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MILITARY HANDBOOK

NASA PARTS APPLICATION HANDBOOK

(VOLUME 4 OF 5)

CRYSTALS, FILTERS, TRANSFORMERS, INDUCTORS, DELAY LINES, MOTORS

AMSC N/A FSC 59GP

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON, D.C. 20546

NASA Parts Application Handbook

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FOREWORD

This handbook provides a technological baseline for parts used throughout NASA programs. The information included will improve the utilization of the NASA Standard Electrical, Electronic, and Electromechanical (EEE) Parts List (MIL-STD-975) and provide technical information to improve the selection of parts and their application, and failure analysis on all NASA projects. This handbook consists of five volumes and includes information on all parts presently included in MIL-STD-975.

This handbook (Revision B) succeeds the initial release. Revision A was not released. The content in Revision B has been extensively changed from that in the initial release.

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8. CRYSTALS

8.1 Introduction. Crystals are not listed in MIL-STD-975, NASA Standard Electrical, Electronic, and Electromechanical (EEE) Part List, but are included in this handbook. Because of the complexity of quartz crystal technology and the variety of application techniques, the information contained herein is restricted to brief reviews of basic design considerations and application factors of crystal units and crystal oscillators.

Both natural and cultured quartz are used for frequency control. Most natural quartz comes from Brazil. Cultured (or synthetic) quartz is grown at several domestic facilities. Natural quartz is variable in size and shape with numerous flaws and inclusions whereas with cultured quartz, the major axis of growth is predetermined and the quality is essentially uniform throughout the stone. Processing natural quartz into resonators of critical dimensions and crystallographic angular orientation is much more labor intensive and wasteful of of material than cultured quartz.

Quartz is useful in the electronics field because it is not only piezoelectric, but also has very stable physical properties and useful behavior over wide temperature ranges. The piezoelectric effect causes an electrical potential difference to appear between two opposite faces of a quartz plate when the plate is mechanically stressed and, conversely, causes mechanical stress and movement to be generated in the quartz plate when a potential difference is applied to two opposite sides.

Quartz plates cut to proper dimensions and appropriately mounted will vibrate in mechanical resonance at the frequency of an alternating voltage applied to opposite faces of the plates. The unusually high stiffness and elasticity of this very hard crystalline material make it possible to produce electromechanical resonators that will operate over a wide band of frequencies extending to 175 MHz; experimental work is being done to 1 GHz.

During the past few years, the quartz crystal art has advanced by what might be considered two orders of magnitude. Part per million accuracy has advanced to part per hundred million and what was part per hundred million is today part per 10 billion. As more and more basic cause and effect relationships are proven, better predictions of expected performance under widely varying environments may be expected.

8.1.1 General definitions

Accuracy. The degree of precision with respect to a referenced, specific, or nominal value. Accuracy and stability are not directly related, yet they are commonly used incorrectly and interchangeably.

Coupled modes. Also known as activity dips, are vibrational modes which generally manifest themselves over a very narrow temperature range, often as little

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as a fraction of a degree. Coupled modes cause the crystal frequency to decrease, with a simultaneous increase in equivalent resistance; thus, the term "activity dip." Their magnitude, width, and quantity are proportional and highly sensitive to the drive level. They may actually be made to disappear at a low enough drive level. Coupled modes are of concern in crystals used in phase-locked loops and in temperature-compensated oscillators.

Crystal cut. Quartz crystals have three mutually perpendicular axes. The angle of rotation with respect to these axes at which the resonator is cut from the stone determines its electrical parameters, frequency range of feasibility, and temperature characteristics. Most crystal cut designators consist of two letters such as AT and SC.

Crystal holder. The sealed enclosure in which a quartz resonator is mounted; it includes a cover, a base or other means of closure, and suitably insulated pins or leads. It does not include the resonator mounting structure.

Crystal unit. An assembly consisting of a quartz resonator suitably mounted in a crystal holder.

Drive levels.

a. Minimum. The lowest value at which the crystal will oscillate. It is used to minimize internal temperature rise when determining frequency change from before to after a test such as vibration or aging.

b. Rated. The power dissipation level at which the crystal unit is designed to operate within specified tolerances of various electrical parameters. This drive level is generally established in a specific test-set at the maximum allowable equivalent series resistance.

c. Reduced. The name of a test used to determine the ability of a crystal to begin oscillating at a much lower level than the rated drive level (typically less than 10 μW). It is indicative of the cleanliness and surface condition of the quartz resonator. This test generally applies to overtone units.

Equivalent resistance. The equivalent resistance of a crystal unit is defined as follows:

a. For crystal units designed to operate at series resonance, equivalent resistance is defined as the equivalent ohmic resistance of the unit when operating in the specified crystal impedance meter (or other test-set) adjusted for the rated drive level and tuned to the specified crystal unit frequency.

b. For crystal units designed to operate at parallel or antiresonance, equivalent resistance is defined as the equivalent ohmic resistance of the unit and a series capacitor of the specified load value when operating in the specified crystal impedance meter (or other test-set) adjusted for rated drive level and tuned to the specified crystal unit frequency.

Operable temperature range. The temperature range over which a unit designed for controlled temperature conditions is to continue to oscillate (not necessarily within specified performance limits).

Operating temperature range. The temperature range over which a unit is to operate within specified performance limits.

Oscillators. A device which has a specific output frequency and accuracy in relation to specific input power. The three types of oscillators are:

a. OCXO. Oven temperature controlled crystal oscillator (ovenized)

b. TCXO. Temperature compensated crystal oscillator

c. XO. Crystal oscillator.

Reference temperature. The ambient temperature at which certain crystal parameter measurements are made. For controlled temperature units, the reference is the midpoint of the controlled operating temperature range. For noncontrolled temperature units, the reference temperature selected is normally room temperature (23 ±1 °C).

Specified frequency. The nominal frequency at which the crystal unit is designed to operate under specified conditions.

Stability. The amount of change due to a specific event, and it may be transient or permanent. Stability and accuracy are not directly related, yet they are commonly used incorrectly and interchangeably.

Unwanted modes. Also known as spurious modes or spurs. Vibrational modes near the desired mode of oscillation that are intrinsic in many crystallographic designs. They will be similar from unit to unit. Because they are predictable, they can be dealt with in oscillator designs by trapping or filtering, and they are often the limiting factor in filter performance. They are not particularly drive-level sensitive.

8.1.2 Symbols. Some of the symbols commonly used in quartz crystal terminology and associated circuitry are listed below.

C_d — Total distributed capacitance across leads or terminals of a cyrstal unit

C_e — Electrostatic capacitance across the quartz resonator

C_1 or C_M — Motional arm (series-arm) capacitance of a crystal equivalent circuit.

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C_O	Total electrostatic shunt capacitance of a crystal unit
C_L or C_X	Load capacitance in series with a parallel-mode crystal unit
C_T	Total capacitance ($C_O + C_X$) shunting series arm of a crystal equivalent circuit
DRAT	Doubly-rotated AT-cut crystal unit
f_a	Antiresonant frequency of a crystal unit
f_O	Oscillator output frequency, frequency of a crystal unit
f_p	Parallel resonant frequency of a crystal unit
f_r	Resonant frequency of a crystal unit
f_s	Series resonant frequency of a series arm
Δf	Any change in frequency, often used to express difference between f_a and f_r; i.e., bandwidth
L_M	Motional arm (series arm) inductance of a crystal unit
Q	Quality factor $\frac{1}{\pi F C_M R_S} = \frac{2\pi F L}{R_S}$
r	Ratio of total electrostatic shunt capacitance (C_O) to motional-arm capacitance (C_M) of crystal equivalent circuit
R_S or ESR	Equivalent series resistance of crystal unit

8.2 Usual applications.

8.2.1 Crystal units. Crystal units are the basic crystal device. They, in turn, are used in crystal oscillators and crystal filters.

8.2.2 Crystal oscillators. Crystal oscillators are made in a large variety of types to suit a large number of widely differing needs. They range from the 100-ppm accuracy class to 10^{-12}/day stability class, from 2 grams to 3 pounds, and from 0.02 cubic inch to over 40 cubic inches. They consume from a few microwatts to several watts and cost from a few dollars to more than $10,000. Designs range from a simple clock output to oscillators with a great array of features (some of which are listed below) and are realizable in many combinations.

This section is intended as an overview of crystal oscillators and not as a catalogue of available devices. Refer to MIL-O-55310 and the parts specialist for further details.

In the basic quartz crystal-controlled oscillator (XO), the crystal serves to stabilize the output frequency of an oscillator circuit.

The largest single source of oscillator frequency instability is the response of the crystal to temperature change. To minimize this effect, oscillators may be temperature-compensated (TCXO) or "ovenized" (OXCO); i.e., incorporating an oven as an integral part of the device construction to provide temperature control for optimum stability. The difference in performance between these oscillator types is shown in Table I.

TCXO. Temperature compensation is achieved by circuits using thermistors, varactors, and resistors. Currently evolving digital compensation techniques will add EPROMs, A/D and D/A converters, and comparators. This circuitry creates a temperature characteristic (TC) equal to, but of opposite slope, of the crystal TC, which maintains frequency stability over temperature by acting as a variable load on the crystal oscillator circuit. The rate of change of ambient temperature (ramp rate) that can be tolerated while maintaining desired frequency stability is rather limited (e.g., 1 °C per minute for $\pm 2 \times 10^{-6}$ stability).

