TEMPEST

TEMPEST is an unclassified name referring to investigations and studies of compromising emanations. It is sometimes used synonymously for the term "compromising emanations", e.g., TEMPEST tests or TEMPEST inspections. TEMPEST approved equipment or systems are those which have been certified under past or existing TEMPEST specifications or standards.

Historically NAG-1A/TSEC was the earliest TEMPEST standard. NAG-1A was superseded in 1965 by Federal Standard 222, "Radiation Standard for Communication and Other Information Processing Equipment." In 1970 a new series of documents entitled, "National COMSEC/EMSEC Information Memoranda (NACSEM)" replaced Federal Standard 222. These new documents are applicable to equipments in the development stage, during and subsequent to production, and after any modification.

The Defense Communications Agency (DCA) has also issued a series of TEMPEST documents concerned with RED/BLACK engineering. The DCA series of documents will be replaced in the near future by a new Military Handbook (MIL-HDBK-232), Military Standardization Handbook RED/BLACK Engineering—Installation Guidelines, prepared by the Naval Electronic Systems Command.

Since the above TEMPEST documents carry security classifications, they are available only to qualified contractors with security cleared facilities and an established need-to-know. The need-to-know must be established with the contracting Government Organization who will authorize the release of the TEMPEST documents to the contractor. The need-to-know can be established when there is a contract for equipment which must meet TEMPEST requirements. If there is no contract of this type, the contractor must be able to show that the release of TEMPEST documents to him would be of direct benefit to the Government in the future.

Commercial firms with TEMPEST related Government contracts should address inquiries pertaining to TEMPEST to their contracting Government Department or Agency. Commercial firms with no TEMPEST related contracts should address inquiries pertaining to TEMPEST to a Government Department or Agency with whom they have (or have recently had) a classified contract, or (if no such contract exists or has recently existed) to the Director, National Security Agency, ATTN: S22, Fort George G. Meade, MD 20755.

The Air Force is conducting a school on NACSEM at their Cryptologic Depot in San Antonio, Texas. This is open to employees of private organizations under contract with the Air Force. An Air Force contractor desiring training for his employees must forward a written request to the major air command or designated subcommand supervising the contract for which the training is necessary, at least 30 days before the date training should begin (refer to paragraph 112, AFT 205-1). If the contractor does not have a current contract but can show that the training would be of direct benefit to the Government in the future, he may forward his request to Headquarters, U.S. Air Force Security Service, ATTN: SRE, San Antonio, Texas 78243. They will evaluate each request on a case by case basis. It should be pointed out that generally the Government will not pay for such training.

The RED Analog Signal Line Conduction Limits and Digital Signal Line Conduction Limits of NACSEM 5100 are unclassified. These limits for the various categories A through G are shown in Figure 1 and 2. Note that the analog signal limits are given in dB above one microvolt r.m.s. while the digital signal limits are given in dB above one microampere per meter per MHz equivalent r.m.s. sinewave.

