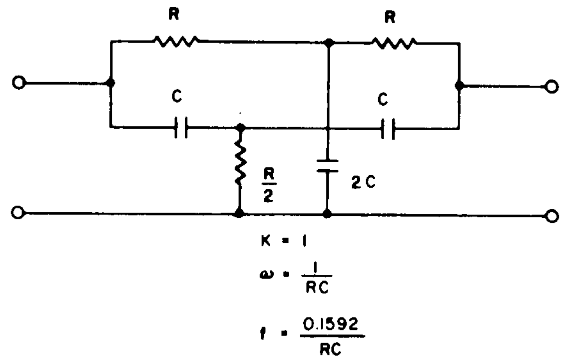


Figure 25. Twin-T Network with K = 1

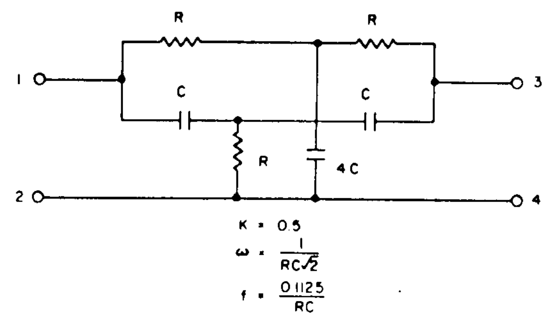


Figure 26. Twin-T Network with K = 0.5

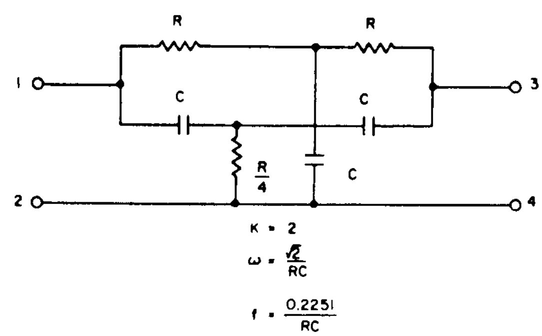


Figure 27. Twin-T Network with K = 2

See LMI on back cover.