OXCO. Temperature control is achieved by various combinations of devices: heater windings, heater blankets, thermostatic control, proportional control, power transistors as the heat source, self-limiting ovens for just the crystal, single and double ovens, booster heaters for fast warm-up, or Dewar flasks of glass, steel, or titanium. Safety devices to prevent thermal runaway may be provided.

The sophistication of temperature control ranges from coarse (several degrees) to very fine (better than 0.01 °C), over a wide ambient temperature range. In some applications only the crystal itself is temperature controlled.

8.2.2.1 Oscillator features. The following list of oscillator features, although not complete, is indicative of the many options available to the designer and it highlights the inadequacy of speaking of a "standard oscillator."

a. Cased crystals

b. Uncased crystals

c. Single and multiple output frequencies

d. TTL, CMOS, ECL, sinewave outputs

e. Reverse polarity protection

f. Supply voltage conditioning

g. Electrical and mechanical adjustment of f_0 and E_0 using a potentiometer, fixed resistor, or variable capacitor

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h. Remote frequency update in 1 x 10^{-11} steps

i. Voltage control of f_0 with linearity adjustment

j. Integral crystal filter (for phase noise control)

k. Integral output buffer

l. Integral wave shaper

m. Integral amplifier

n. Integral impedance matcher

o. Integral multipliers and dividers

p. Test points (for oven voltages)

q. Output disable (for more rapid on and off)

r. Any number of physical configurations, mounting means, connectors, and terminals

s. Discrete components or hybridized construction (perhaps in combination) with various criteria for selection and screening.

8.2.3 Crystal filters. Crystals are used in band-pass (and occasionally band-reject) filters. Narrow bandwidths and high attenuation are attainable in a small package because of the high Q of the crystals. Filters with only AT-cut crystals are discussed here. The number of crystals per filter varies from 2 to more than 16. In size and weight, filters range from those with discrete components in boxes of 6 cubic inches at 6 ounces, to monolithic filters in TO-8 or flatpack packages at 1 cubic inch and 3 grams. Bandwidths of 0.01 to 3 percent of center frequency are practical for fundamental frequency AT-cut crystals. On the third overtone, bandwidths of up to only a few tenths of one percent are realizable. The upper bandwidth limit is determined by the spurious responses of the crystals. The lower limit is determined by the need for the bandwidth to be sufficiently wider than the desired signal spectrum to allow for temperature and aging effects.

Attainable stopband attenuation ranges up to 100 dB with the most common applications being in the range of 40 to 70 dB. The ultimate attenuation is limited by the grounding and shielding techniques applied externally to the filter.

Not all bandwidths are available at all frequencies. Some typical values are shown in Table II.

TABLE I. Typical crystal oscillator categories

Type of Oscillator	Frequency Stability	Temperature Range	Power Consumption	Configuration, Volume, Weight	Comments	Relative Cost
Crystal controlled, with TTL, CMOS, ECL, or sine-wave output	±50 ppm ±20 ppm ±10 ppm	-55 to +125 °C -20 to +70 °C 0 to +70 °C	<100 mW	Cold-weld or seam-sealed TO-5, TO-8, DIP, or LCC; 0.02 cubic in; 3 grams	Components may be discrete or hybridized. Crystals may be uncased. Power depends on frequency and type of output.	$X
Temperature-compensated crystal oscillator (TXCO)	±1 ppm ±2 ppm	-10 to +70 °C -55 to +85 °C	10 to 100 mW	1-3 cubic in, 2 oz	There is a warm-up time of several seconds. There is a permissible ambient temperature ramp of 1 °C/ minute max.	$10X
Ovenized crystal oscillators (OCXO)	$\pm1 \times 10^{-7}$ per day to $\pm1 \times 10^{-12}$ per day	-40 to +85 °C	4 W warm-up; 1 W sustaining; 0.5 W oscillator	40 cubic in, 3 lb	Warm-up time may be hours or days.	$100X

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TABLE II. Typical filter bandwidths

Center Frequency	Mode of Oscillation	Bandwidth
30 MHz	Fundamental	500 kHz 1.6%
60 MHz	3rd Overtone	60 kHz 0.1%

8.2.4 Other applications. Quartz crystals are also used in discriminators. The output of a discriminator is a dc voltage, the polarity and amplitude of which is directly relatable to the frequency of the rf input.

Certain crystal cuts have a reasonably linear temperature characteristic of 200 to 300 ppm/°C, making them ideal as high resolution thermometers. Because the frequency of crystals is sensitive to pressure and weight, they are used as indirect indicators in industrial processes such as measuring plating thickness, detecting liquid flow, and determining the presence of atmospheric impurities.

8.3 Materials and physical construction. Crystals are typically edge-clamped in a two- or three-ribbon mounting system. Electrodes are plated on the opposite crystal surfaces with the plating extending to the opposite edges to provide attachment to the mounts. The crystal faces are only partially plated so that the effective electrode area is confined to a small circular region at the center of the blank. Thus, the capacitance is kept to a minimum and the principle resonating activity is confined to the middle where the crystal is most likely to be of uniform thickness. Both of these factors contribute to frequency stability. Final plating is done to fine tune the crystal frequency response. Figure 1 shows a typical crystal unit construction.

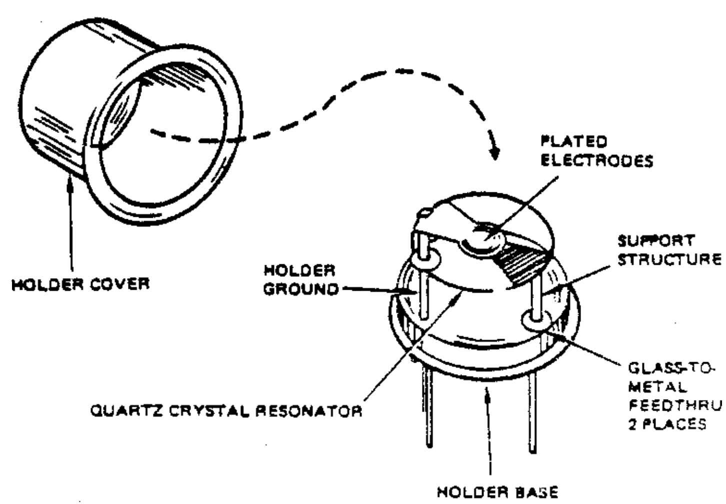

FIGURE 1. Typical construction of a quartz crystal unit in a transistor style holder.

8.3.1 Quartz material. The quartz resonator should be pure Z-growth cultured quartz. The crystal should be swept (impurities removed by an electrodiffusion process) unless it can be clearly demonstrated to be unnecessary for the application. The fundamental frequency should not be less than 1 MHz and preferably greater then 3 MHz. Minimum thickness of the crystal should be 0.0025 inch with 0.003 inch preferred. The base plate should be gold. Gold applied in a dry plating process should be used for final frequency adjustment.

The crystal should be of a high-frequency crystallographic cut, either AT or doubly-rotated AT (DRAT) cut.

8.3.2 Crystal cut. The crystal cut is the angle in respect to the three crystallographic perpendicular axes to which the crystal is ground or cut. It is the determining factor in crystal performance. The AT and double-rotated AT cuts are preferred. Lower frequency cuts should be avoided.

The advantages and disadvantages of the DRAT versus AT crystallographic cuts are stated in generalities and approximations because the specific values are dependent upon frequency, crystallographic angle, surface finish, plating configuration, support structure, holder, and the precision of manufacture.

The DRAT-cut crystals have lower acceleration sensitivity, can operate at a high drive level to minimize phase noise without the appearance of activity dips, display rapid thermal equilibrium during warmup, and exhibit higher fundamental frequencies and better aging. The DRAT crystals also have a much wider inflection point in temperature characteristics which reduce frequency to temperature changes. Figures 2, 3, 4, and 5 demonstrate this temperature-frequency relationship for one AT and three double-rotated cuts. For reference, Figure 6 shows the relationship of the zero angle cut for each.

The disadvantages of DRAT-cut crystals compared with AT cut are that they have a relatively large and steep negative frequency deviation at temperatures below 0 °C which limits DRAT-cut crystals to ovenized constructions, they are very frequency-sensitive to impressed dc voltages, and they require more complex circuitry.

The DRAT-cut crystals are more expensive due the greater manufacturing difficulties associated with maintaining two crystallographic angles simultaneously rather than a single angle.

For these reasons, the AT-cut crystal is by far the more popular cut. The DRAT cut is reserved for precision applications.

8.3.3 Support structure. The support structure can be a 2-or 3-ribbon structure. The resonator crystal should be bonded to the support structure by electrically conductive cement or by thermocompression bonding.

8.3.4 Holders. Holders or enclosures should be metal, metal-glass, or all glass constructions. The holders should be evacuated and cold-welded. If resistance welding is unavoidable, PIND testing should be performed. Do not back-fill the enclosure or use solder sealing methods to complete the seal. Figure 7 shows crystal unit holders and Figure 8 shows oscillators.