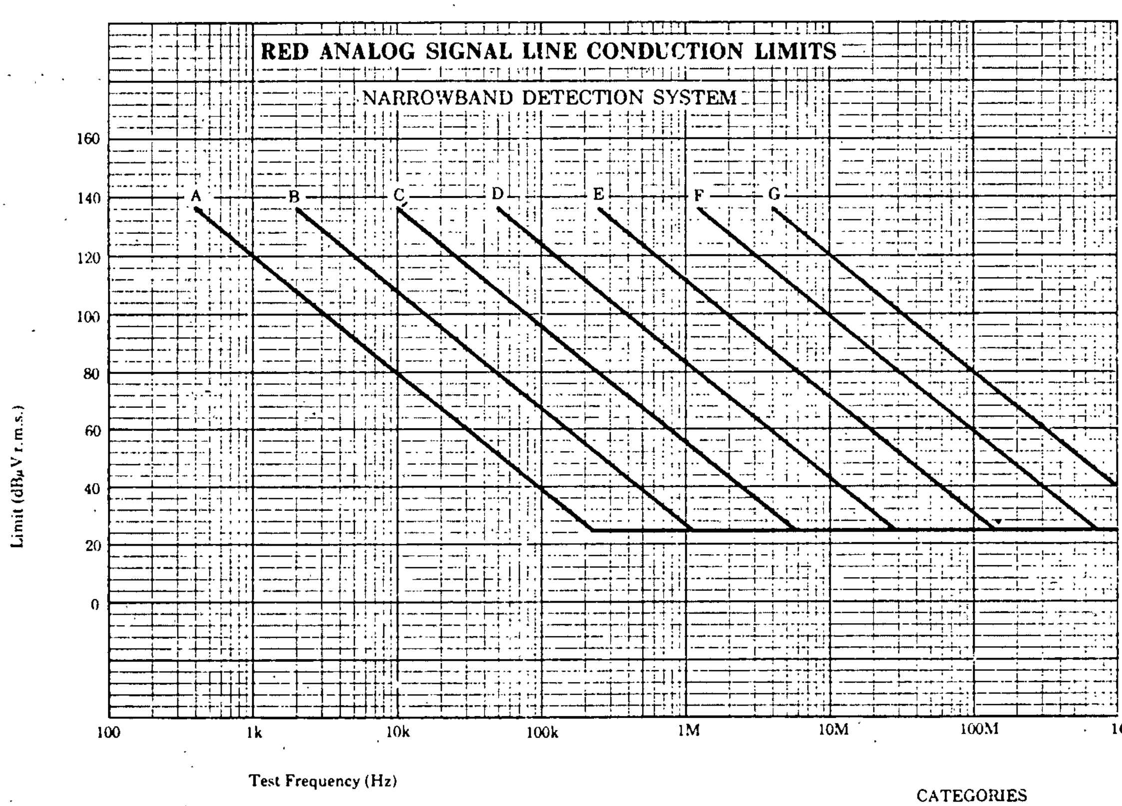


FIGURE 1

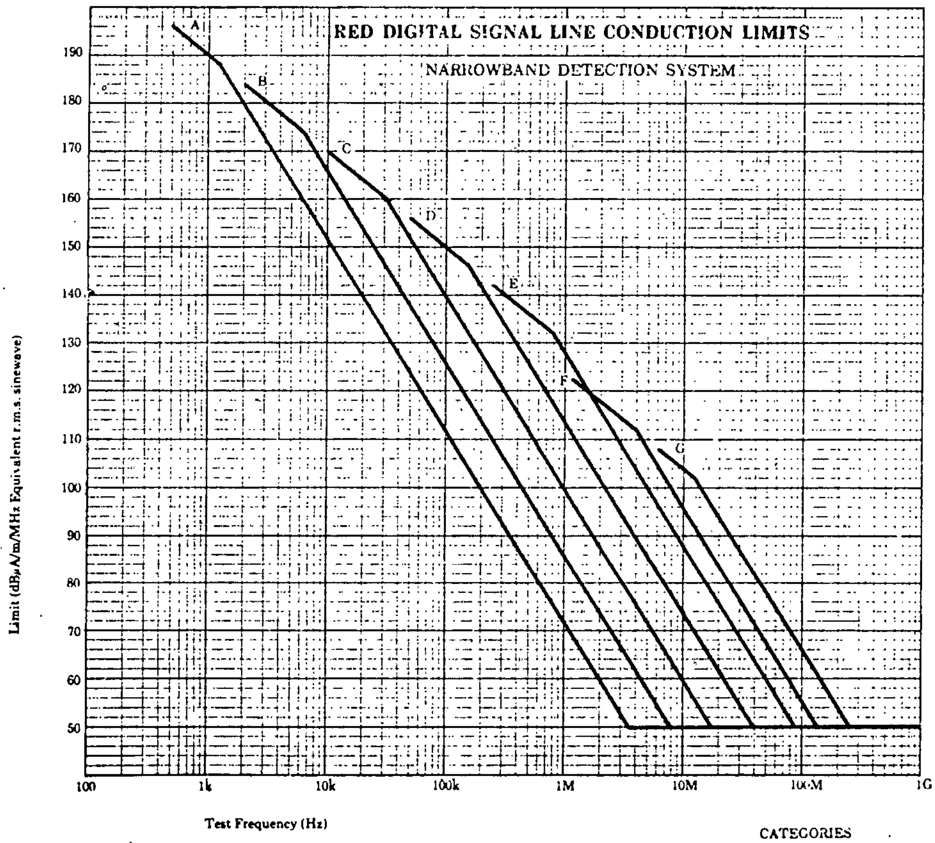


FIGURE 2

TEMPEST TERMS AND DEFINITIONS

Access . . . The ability and opportunity to obtain knowledge or classified information or to be in a place where one could be expected to gain such knowledge.

Alternating Current (AC) Protective Ground System . . . A ground system which provides a low resistance electrical connection to Earth Ground for the protection of personnel and equipment from AC power potentials, lightning hazards, and electrical circuit failures. The integrity of the system is normally insured by the connection of an insulated green colored conductor between the cases and frames of equipments afforded AC power service. The AC protective ground system is therefore often referred to as the Green Wire Protective Ground.

Black Designation . . . A designation applied to wirelines, components, equipment, and systems which handle only unclassified signals, and to areas in which no classified signals occur.

BLACK Equipment Area(s) (BEA) . . . The space within a Limited Exclusion Area (LEA) which is designated for installation of BLACK information-processing equipment, power, signal, control, ground feeder and distribution facilities

Classified Intermediate Distribution Frame (CIDF) . . . An Intermediate Distribution Frame used for RED wiring.

Combined Distribution Frame (CDF) . . . A distribution frame which serves as both a Main Distribution Frame and Intermediate Distribution Frame.