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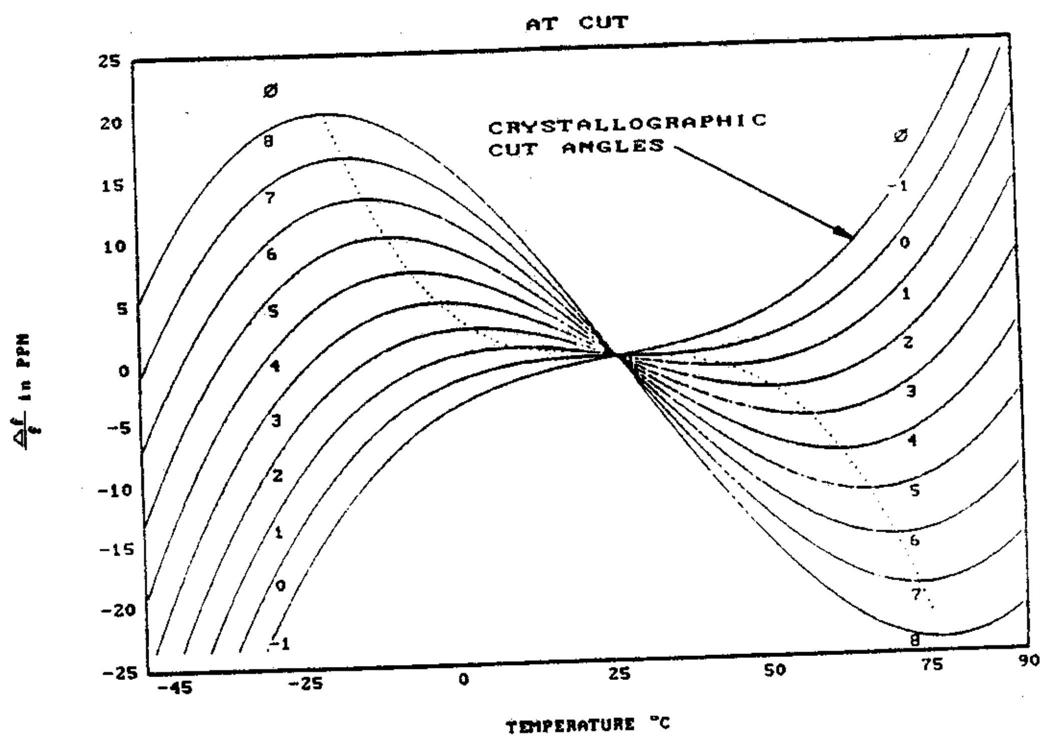

FIGURE 2. Generalized temperature/frequency characteristics for several AT crystals.

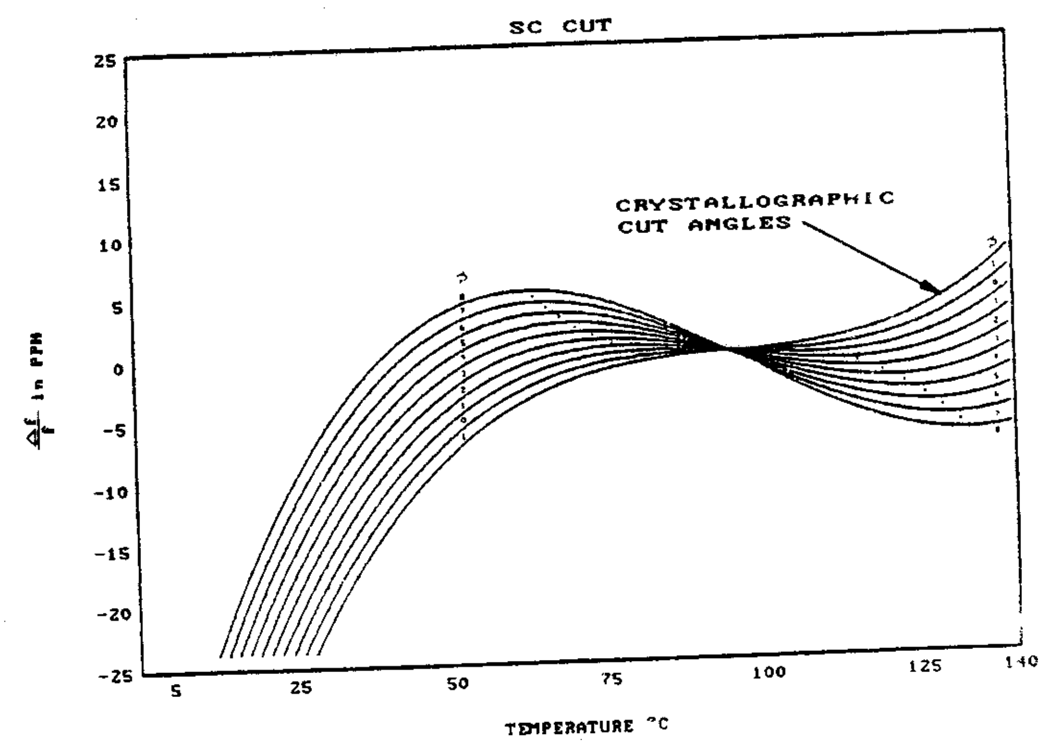

FIGURE 3. Generalized temperature/frequency characteristics for several double-rotated SC crystallographic cuts.

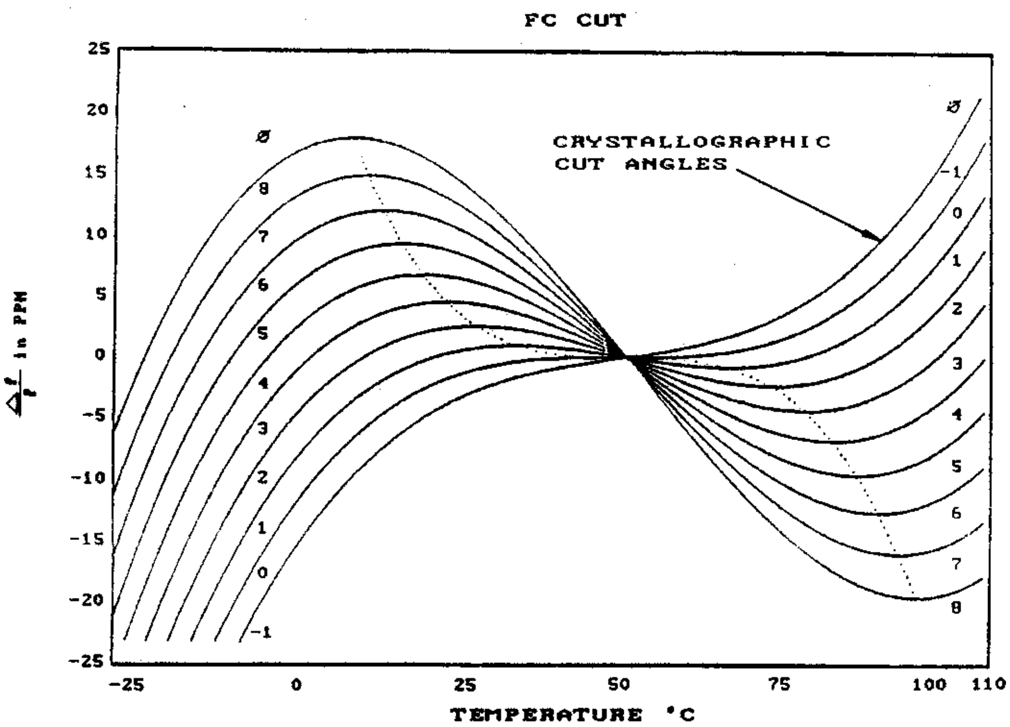

FIGURE 4. Generalized temperature/frequency characteristics for several AC double-rotated crystallographic cuts.

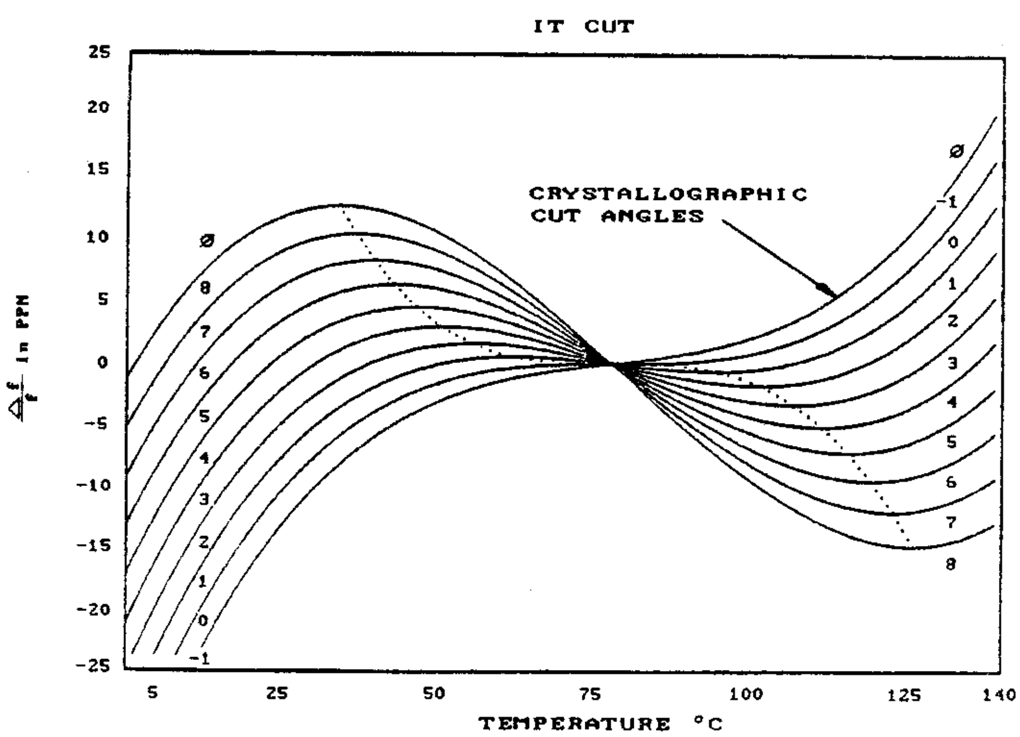

FIGURE 5. Generalized temperature/frequency characteristics for several IT double-rotated crystallographic cuts.

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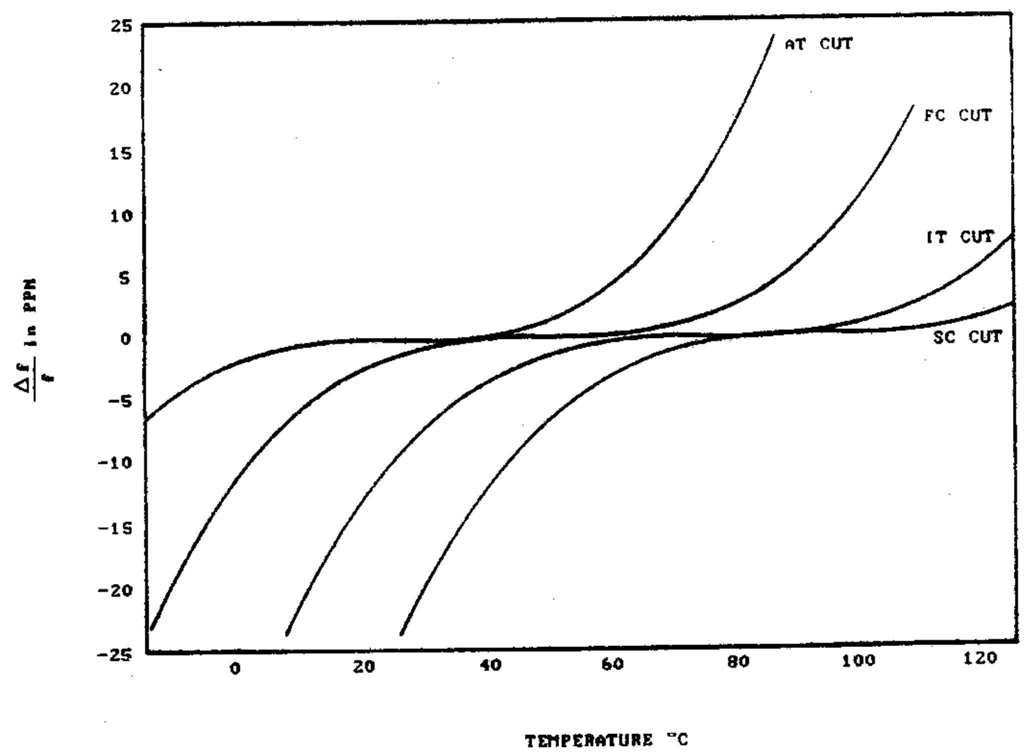


FIGURE 6. Temperature/frequency characteristics for zero angle crystallographic cuts.

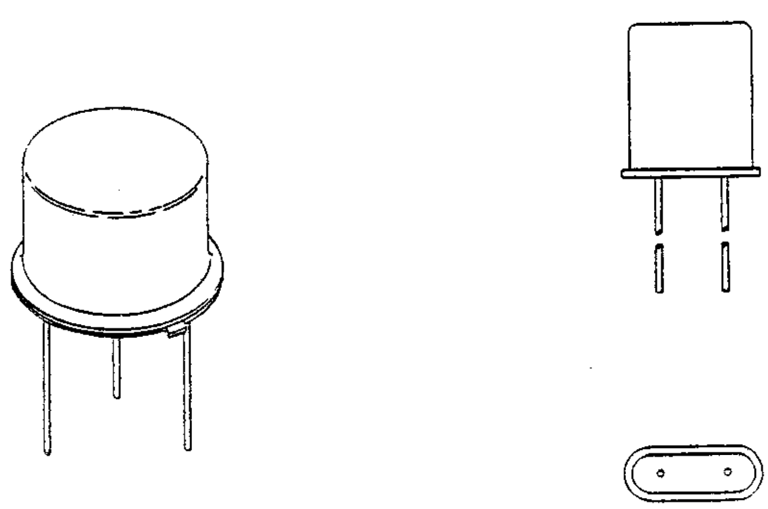
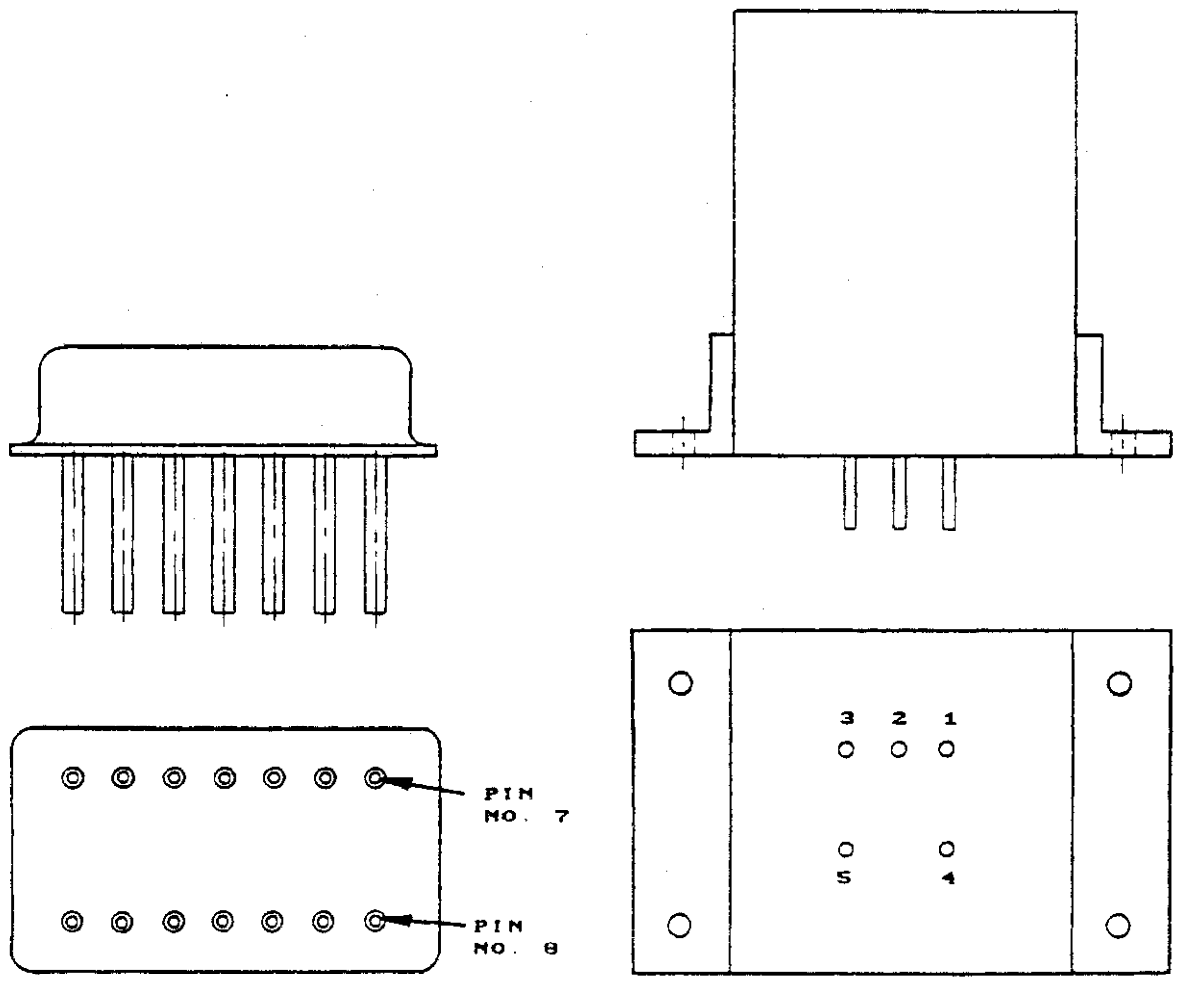


FIGURE 7. Outline drawings for typical crystal units.



A. Oscillator (XO)

B. Oven controlled oscillator

FIGURE 8. Outline drawings for typical oscillators.

8.4 Military designation. The military specification for quartz crystal units is MIL-C-3098. The designation is:

CR	-15	/U
Component	Crystal unit number	Basic indicator

The military specification for crystal oscillators is MIL-O-55310. The designation is:

M	55310/01	-A	-01
Military designator	Document sheet number	Screening	Dash number

No crystals are listed in MIL-STD-975.

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8.5 Electrical characteristics.

8.5.1 Equivalent electrical circuit of a quartz resonator. For electrical design considerations, the schematic representation of a crystal is shown in Figure 9 and the lumped constant equivalent circuit is shown in Figure 10.

As is characteristic of most mechanical resonators, the motional inductance (L_M) resulting from the mechanical mass in motion is generally relative to that obtained from coils and their magnetic fields. The L_M ranges from thousands of henries for the low frequency cuts to millihenries for frequencies over 100 MHz. The extreme stiffness of this glass-like crystalline material allows very small values of the motional capacitance (C_M), whereas the very high order of elasticity allows the motional resistance (R_M) to be relatively low. The L, C, R equivalent circuit, therefore, is one having a high L/C ratio, and a very high (L/C)/R, or Q ratio. Representative values in frequency regions of interest are shown in Table III.