Communications Security . . . The protection resulting from all measures designed to deny unauthorized persons information of value which might be derived from the possession and study of telecommunications, or to mislead unauthorized persons in their interpretations of the results of such possession and study.

Compromise . . . Any occurrence which results in unauthorized persons gaining access to classified or other information requiring protection.

Compromising Emanation . . . Unintentional data-related or intelligence-bearing signals which, if intercepted and analyzed, disclose the classified information transmitted, received, handled or otherwise processed by any information-processing equipment.

Conducted Signals . . . Electromagnetic or acoustic signals propagated along wirelines or other conductors.

Controlled Access Area (CAA) . . . The complete building or facility area under direct physical control which can include one or more Limited Exclusion Areas, Controlled BLACK Equipment Areas, or any combination thereof. Spaces within a facility which are not under direct physical control but to which access is controlled (administration offices, halls, restrooms) are not a part of the actual Controlled Access Area but are considered as a part of the overall Physical Control Zone.

Controlled Black Equipment Area(s) (CBEA) . . . A BLACK Equipment Area which is not located in a Limited Exclusion Area but is afforded the same physical entry control which would be required if it were within a Limited Exclusion Area.

Equipment TEMPEST Radiation Zone (ETRZ) . . . A zone established as a result of determined or known TEMPEST equipment radiation characteristics. The zone includes all space within which a successful hostile intercept of Compromising Emanations is considered possible.

Fortuitous Conductor . . . Any conductor which may provide an unintended path for intelligible signals; for example, water pipe, wire or cable, metal structural members, and so forth.

Green Wire Protective Ground . . . See Alternating Current (AC) Protective Ground System.

Hardened Cable Path (HCP) . . . See Intrusiŏn-Resistant Communications Cable (IRCC).

Intrusion-Resistant Communications Cable (IRCC) . . . A cable designed to provide substantial physical protection and electrical isolation for the wirelines making up the information-carrying core. When the protective measures used are devices which detect slight changes in the physical or electrical state of the cable and which provide visible or audible indications at a central control point of attempted intrusion, the cable is known as an Alarmed Cable. When the protective measures used are physical protection to provide a penetration delay factor, the cable is known as a Hardened Cable Path.

Isolation Device . . . A device designated to provide isolation and maximum attenuation of undesired signals with minimum insertion loss and distortion of the desired signal.

Limited Exclusion Area (LEA) . . . A room or enclosed area to which security controls have been applied to provide protection to a RED information-processing systems equipment and wirelines equivalent to that required for the information transmitted through the system. An LEA must contain a RED Equipment Area.

Normal Input Keying . . . Low level keying in which battery to the teletypewriter keying contacts is provided by the crypto-equipment.

Off-Line Crypto-Operation . . . Encryption or decryption performed as a self-contained operation distinct from the transmission of the encrypted text, as by hand or by machines not electrically connected to a signal line. See On-Line Cypto-Operation.

On-Line Crypto-Operation . . . The use of crypto-equipment that is directly connected to a signal line, making encryption and transmission, or reception and decryption, or both together, a single continuous process. See Off-Line Crypto-Operation.

Physical Compromise . . . The compromise of information through loss, theft, capture, recovery by salvage, defection of individuals, unauthorized viewing or photography, or by any other physical means.

Physical Control Zone (PCZ) . . . The space surrounding equipment processing classified information, which is under sufficient physical and technical control to preclude a successful hostile intercept of any classified information from within this space.

Protected Wireline Distribution System . . . A communications system to which electromagnetic and physical safeguards have been applied to permit secure electrical transmission of unencrypted classified information, and which has been approved by the cognizant department or agency. The associated facilities include all equipment and wirelines so safeguarded. Major components are wirelines, subscriber sets and terminal equipment. Also known as Approved Circuit.

RED/BLACK Concept . . . The concept that electrical and electronic circuits, components, equipments, systems, and so forth, which handle classified plain language information in electric signal form (RED) be separated from those which handle encrypted or unclassified information (BLACK). Under this concept, RED and BLACK terminology is used to clarify specific criteria relating to, and to differentiate between such circuits, components, equipments, systems, and so forth and the areas in which they are contained.

RED Equipment Area (REA) . . . The space within a Limited Exclusion Area (LEA) which is designated for installation of RED information processing equipment, power, signal, control, ground feeder and distribution facilities.

Signal Ground Point . . . A single designated point in a station to which all RED/BLACK grounds are either directly or indirectly connected. This point serves as the common zero potential reference for the station.

Signal Ground Reference Plane . . . An intermediate focal point between an equipment and the Signal Ground Plane for terminating an equipment's or Terminal System's RED or BLACK ground circuits. The Signal Ground Reference Plane is isolated from the equipment's AC Protective Ground and is connected to the Signal Ground Plane by a Signal Ground Bus.

Signal Ground Reference Point . . . Same as a Signal Ground Reference Plane but serving one of several Limited Exclusion Areas device or equipment or Terminal System.

Signal, Quasi-Analog . . . A quasi-analog signal is a digital signal, after conversion to a form suitable for transmission over a specified analog channel. The specification of an analog channel would include frequency range, frequency bandwidth, signal-to-noise ratio and envelope delay distortion. When this form of signaling is used to convey message traffic over dialed-up telephone systems, it is often referred to as voice data.

Single Point Ground . . . The basic technique used in RED/BLACK installations in which separate ground conductors are used for the various grounding functions (signal, power, hazard, and so forth) with each conductor connected directly or indirectly to a single point (Signal Ground Point).

Spurious Signals . . . Undesired signals appearing external to an equipment or circuit. They may be harmonics of existing desired signals, high frequency components of complex wave shapes, or signals produced by incidental oscillatory circuits.

TEMPEST . . . An unclassified short name referring to investigations and studies of compromising emanations. It is sometimes used synonymously for the term "comprising emanations"; for example, TEMPEST tests, TEMPEST inspection.

TEMPEST Approved Equipment or Systems . . . Equipment or systems which have been certified under existing (NACSEM 5100, KAG-30A, or DCAC 370-D195.2) or past (FED-STD-222) TEMPEST specifications as determined by the command or agency concerned.

TEMPEST Inspection . . . A general term which encompasses various means for conductng facility evaluations to determine the adequacy of TEMPEST control measures; for example, installation-engineering surveys.

TEMPEST Test . . . A laboratory or on-site (field) test to determine the nature and amplitude of conducted or radiated signals containing compromising information. A test normally includes detection and measurement of these signals, and analysis to determine correlation between received signals and potentially compromising transmitted signals.

Terminal Control Unit (TCU) . . . The device in an integrated complex of units constituting a complete Terminal System (TSY) which serves as the single interface point between the TSY and wireline distribution facilities of the Limited Exclusion Area. For example, the control device of a data terminal complex which has card or tape or card and tape devices and which control device is the single interface to the station wireline distribution facilities is considered, for engineering-installation purposes, as the Terminal Control Unit.

Timing Line . . . Line intended for the transmission of timing information, clock pulses, and crypto step.

Uncontrolled Access Area (UAA) . . . The area external or internal to a facility over which no personnel access controls can be or are exercised.

Vocoder . . . A vocoder (voice-operated coder) is a device used to compress the frequency bandwidth requirement of voice communications. It consists of an electronic speech analyzer which converts the speech waveform to several simultaneous analog signals and an electronic speech synthesizer which produces artificial sounds in accordance with analog control voltages.

L-C FILTERS FOR TEMPEST TESTING

Introduction

The TEMPEST or EMI/RFI test engineer frequently finds it necessary to use filters having specific cutoff frequencies to completely fulfill the requirements of the usual TEMPEST or EMI/RFI test specifications. These filters may be required to provide a specific bandwidth for non-tunable detection systems, to protect receiver input stages from front end overload caused by high level out-of-band signals, or to provide general-purpose filtering of signal or control lines of an equipment under test (EUT). One course of action for the test engineer is to design and construct these filters himself since the desired performance characteristics are usually satisfied by relatively simple design and construction techniques. However, unless the test engineer is well acquainted with filter design procedures, it is not likely that an optimum design can be quickly realized. This problem can be eliminated by using a tabulation of pre-designed filters which have been selected to meet the majority of everyday needs. The filter design tabulation to be discussed herein is based on computer calculated designs in which only standard capacitor values are needed. This simplifies construction of the filter.

Criteria Used in the Filter Selection

Thirty-two designs (16 low-pass and 16 high-pass) of 5-element filters are listed in Table 1. All designs were normalized for 50-ohm terminations and the designs were selected to cover the 0.1 to 1 MHz frequency decade. In selecting these designs, the variables of cutoff frequency, VSWR, component values, number of filter elements, filter input impedance, and input and output termination resistance were all considered. The tabulated designs are believed to be a satisfactory compromise of all these variables so the resulting filter design is optimally suited for the majority of the filter requirements.

Cutoff Frequencies: Sixteen cutoff frequencies, approximately equally spaced throughout the 0.1–1 MHz decade, were selected to provide at least one filter design within 10% of any cutoff frequency that may be desired. The customary 3 dB cutoff frequency is listed as this value was the parameter used in designing the filter. The 6 dB cutoff frequency is also listed as this parameter is specified in most TEMPEST test specifications. Filters having cutoff frequencies outside 0.1–1 MHz or termination resistances other than 50 ohms can be obtained by a simple scaling process described later.