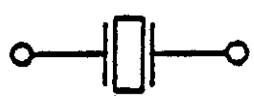

FIGURE 9. Schematic diagram of crystal unit.

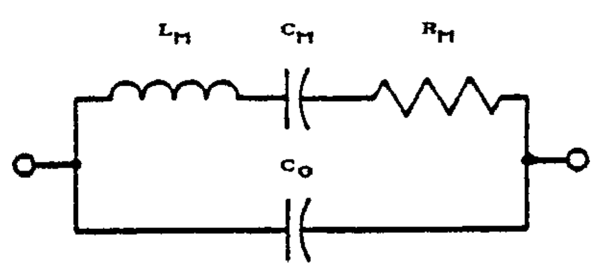

FIGURE 10. Lumped-constant equivalent circuit of crystal.

TABLE III. Representative crystal unit values

Frequency	Near 1 MHz	High frequency overtones
LM	10 H	mH
CM	0.0X pF	0.000X pF
Q	2.5×10^6	$<100 \times 10^3$

The shunt capacitance (C_0) is the electrostatic capacitance existing between the crystal electrodes with the quartz plate as a dielectric. It is present whether or not the resonator is vibrating. The value of C_0 varies with the area and thickness of the quartz plate. Electrode size is part of the crystallographic design and is selected as a compromise value primarily for natural bandwidth (Δf), R_s, unwanted modes, or pulling linearity.

The values of C_0 are large with respect to the values of C_M. The ratio C_0/C_M varies from a low of 125, to a high of over 10,000. The ratio, C_0/C_M, sometimes referred to by the symbol "r," is a very important performance parameter for crystal resonator design and application considerations. If a dc voltage is applied across the terminals of the equivalent circuit shown in Figure 10, it can be seen that the reactive energy stored in the C_M is actually stored as strain or deformation of the resonator, whereas that stored in C_0 has nothing to do with mechanically activating the resonator. Thus, crystal resonator designs having higher C_0/C_M ratios exhibit higher equivalent electrical impedances.

8.5.2 Reactance curve of a quartz resonator. The other important effect of the C_0/C_M ratio has to do with the natural bandwidth (Δf) of the crystal unit. Figure 11 shows a curve of reactance versus frequency of a crystal unit.

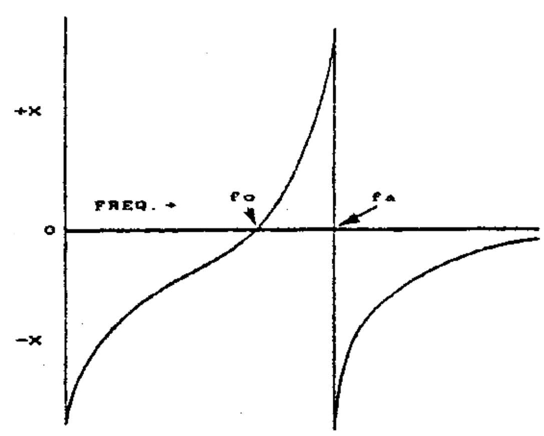

FIGURE 11. Reactance vs frequency of a crystal unit.

As can be seen, this curve is what would be expected if the reactance C_0 alone were plotted, except in the vicinity of mechanical resonance. Mechanical resonance occurs where the curve goes through zero at f_0, and proceeds at a much higher rate to a very high positive value and then plunges rapidly downward through zero reactance to a very large negative value, returning to the expected C_0 curve only slightly higher than f_a. The frequency of zero reactance f_0 occurs very close to the frequency where X_{LM} is equal to X_{CM} and is given by the equation:

$$f \cong \frac{1}{2\pi\sqrt{L_M C_M}}$$

where f_0 is the resonant frequency of the crystal unit.

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The frequency f_a occurs when $X_{LM} - X_{CM} = X_{C_0}$ and is given by the equation:

$$f_a \approx \frac{1}{2\pi \left[\frac{(L_M C_M C_0)}{(C_0 + C_M)}\right]^{1/2}}$$

where f_a is the antiresonant frequency of the crystal unit.

The natural bandwidth Δf is $f_a - f_0$. If the equations above are substituted, Δf can be shown to be equal to:

$$\Delta f = \frac{f_0}{2\, C_0/C_M} = \frac{f_0}{2r}$$

8.5.3 The crystal unit as an electronic resonator. An oscillator may be defined as an electronic device for converting dc into ac. Such devices are inherently closed loop systems and are composed of an amplifier, a resonator, and some means of limiting the amplitude of oscillation. A block diagram of such a system is shown in Figure 12. In this system, the amplifier provides its own limiting.

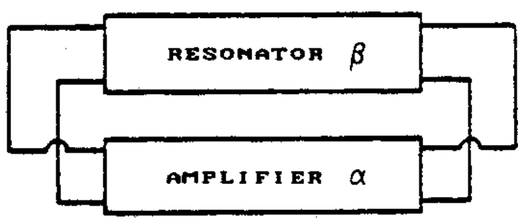

FIGURE 12. Block diagram of an oscillator.

The amplifier has a gain of α, and the resonator has a transmission coefficient of β. If the product of $\alpha\beta$ is greater than unity and has a zero phase angle at a particular frequency, oscillation will normally occur at this frequency. The amplitude of oscillation will increase at this frequency until limiting, as provided by the amplifier or an external means, satisfies the condition of $\alpha\beta = 1$, known as Barkhausen's condition for oscillation.

If a phase shift occurs in the amplifier α, there must be an equal and opposite shift in phase in the transmission characteristic of β.

This phase-shift correction by the resonator is accomplished by the system experiencing a change in frequency of oscillation. It is the purpose of a good resonator to provide phase correction with minimum frequency shifts. If the resonator is assumed to be working at or very near a frequency of resonance, and because we are concerned with only very small changes in phase so that the change in phase angle can be assumed to be equal to the change in the tangent of the phase angle, then:

$$\Delta\phi\alpha = -\Delta\phi\beta$$

$$\Delta\phi\beta = \frac{\Delta X}{R} = \frac{4\pi L\Delta f}{R}$$

and

$$\frac{\Delta f}{f} = \frac{\Delta\phi}{(4\pi L\Delta f/R)} = \frac{\frac{\Delta\phi/2}{2}}{2\pi\Delta f CR} = \frac{\Delta\phi}{2Q}$$

Where

L = effective series inductance
C = total effective series capacitance
R = total effective series resistance of the loop

The fractional change in frequency for a phase shift change of ϕ will be small if the effective Q of the resonator is large. The Q of typical quartz crystals is in the range of 10,000 to 100,000 and runs above 1,000,000 for special precision units. These high Q values, coupled with the high degree of performance of physical and electrical properties, make the quartz crystal outstanding as a resonator.

8.5.4 Series resonance. In the circuit shown in Figure 13, at the frequency of series resonance,

$$f = \frac{1}{2\pi\sqrt{L_M C_M}}$$

Because the magnitudes of X_{CM} and X_{LM} are equal, one cancels the other, resulting in a minimum impedance equal to R_M and essentially zero phase shift. In most series resonant applications below VHF, C_0 may be neglected.

8.5.5 Parallel resonance. At frequencies slightly higher than series resonance, X_{LM} will increase and X_{CM} will decrease, resulting in a net inductive reactance, X_L.

When this met $X_L = X_{C_0}$, then $f = \dfrac{1}{2\pi\sqrt{L_M (C_M C_0)/(C_M + C_0)}}$

At this point, maximum impedance will appear at the terminals, indicating parallel resonance of the crystal unit. The frequency separation between series and parallel resonance is determined by the capacitance ratio, C_0/C_M.

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In practical oscillators not operating at the series resonant frequency of the crystal, the circuit adds its input capacitance (C_X) to C_O, resulting in a total C_T.

The formula for frequency then becomes $f = \dfrac{1}{2\pi\sqrt{\dfrac{(C_T C_M) L_M}{(C_T + C_M)}}}$

C_X is the oscillator input capacitance at the crystal terminals and its value must be known in order to adjust the crystal to the desired frequency, just as the capacitance must be known for an inductor to be preadjusted to resonate at a given frequency.

Parallel resonant crystals can be excited by a high impedance oscillator (Figure 14) or one with low impedance (Figure 15). It can be seen from Figure 14 that if C_X is zero, the crystal will be at its own parallel self-resonant frequency. As C_X is increased, the frequency is lowered, with the net inductance of the series arm resonating with C_T. As C_X increases, the voltage to the crystal decreases until infinite C_X results in no coupling to the crystal.

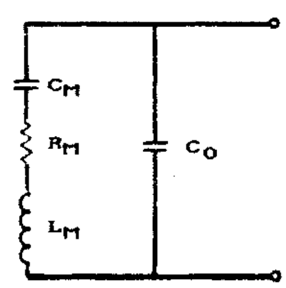

FIGURE 13. Simplified equivalent circuit.

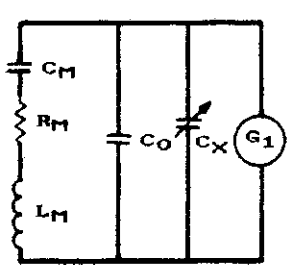

FIGURE 14. High Z generator.

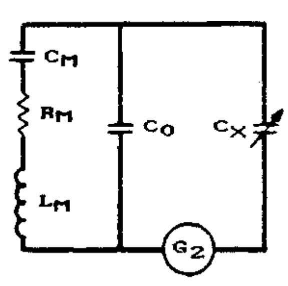

FIGURE 15. Low Z generator.

In the circuit of Figure 15, if C_X is zero, there is no coupling to the crystal. As C_X increases, C_T increases, gradually lowering the frequency of operation, just as in Figure 14. Thus a given capacitance, C_X, will result in essentially the same frequency in Figures 14 and 15 for a given crystal. If C_X reaches infinity in Figure 15, the crystal will be at its series resonant frequency.

Thus, it can be seen that the only difference between crystals designed for series resonance and those for parallel resonance is the oscillator input reactance for which they are calibrated. In fact, a crystal calibrated for parallel resonance will operate at its calibrated frequency in a series resonant circuit with the addition of an appropriate value of series capacitance.

From the above, it is obvious that a crystal cannot be properly specified without stating the reactance with which it is to be calibrated.

8.5.6 Consideration of frequency stability as a function of the crystal resonator in an oscillator. The equation for the fractional frequency change of the resonator to offset incremental changes in phase angle in the associated circuitry has been previously discussed, and has been stated as

$$\frac{\Delta f}{f} = \frac{\Delta\phi}{2Q}$$

Oscillators are generally nonlinear devices, but will be assumed to be linear in operation for this discussion. Small changes in phase angle in the oscillator circuitry associated with the resonator may be due to many causes. One important universal cause, for almost all conceivable oscillator designs, are small changes in capacitance to ground on either side of the amplifier. The small change in capacitance across this resistance will result in a change in phase angle, $\Delta\phi$, which may be expressed as $R\pi\Delta C$. The fractional frequency change of the circuit will then be:

$$\frac{\Delta f}{f} = \frac{\Delta\phi}{2Q} = \frac{R\pi\Delta C}{2Q} = \frac{R2\pi f\Delta C}{2Q}$$

The conclusion so reached is important, because it states that as the frequency of operation increases, the Q of the resonator must increase proportionally, to obtain the same fractional frequency stability, when phase shift changes of this type are considered.

8.6 Environmental considerations. Quartz crystals are uniquely useful as an electronic component not only because of the high Q factors available but also because of the relatively small and generally predictable effects induced by exposure to environmental stress.

8.6.1 Frequency stability versus environmental changes. The reactance and resistance of the equivalent circuit of the crystal are changed in value when the crystal is subjected to the following:

a. Change in temperature

b. Change in excitation or crystal drive

c. Change in mechanical stress

d. Passage of time

e. Change in the load reactance.

8.6.2 Frequency stability versus temperature. Frequency versus temperature characteristics are fairly well established for many crystal designs covering the frequency range of from approximately 1 KHz to over 200 MHz. The general behavior of the preferred type crystal cuts versus temperature were shown in Figures 2 through 6.

8.6.3 Frequency stability versus crystal excitation. The driving excitation current flowing through the crystal affects the frequency of operation. This is the result of temperature gradient strains due to localized heating of the quartz. Because the power dissipated in the crystal is proportional to the square of the current, the slope of the frequency change versus crystal current increases as the current is increased. It is highly advisable to operate the crystal at a low level of drive current and ensure that the oscillator will start and maintain a most constant crystal drive current, regardless of small changes in the voltage applied to the oscillator by some means of AGC action. Lightly driven (less than 10 μW) precision AT-cut crystals will change less than a couple of parts per billion per decibel change in drive level. If the same crystals are driven at 5-mW levels in a manually adjusted gain test oscillator, it is practically impossible to repeat frequency measurements to 1×10^{-8} accuracy, even when a voltage regulator is used with the oscillator. Higher drive levels are useful when spectral purity of the oscillator output signal outweighs all other considerations for frequency stability, aging, and activity dips. At some point, drive level can cause incipient or catastrophic fractures.

8.6.4 Frequency stability versus shock and vibration. Environmental changes which mechanically induce strains in the quartz cause a change in the frequency of operation, and mechanically induced strains in the mount will have an additional effect upon the frequency.

The tip-over test measures the change in frequency resulting from a 2 G; i.e., the pull of gravity first from one side of the crystal then from the other. From this test, the fractional frequency change per G may be determined for various orientations of the crystal. The change in frequency resulting from a larger, but constant, stress may be obtained by subjecting the crystal to the centrifugal force of a centrifuge.

If the crystal resonator and its mounting system are rigid enough to remain free of mechanical resonance over the frequency range of the mechanical disturbance, then the frequency deviation per G of disturbance, as determined from the tip-over or centrifuge test, may be used to predict the expected frequency deviation for applied sinusoidal vibration up to the level where the the elastic limits of the design are exceeded.

Frequency changes of three general types are encountered in conducting vibration and shock tests. First, there are those which dynamically follow the mechanical excitation and disappear completely and instantly upon cessation of the excitation.

Second, during the course of the vibration run, or during initial subjection to shock, the reference frequency may undergo a temporary change from that observed before the test, but returns within a few moments to its original value. The phenomena will repeat and is probably associated with the plasticity and flow-back nature of the solder or cement used to attach the resonator to its support.

Finally, there are permanent changes that may result from the chipping of the resonator, permanent deformation or fracture of the mounting system, or damage to the attachment points of the mount to the resonator.

The stiffer and more rigid the mounting system, the higher the natural resonance of the system but the lower the capability to withstand high impact shock. If the design is to undergo no permanent damage from high mechanical shock, either the deceleration time must be short enough for the natural compliance of the system to prevent the system from exceeding its elastic limits, or shock buffers must be designed into the system to limit the excursion of the resonator to a displacement safely within the elastic limits of the regular mounting system. Designs incorporating shock buffers cannot be expected to provide frequency stability during shock, but if carefully designed, can provide minimal frequency change on a before-and-after exposure basis.

The AT-cut crystal, with its relatively inactive peripheral mounting points, provides opportunity for designs capable of withstanding much higher shock and vibration than designs with the resonator soldered to fine wire leads (low frequency cuts). The periphery of AT-cut crystals operating on overtone modes is even more quiescent than those operating on the fundamental mode, and such designs are generally preferred for maximum stability under shock and vibration.

8.6.5 Frequency change versus time (aging). In most applications, the crystal is relied upon to control or minimize the effects of changes in value with the passage of time on all other circuit elements of the frequency generating (or controlling) system. Therefore, it is most important that the crystal itself change as little as possible with time, and that whatever change that does occur is predictable.

There is still much to be learned concerning the basic cause and effect relationship associated with the aging process of crystal units. It is generally agreed that the principal cause of change in frequency with time of AT-cut crystals is due to a gradual transfer of mass to or from the crystal resonator. The material (solid, liquid, or gas in nature), which after final processing remains within the enclosure (where it can tranfer to or from the resonator) is considered to be a contaminant. This contaminant may be set in motion by thermal agitation and the direction of transfer is from the hotter to the cooler surface.

Stress and a change of stress imparted to the crystal by its mounting structure is another major contributor to aging. In the application, the drive level must be minimized to limit its effect on aging. Storage and operating temperatures should be kept to their lowest applicable values to diminish the aging process.

Processing techniques are continually being improved to reduce contamination as a cause of aging. The behavior generally observed in precision-made crystals is an increase in frequency with an exponential reduction in rate with the passage of time as the free material gradually assumes a quiescent state.

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The major amount of change takes place in the first few weeks after manufacture and may be accelerated by high-temperature storage or temperature cycling, thus attaining the minimal and decreasing rate upon application.

The thermal transfer of free contaminant theory reasonably explains the observation that crystals once stabilized may not retrace to the same frequency when cooled off and reheated. This effect can be minimized if the heating pattern is consistent, a condition which is approached if the crystal is used in an oven with a highly repeatable warm-up characteristic. Further, the more care taken in the processing to minimize the possibility of free contaminants, the better the retrace behavior becomes.

The use of modern clean room processing techniques and ion pump high-vacuum systems, the continual improvement in measurement techniques, and the availability of the atomic standard reference frequency have made possible precision AT-cut crystal resonators that exhibit aging stabilities approach one part in 10^8 per year.

It is important to realize that even though the same careful control of contaminants can be applied in the processing of other types of crystals, there are other basic reasons why this high order of fractional stability is generally limited to the AT-cut that operates in the 1- to 5-MHz range. As previously pointed out, the effects of the mounting system must be negligible before the intrinsically stable properties of the quartz plate and its gold electrodes can be used to full advantage. This becomes increasingly difficult, if not impossible, at frequencies much lower than 1 MHz, regardless of the type of quartz cut used.

The frequency-determining thickness dimensions of an AT-cut crystal varies inversely with frequency; therefore, so does the fractional frequency stability for a given amount of free contaminant within the enclosure . It is possible to use higher orders of overtones to offset this situation, but even so, the best Q realizable will be inversely proportional to the frequency. Accordingly, it is generally recognized that the use of 1- to 5-MHz frequency precision crystals in oscillators, followed by well designed multipliers, will provide higher stability at the higher frequencies than that possible with the best frequency crystals.

8.6.6. Short Term Stability. If the output of an oscillator is frequency or phase modulated, the sideband energy frequencies will mix with frequencies contained in the noise or phase jitter of subsequent multipliers, thereby degrading the spectral purity of the output frequency. The degradation increases exponentially with the multiplication. For signal-to-noise ratios generally encountered with broad band frequency multipliers, the ratio of power in the side bands of the multiplied signal to that in the carrier of the multiplied signal will N^2 times the same power ratio of the signal before multiplication, where N represents the number of times the signal is multiplied.