Voltage Standing Wave Ratio (VSWR): Attempts were made to minimize the VSWR value to provide a filter design having a relatively constant input impedance. VSWR is the ratio of the actual filter input impedance (with the filter correctly terminated at its other end) to the nominal termination impedance. The low-pass filter VSWR is no greater than 1.041 and the high-pass filter VSWR is no greater than 1.247. These low values of VSWR allows the cascading of low and high-pass filters to provide a bandpass response, but the passband must be greater than one octave to prevent undesired interaction of the filter elements. When used in a bandpass configuration, each filter will operate as expected if it is correctly terminated. This condition will be realized with the tabulated filters because of their relatively constant input impedance within their passband frequency range.

Standard Capacitor Values: To simplify filter construction, only those designs requiring standard capacitor values are tabulated. In addition, whenever feasible, those filter designs with inductance values closest to the standard inductance values were chosen for tabulation. The need for standard inductor values, however, is not too important since inductors are usually conveniently hand wound to the exact design value. Standard commercial unpotted toroidal inductors can be modified by the removal of turns to achieve a desired inductance value.

5-Element Configurations: Any number of filter elements could have been specified in the filter tabulation, but as a compromise between good attenuation roll-off and circuit complexity, the five-element filter was selected. The typical TEMPEST test specification requires band limiting filters having an attenuation roll-off of 40 dB/decade which is equal to 12 dB/octave. This non-stringent requirement could easily be met with a 3-element filter having a roll-off of 18 dB/octave but the 30 dB (or more) per octave attenuation of the 5-element filter will allow the filter to be used for other filtering applications where better skirt selectivity is desired.

FILTER INPUT IMPEDANCE

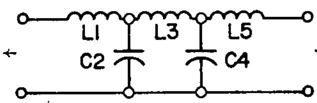
Attenuation of frequencies in the filter stopband is obtained by the reactances of the filter providing either a very low shunt impedance to ground or a very high series impedance between source and load. The input reactances of the filter can therefore be either a shunt or a series reactance. It is important that the filter input impedance be considered and the proper input reactance be selected because the type of input impedance has a definite effect on the performance of the filter when it is applied to TEMPEST or EMI/RFI testing. From a TEMPEST standpoint, it is desirable that both the low-pass and high-pass filters have an input impedance that increases as the frequency proceeds into the stopband region. In the low-pass filter, this effect is achieved with an inductor input and in the high-pass filter, with a capacitor input. This means that for the low-pass filter, three inductors and two capacitors are needed for the 5-element filter configuration instead of the more familiar alternate arrangement of three capacitors and two inductors. The three inductor filter is more bulky, more costly, and has higher losses than the alternate configuration but the high input impedance in the filter stopband is too important a characteristic to compromise. The inductive input of the low-pass filter will tend to eliminate high level circulating ground currents of stopband frequencies which if permitted to occur (as with a capacitor input filter) might cause spurious signal coupling problems in the test setup. The avoidance of such problems is extremely important because of the very low signal levels being sought. This condition makes the test setup very sensitive to the presence of any spurious signals.

The characteristic of high input impedance is also applicable to the high-pass filter. In this case, the input filter reactance is a series capacitor and this has a number of useful properties. First, the input capacitor in the high-pass filter has the desired effect of providing an increasing filter input impedance as the frequency proceeds into the filter stopband. Second, the input capacitor provides d.c. blocking which is advantageous in many applications. And third, by maximizing the number of capacitors and minimizing the number of inductors the losses in the filter passband are reduced. The high input impedance characteristic of the capacitor-input high-pass filter is particularly useful in TEMPEST and EMI/RFI testing where the levels of spurious line conducted signals are measured by connecting a 50-ohm detection system to various data, clock, control, and power lines. If the levels of the spurious signals present on these lines are excessive, they may cause a malfunction in other equipments or may compromise the security of the component. It is therefore important that the levels of these spurious signals be determined, but the measurement of the levels must be made in such a manner that operation is not affected by the connection of the 50-ohm detection system to any of the lines being tested. Also, it is important that the detection system not be saturated or "blocked" by any d.c. voltages or high level baseband data or clock signals that might be present on any of the lines being tested.

A coupling device for the detection system is needed which includes (1) a d.c. block, (2) a high input impedance to the EUT baseband frequencies (preferably an input impedance more than three times the source impedance of the line being tested), and (3) a transmission characteristic that will attenuate the baseband frequencies by 90 dB or more before reaching

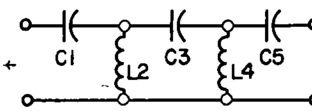
Table 1. Component Values and VSWR for .1 to 1 MHz Filters