The noise, or sideband energy, associated with the signal from the crystal oscillator, is attributable primarily to the amplification required to bring the crystal resonator energy to a useable level. Operating the crystal resonator at very low-power levels with high gain in the following amplifier stages is most desirable for better long-term stability, but tends to degrade the spectral purity of the oscillator output signal.

The problem of separating the contribution of the measurement system from the inherent short-term stability of the oscillator is a difficult one. However, good precision reference oscillators in the 1- to 5-MHz range can be produced which exhibit a frequency stability in the region of 1×10^{-10} rms for 1-s periods and also maintain long-term stabilities in the order of a few parts in 10^8 per week.

8.6.7 Effect of over-specifying crystals. It is not uncommon when establishing performance requirements to make the operating temperature range wider than what actually will be encountered. This is to establish a safety margin. Because of the nonlinear nature of the frequency versus temperature characteristic of high-frequency crystals (a cubic curve in the case of AT-cut crystals), this practice can be counter-productive.

In the case of AT-cut crystals, the temperature characteristic is forced to become steeper in the region symmetrical near room temperature as a more radical crystallographic angle is chosen to accommodate specified requirements. This could necessitate the use of temperature compensation or temperature control to achieve the desired frequency stability.

In the case of DRAT-cut crystals, lowering the cold temperature end unnecessarily below 0° or -20 °C may obviate the use of a DRAT crystal or, at least, force the addition of a heater for temperature control.

Thus, it is apparent that great care is warranted in establishing the frequency stability versus the operating temperature range requirement.

8.6.8 Effects of radiation. When AT- and DRAT-cut crystals are exposed to nuclear radiation, there is a measureable, often significant change in frequency and equivalent resistance (low-frequency cut crystals may cease to oscillate completely). Design criteria to minimize this effect include the use of swept quartz and gold electrodes. It may not be necessary to observe these precautions on all crystal-controlled devices such as wideband filters and low-stability oscillators.

When crystal-controlled oscillators are irradiated, there is a measureable (often significant) change in the output frequency whereas the output waveshape may not be affected. With the current oscillator designs and component technology, most of the output frequency change can be attributed to the crystal, whereas the contribution of the associated circuitry can be made negligible. An improper oscillator circuit design may result in burn-out.

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No single number can fully describe this behavior of a crystal or oscillator because it is a function of the following:

a. The design of the specific device

b. The type of radiation (such as CO^{60}, FXR, and N) and whether the exposures are in series or combination

c. The pulse spectrum and duration of impingement

d. The exposure history of the device

e. The fact that some of the effects are permanent whereas some are transient

f. Indirectly, the technique and timing of the very precise frequency measurements which must be made under the most difficult of circumstances.

Tests performed on the best of radiation-hardened crystal-controlled oscillators at the kilo-Rad and mega-Rad levels have indicated an average decrease in frequency ($\Delta f/f$) in the range of 10^{-13} to 10^{-15} per Rad. A conservative working estimate appears to be 10^{-12} per Rad. At low exposure levels of only a few Rad, the change may be even more severe. Positive frequency shifts in the 10^{-10} to 10^{-11} region preceding the negative shift have been observed .

As stated before and emphasized here, the actual performance obtained is a function of the specific device and the specific radiation conditions. Therefore, the values stated above are intended to convey only a general ideal of crystal behavior under nuclear radiation.

8.7 Reliability considerations. Quartz crystals, properly used, are among the most reliable of electronic components.

8.7.1 Failure modes and mechanisms. For all practical purposes, there is no wearout mechanism associated with the operation of a quartz crystal when it is operated within its specifications at or below rated drive level. As described in paragraph 8.6.5, there is a continuous aging process, the rate of which reduces exponentially with time. Operation above the rated drive level will result in deterioration of stability, even though the dissipation is well below the level at which the crystal may shatter. A high drive level will also cause degradation of the aging characteristics.

There are certain failure mechanisms associated with manufacturing defects which, if not detected prior to equipment installation, can result in either catastrophic failure or excessive drift after some period of operation. Some of the more common defects are listed below.

a. Poor seal

b. Excessive contamination

c. Excessive internal mechanical stresses introduced by the resonator support structure

d. Poor electrical connections

e. Poor plating (electrode) adherence

f. Incipient fractures of the resonator

g. Support structure fracture.

A poor seal will result in a gradual downward frequency drift and an increase in crystal resistance due to the entrance of atmosphere and moisture and other surface contaminants. The crystal may fail either by drifting out of tolerance or by an increase in resistance to the point that it may no longer oscillate.

The effect of excessive contamination is the same as that of a poor seal, except that the contaminants are present from the time of manufacture. This defect is relatively rare among quality manufacturers and the use of cold-welded cases reduces the problem of contaminants (such as solder flux) being introduced during the sealing operation. Occasionally, the design of the internal mounting structure and/or the assembly techniques used on a batch of crystals will result in the resonator being under mechanical stress in its mounted condition. Such stresses can also be introduced by high shock loads introduced by improper handling. This condition increases the effective resistance of the crystal and can cause it to be temperature sensitive, either failing to operate or operating out of frequency tolerance in the operating temperature range. Units with this type of defect, when it is sufficient to cause the crystal to exceed the frequency tolerance limits, will usually be out of tolerance on the low side.

Poor electrical connections may result in intermittent operation or total failure depending on the nature of the joint.

8.7.2 Screening. One hundred percent screening techniques are effective in eliminating most of the manufacturing defects described above. Recommended screening techniques are listed in Table IV in the sequence in which they should normally be conducted.

8.7.3 Reliability derating. No derating of quartz crystals is required. As emphasized previously, the drive level must not exceed the maximum rated level to preclude incipient damage and the crystal must be at the rated drive level for specified tolerances to apply.

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TABLE IV. Recommended screening techniques for crystals

Screening Test	Purpose
Thermal shock	To stabilize the crystal and to aggravate any imperfection in the seal or electrical connections
Reduced drive level	To check quartz resonator surface quality
Random vibration	To check for undesirable mechanical resonance of the mount and manufacturing defects
Gross and fine leak test	To ensure seal integrity
Aging	To stabilize performance
Performance over temperature range	To verify performance

8.7.4 Failure rate. Because quartz crystals are low-population parts, significant statistical data on failure rate is lacking. MIL-HDBK-217 lists the average failure rate as 0.02%/1000 hours. Pending further accumulation of data, a figure of this order of magnitude may be used for predictions.

9. FILTERS, ELECTRICAL

9.1 Introduction. Electromagnetic interference (EMI) control requires suppression of unwanted electrical noises, transients, harmonics, and other spurious signals which may prevent proper operation of either the equipment being designed or other electronic systems within the associated environment. Anticipation and disposition of noise is best accomplished as early in the design stage as possible, so that optimum techniques of lead dress, shielding, decoupling and mechanical design can be used to the maximum extent possible, thus minimizing problems associated with the addition of EMI filters as the design approaches completion.

An interference filter may be a single inductor or capacitor or it may combine inductive and capacitive elements in various combinations. If space and cost permit, almost any desired performance can be obtained. For the purposes of this section, discussion is limited to standard electromagnetic interference filter sections, with emphasis on standardization of types.

9.2 Usual applications. EMI filters used in dc lines are usually single capacitors or pi networks or sections and are usually used in 28 Vdc applications. EMI filters used in ac lines are usually L or T networks. The ac line filters are usually used in higher voltage applications of 120 Vrms. The current applications of both dc and ac line filters vary and devices are available in current ratings of up to 20 A. Both dc and ac filters use toroidal inductors and ceramic discoidal capacitors in their construction and are intended for low frequency applications.

Another type of ceramic filter uses a ferrite bead as the inductive element. These are also available in the three basic electrical configurations, but are effective only at higher frequencies (10 MHz and up). Here, the ferrite bead functions not as a true inductor, but as an absorber of rf energy.

9.3 Physical construction. EMI filters are made in many sizes, shapes, and combination of sections, depending on their electrical ratings and characteristics. Standard filters, however, tend toward single-section units of tubular and discoidal configuration with axial terminations and a threaded bushing mount. An example of typical physical construction is shown in Figure 1.

9.4 Military designation. The military specification for EMI filters is MIL-F-28861. This specification includes a number of individual specification sheets (slash sheets) for various styles.

The part number is in the following format:

M28861/01-	001	T	S
Specification and slash sheet	Dash number	Case finish	Product assurance level

9. FILTERS, ELECTRICAL

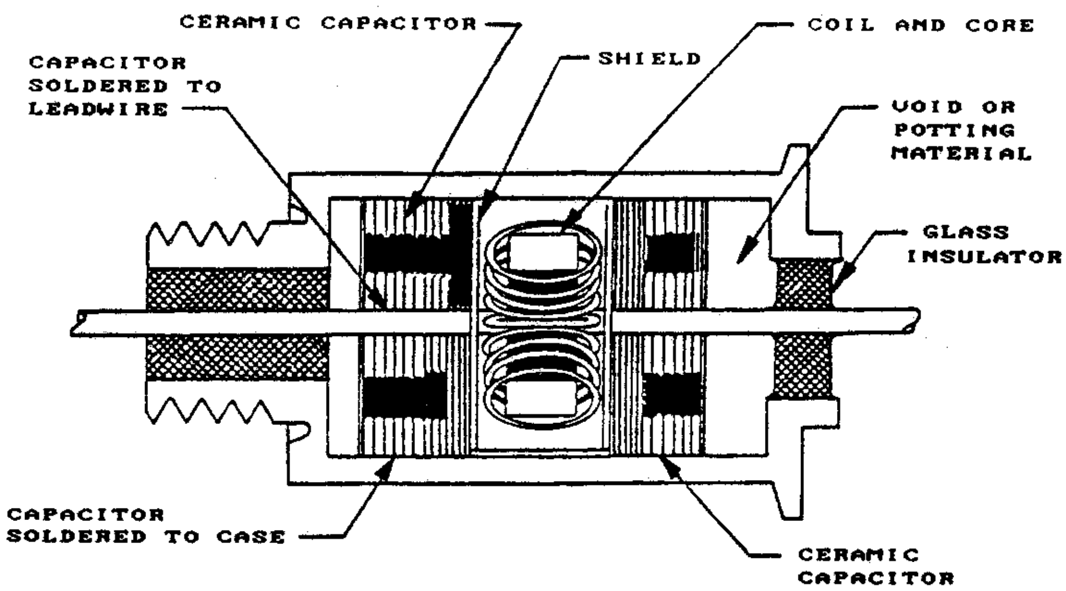

FIGURE 1. Typical construction of EMI filters.