LOW-PASS FILTERS



f_{co} (MHz)		VSWR	L1, 5	L3	C2, 4
3 dB	6 dB		μH		μF
0.103	0.115	1.000	47.8	155.0	.050
0.110	0.123	1.000	44.9	145.0	.047
0.132	0.147	1.000	37.3	121.0	.039
0.156	0.174	1.000	31.5	102.0	.033
0.180	0.196	1.041	37.5	88.0	.030
0.20	0.22	1.041	33.8	79.1	.027
0.23	0.26	1.000	21.0	68.0	.022
0.29	0.32	1.000	17.2	55.7	.018
0.30	0.33	1.041	22.5	52.7	.018
0.36	0.39	1.041	18.8	43.9	.015
0.43	0.48	1.000	11.5	37.1	.012
0.45	0.49	1.041	15.0	35.2	.012
0.54	0.59	1.041	12.5	29.3	.010
0.66	0.72	1.041	10.3	24.0	.0082
0.76	0.84	1.000	6.50	21.0	.0068
0.87	0.95	1.041	7.76	18.2	.0062

HIGH-PASS FILTERS



f_{co} (MHz)		VSWR	C1, 5	C3	L2, 4
3 dB	6 dB		μF		μH
0.105	0.097	1.073	.033	.015	45.0
0.123	0.115	1.247	.022	.012	40.4
0.134	0.124	1.051	.027	.012	34.8
0.158	0.141	1.000	.033	.010	31.5
0.182	0.171	1.235	.015	.0082	27.1
0.20	0.189	1.151	.015	.0075	23.8
0.24	0.22	1.062	.015	.0068	19.9
0.29	0.27	1.073	.012	.0056	16.4
0.33	0.31	1.094	.010	.0047	14.3
0.37	0.34	1.041	.010	.0043	12.5
0.40	0.37	1.094	.0082	.0039	11.7
0.49	0.45	1.020	.0082	.0033	9.51
0.58	0.54	1.105	.0056	.0027	8.19
0.63	0.56	1.000	.0082	.0025	7.82
0.75	0.71	1.174	.0039	.0020	6.44
0.84	0.79	1.210	.0033	.0018	5.75

the detection system input but which will also pass the signals in the frequency range of interest with little attenuation. When the frequency range to be evaluated is several octaves or more above the EUT baseband signal frequency, the capacitor-input high-pass filter makes an excellent coupling device.

Termination Resistance

The tabulated filters were all designed for 50-ohm terminations because the majority of detection systems and signals lines use this impedance level. The input and output termination values were made identical because this condition occurs most frequently in filtering applications. Also, the use of equal termination values causes elements #1 and #5 to have identical values as do elements #2 and #4 in both the low and high-pass filters. This characteristic of equally terminated filters facilitates the construction.

The filter output will be correctly terminated by the 50-ohm detection system; however, the termination impedance at the filter input will depend on the source impedance of the line being tested. The impedance of the line being tested can be as low as six ohms or as high as 400 ohms before the filter attenuation performance is significantly changed. When the line impedance becomes less than six ohms, an undamped resonance effect between the input reactance and the remainder of the filter reactances causes an undesired rise in signal level up to 13 dB to occur to signals at frequencies near the cutoff frequency. Because most lines tested will have some source resistance and there will usually be resistive losses associated with the filter inductors, this extreme condition probably will not occur. Nevertheless, the test engineer should anticipate this possibility. If an unexpected and unaccounted rise in signal level is observed in the vicinity of the filter cutoff frequency, this condition can be eliminated by installing a 6.8-ohm resistor in series with the filter input reactor. This added resistance will sufficiently damp out the resonant effect without appreciably reducing the detection system sensitivity.

Attenuation Slope Vs. VSWR

The attenuation slope of a 5-element filter with a VSWR of 1.000 is equal to 30 dB/octave. This filter type is commonly called a "Butterworth" filter. The attenuation slope of filters having a VSWR greater than 1.000 will be greater than 30 dB/octave and the slope will increase with increasing values of VSWR. The filters used in the tabulation with VSWR's greater than 1.000 are the "Chebyshev" type. They have equi-ripple attenuation in the passband and a constantly increasing attenuation response in the stopband. The low-pass filter designs have only two VSWR values, that of 1.000 and 1.041. The high-pass filter tabulation required a larger selection of VSWR values to adequately cover the 0.1–1 MHz frequency decade. For this reason, thirteen different VSWR values are listed, ranging from 1.000 to 1.247. The relationship between the filter attenuation, frequency, and VSWR is shown in Table 2. Approximately one octave from the cutoff frequency the attentuation slope assumes a constant value of 30 dB/octave. The attenuation versus frequency for any of the tabulated filters can therefore be closely approximated if the VSWR and the 3 dB cutoff frequency are known.

HOW TO USE THE FILTER TABLES

Before a filter design can be selected from the tables, the filter type, termination resistance, and cutoff frequency (either the 3 or 6 dB value) must be known. The component values for designs with 50-ohm terminations and a cutoff frequency in the 0.1–1 MHz frequency decade are read directly from Table 1. The filter elements are connected in accordance with the schematic diagram shown at the top of the table. If the desired cutoff frequency does not exactly agree with any of the tabulated values, a tabulated design having a cutoff frequency nearest to the desired frequency will have to suffice. For termination resistances other than 50 ohms and cutoff frequencies outside the 0.1–1 MHz range, use the scaling equations shown below. However, to retain the new capacitor values in standard sizes, the resistance or frequency multipliers must each be an integral power of ten. For example, if a 500-ohm, 2 kHz (3 dB) lowpass filter is required, the resistance and frequency multipliers are R=10 and $F=10^{-2}$. The tabulated 0.20 MHz low-pass filter design would be selected for scaling. The corresponding inductance and capacitance values–33.8 uH, 79.1 uH, and .027 uF–after scaling become 33.8 mH, 79.1 mH, and .27 uF, respectively.

SCALING EQUATIONS–For cutoff frequencies outside the 0.1–1 MHz range and terminations other than 50 ohms, use the following scaling equations:

$$L' = L\left(\frac{R}{F}\right), \quad C' = \frac{C}{(R)(F)}$$

L′ and C′ = New Component Values

L and C = Tabulated Values

MULTIPLIER

$$R = \frac{R'}{50}$$

where R′ is a new termination resistance chosen to make R an integral power of ten.

MULTIPLIER

$$F = \frac{f'_{co}}{f_{co}}$$

where f'_{co} is a new cutoff frequency and f_{co} is a tabulated cutoff frequency, both chosen to make F an integral power of ten.

If the 500-ohm filter must be installed in a 600-ohm line, two minimum loss, 500/600-ohm L-matching pads should be placed at each end of the filter. Each pad consists of a 240-ohm resistor, connected in series between the filter and the line, and a 1200-ohm resistor, connected across the filter terminals. The total insertion loss of the two pads is approximately 7.5 dB.

Recommended Capacitors

The design of low-pass and high-pass filters has been greatly simplified by the tabulated filter designs; however, the problem of selecting the capacitors and inductors to be used in constructing the filter still remains. For capacitor values greater than .05 μF, the MYLAR dielectric capacitors are suitable. For values of .05 μF and less, the polystyrene type is recommended. This type is available in tolerances of 2.5% and 5%, has excellent temperature and dissipation characteristics (which are superior to MYLAR), and is inexpensive. The dipped silver mica capacitor is also an excellent choice for capacitor values less than 1000 pF. For low-pass filters requiring exceptional stopband performance up to 1000 MHz with no "holes", the ceramic feed-through or button-mica capacitors must be used. However, the filter case must be constructed so that the inductors are separated by bulkhead partitions with the feed-through capacitors providing the only entrance and exit. This type capacitor is available only in a few standard catalog values and the number of low-pass filter designs are correspondingly restricted. This will generally be no problem since the main purpose of the filter using feed-through capacitors will be to extend the stopband range of another filter having a lower cutoff frequency.

For example, it may be necessary to construct a 500 kHz low-pass filter with its stopband extending to 1000 MHz. The capacitors used for this filter will be in the order of .01 μF to provide the 500 kHz cutoff. The stopband performance of such a filter may be expected to fail around 40 MHz due to the undesired and unavoidable series inductance associated with foil-wrapped capacitors.

To keep the stopband attenuation above 100 dB or so, a second low-pass filter, specifically designed for high-frequency stopband performance, should be placed in cascade with the first filter. The second filter should have separate compartments for the three inductors and should have bulkhead mounted feed-through capacitors. The cutoff frequency of the second filter is not critical but should be about a decade above the cutoff frequency of the first filter to eliminate undesired interaction between the two filters. Also, the cutoff frequency should be low enough to give the attenuation level of the second filter a chance to build up before the deficient stopband range of the first filter is reached.

The leniency in selection of cutoff frequency allows a design to be chosen in which one of the few readily available button-mica capacitor values can be used. For the example of the 500 kHz low-pass filter, the second filter can have a cutoff between 5 and about 10 MHz. Checking the low-pass filter tabulation, a design for 11 MHz is available which requires two 470 pF capacitors and inductors of .449 and 1.45 μH. This design will be satisfactory and is chosen because the 470 pF button capacitor values are listed in several distributor catalogs and therefore should be readily available. The inductors can be the standard encapsulated chokes with standard catalog values of .47 and 1.5 μH. With a cutoff frequency of 11 MHz, an attenuation level of approximately 60 dB should be reached at four times the 3 dB cutoff frequency (see Table 2), which is 44 MHz. The attenuation of the second filter will continue to rise as the frequency increases and thereby provide the desired additional stopband attenuation to 1000 MHz. Note that the component values of the second filter are so small that they are not significant at 500 kHz and therefore will have no effect on the low frequency performance of the first filter.

Recommended Inductors

The hand-winding of toroidal inductors is generally the most convenient procedure to use for obtaining the many odd values of inductance required for filter construction. Inductors with Q greater than 50 and inductance values from .1 μH to 200 μH can be obtained using inexpensive toroidal cores costing between 19 and 50 cents each. In addition to the satisfactory Q, the toroidal coil is essentially self-shielding and this characteristic minimizes coupling to adjacent components. For inductance values greater than 200 μH, the hand winding of the toroidal core becomes unreasonably tedious and the pot core inductor should be considered for use as it is easier to wind when more than 100 turns are involved. If commercial toroidal inductors are purchased, it is recommended that the upotted type be ordered so the inductance value can be changed for different applications by simply adding or removing turns. As the filter designer becomes more experienced, he will develop his own techniques to obtain the many different high Q inductors required for the construction of his filters.

A 60-page booklet, *Q curves for Iron Powder Toroidal Cores* is available from Micrometals[1] for a nominal charge. In this booklet, Q versus frequency curves are plotted over the 10 kHz to 400 MHz range. The core type and winding specifications are included for each curve.

To get inductance values between 2 mH and 88 mH, use the 44 mH and 88 mH telephone line loading coils now available from several distributors specializing in surplus electronic components. These unpotted toroidal inductors (1-1/4," O.D., by 5/8" Ht.) have two windings which may be wired in series or parallel. One type inductor will provide either 22 or 88 mH for the parallel or series connection. The other type will provide either 11 or 44 mH. Because the inductors are unpotted, it is easy to remove turns to get any value of inductance between 2 mH and 88 mH with reasonable Q. These inductors are useful for constructing filters with cutoff frequencies in the 1 kHz to 20 kHz range.

[1]Micrometals, 228 North Sunset, City of Industry, California 91744

Filter Assembly

After the required inductors and capacitors have been obtained they must be interconnected and assembled in some form of protective box. The standard BUD aluminum mini-box is a simple and inexpensive case but holes must be placed in both ends for the input and output connectors and a ground lug must be installed for the grounding of the shunt filter elements. Another possibility is the use of a specially designed electronics packaging system from MODPAK[2] consisting of a nickel-plated aluminum case, two connectors and special grounding clips for p-c board installation. Special features of the MODPAK system permit the case to be used with microstrip p-c board construction which is necessary for high-pass filters requiring passbands to 1 GHz.

An example of a low-pass filter assembly is shown in Figure 1 where the MODPAK case Model 7081 is used to contain a 1.56 MHz low-pass filter. The inductors are cemented to the blank side of a 1/16" thick strip of G10 epoxy-glass single sided p-c board. The board is mounted between and soldered to the grounding clips of the case. The shunt capacitors are grounded to the copper foil on the under side of the p-c board. In spite of the open construction, the filter stopband (75 dB or more) extends to 100 MHz.

CONCLUSION

The design and construction techniques discussed in this article have been found to be satisfactory in meeting most of the filtering requirements encountered by the author in his TEMPEST test work over the past five years. It is hoped this information will be useful to others involved in similar types of work which require the use of simple passive L-C filters. Any comments, suggestions, or criticisms will be appreciated, and should be directed to E.E. Wetherhold, 102 Archwood Ave., Annapolis, Md. 21401.

[2]MODPAK[tm] 31A Green St., Waltham, Mass. 02154

BIBLIOGRAPHY

1. *Simplified Modern Filter Design,* Philip R. Geffe, John F. Rider Publisher, Inc. New York, 1963
2. *The Design of Filters Using the Catalog of Normalized Low-Pass Filters,* R. Saal, Telefunken Gmbh, Backnang (Wurtt.), Western Germany, 1966
3. *Handbook of Filter Synthesis,* Anatol I. Zverev, John Wiley and Sons, Inc. New York, 1967
4. *Inductance and Q of Modified Surplus Toroidal Inductors,* E.E. Wetherhold, QST, September 1968, p.p.36-39
5. *Design Your Own Filter by Computer,* E.E. Wetherhold, & H.A. Lee, Jr., ELECTRONIC DESIGN, January 20, 1972, pp 48-50
6. *Pick a Filter From This Chart,* E.E. Wetherhold, ELECTRONIC DESIGN, November 23, 1973, pp 166-167
7. *The RF Capacitor Handbook,* Vincent F. Perna, Jr. American Technical Ceramics
8. *To You it's a capacitor–but what does the circuit see?* , V.F. Perna, Jr. and S.J. Klein, EDN, November 5, 1973, pp 54-58
9. *Q Curves For Iron Powder Toroidal Cores,* Micrometals 228 North Sunset, City of Industry, California 91744
10. *Use ECL for your high-speed designs* (Design equations for microstrip construction), Lloyd Maul, EDN, July 20, 1973, Figure 3, page 34.

The above filter article has been prepared by E.E. Wetherhold, Senior Engineer, Honeywell Inc., P.O. Box 391, Annapolis, Md. 21404.

Figure 1. 1.56 MHz Low-pass Filter Installed in MODPAK Case 7081