9.5 Application and design considerations.

9.5.1 Electrical considerations.

9.5.1.1 Definition of requirements. In selecting a filter for a particular application, the following parameters should be taken into consideration if the filter is to be effective in its intended application.

a. Insertion loss. The insertion loss is affected by load current, temperature, and voltage and is dependent on source and load impedance

b. Voltage and current ratings

c. Maximum voltage drop, if applicable

d. Maximum and minimum inductance and capacitance

e. Peak transient voltage and its duration

f. Minimum filter life under rated conditions at maximum temperature

g. Temperature range of operation.

9.5.1.2 Selection of filter circuits. Although selection of an optimum filter to accomplish the required interference attenuation can be quite complex, the following general rules can be utilized for the selection of the filter parameters.

9.5.1.2.1 Bypass capacitor. A bypass capacitor can be used as a filter when both source and load impedances (Z_S and Z_L) are large with respect to capacitor reactance (X_C).

Under these conditions,

$$\text{Attenuation (db)} \approx 20 \log \frac{1}{X_C}\left[\frac{Z_S\, Z_L}{Z_S+Z_L}\right]$$

Thus, it can be seen that as $\frac{Z_S\, Z_L}{Z_S+Z_L}$ increases with respect to X_C, attenuation increases.

However, if either Z_S or Z_L approaches zero, the bypass capacitor is not an effective filter.

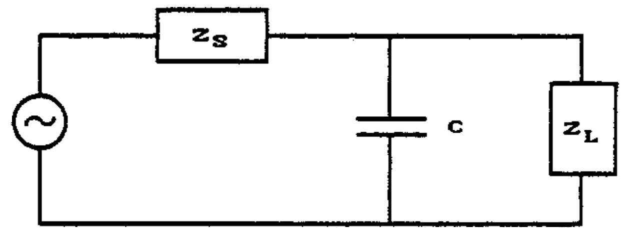

FIGURE 2. Bypass capacitor filter.

9.5.1.2.2 Inductor. A series inductor can be used as a filter when both Z_S and Z_L are low with respect to inductor reactance (X_L).

Under these conditions,

$$\text{Attenuation (db)} \approx 20 \log \left[\frac{\omega L}{Z_S + Z_L}\right]$$

Thus attenuation is significant when Z_S and Z_L are both small with respect to X_L.

9. FILTERS, ELECTRICAL

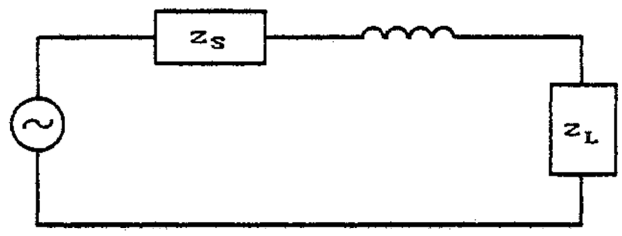

FIGURE 3. Inductor filter.

9.5.1.2.3 Inductive input "L" section. This circuit should be used whenever Z_S is much smaller than Z_L.

Under this condition, above cutoff,

$$\text{Attenuation} \approx 20 \log \left[\frac{\omega L}{Z_L} + LC\omega^2 \right]$$

and if $\omega L \approx Z_L$

$$\text{Attenuation} \approx 20 \log \left[LC\omega^2 \right]$$

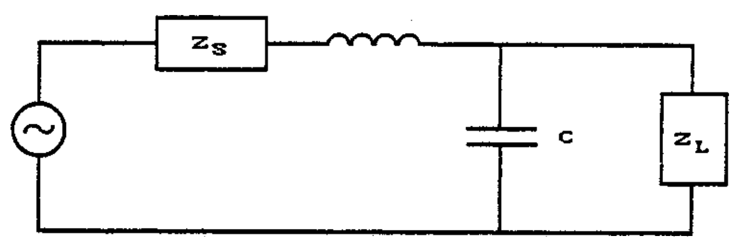

FIGURE 4. Inductive input "L" section filter.

9.5.1.2.4 Inductive output "L" section. This circuit should be used whenever Z_L is much smaller than Z_S.

Under this condition, above cutoff,

$$\text{Attenuation} \approx 20 \log \left[\frac{\omega L}{Z_S} + LC\omega^2 \right]$$

and if $\omega L \approx Z_L$

$$\text{Attenuation} \approx 20 \log \left[LC\omega^2 \right]$$

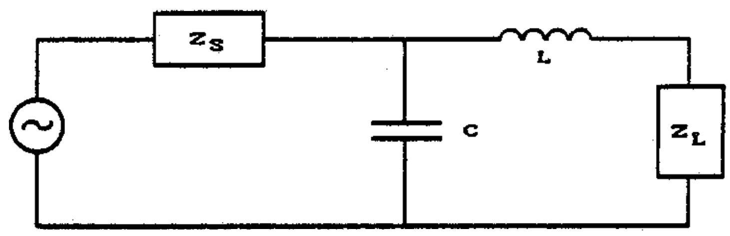

FIGURE 5. Inductive output "L" section filter.

9.5.1.2.5 "T" section. A "T" circuit should be used whenever Z_S and Z_L are small in value or are capacitive.

If Z_S and Z_L are both small:

$$\text{Attenuation} \approx 20 \log \left[\omega^2 LC + \frac{L^2 C \omega^2}{Z_S + Z_L} + \frac{2\omega L}{Z_S + Z_L} \right]$$

It can be seen that, as Z_S and Z_L approach zero, the last two terms become very large.

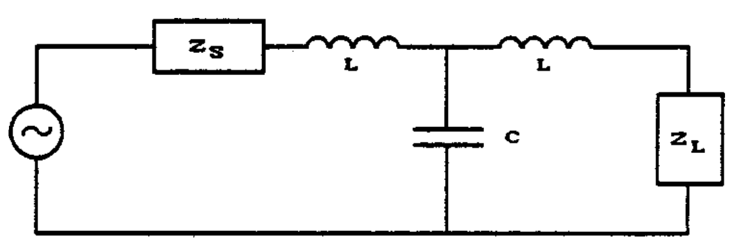

FIGURE 6. "T" section filter.

9.5.1.2.6 Pi section. This circuit should be used whenever Z_S and Z_L are large in value or are inductive.

If Z_S and Z_L are both large,

$$\text{Attenuation} \approx 20 \log \left[\omega^2 LC + \frac{LC^2\omega^3 Z_S Z_L}{Z_S + Z_L} + \frac{2\omega C Z_S Z_L}{Z_S + Z_L} \right]$$

It can be seen that, as Z_S and Z_L increases, the attenuation increases for Pi filters.

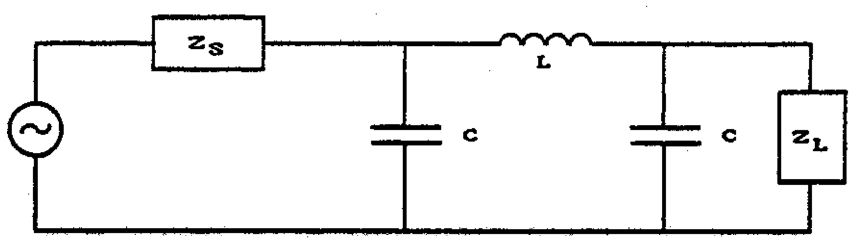

FIGURE 7. Pi section filter.

9.5.1.3 Selection of materials. Magnetic materials generally used for these filters are molypermalloy powder, iron powder and ferrite beads. Molypermalloy powder and iron powder cores are stable with temperature and load current, but ferrite beads become unstable when load current and temperature increase. Ceramic materials generally used for these filters are Z5U, X7R, and BX dielectrics. However, for space use, X7R/BX dielectrics should be considered with limitations on voltage stress and temperature coefficients. BX and X7R (lower range of dielectric constant) are more stable with higher voltages and temperatures. Like ferrites, Z5U becomes unstable when load voltage and temperature increases.

The following guidelines should be considered in the filter construction.

a. Plating and marking should be resistant to solvents.

b. The plating composition and solder composition should be compatible. The melting point of the solder should not be lowered after mixing with the plating material.

c. Encapsulant used in the filter construction should have a low moisture absorption coefficient, good adhesion to metal, good thermal shock resistance, and a low expansion coefficient.

9.5.2 Mechanical considerations. Once a filter has been selected for a particular application, its contribution to EMI control should not be degraded through faulty installation. Quite often, filter insertion loss characteristics are compromised by improper application. The following guidelines are suggested for proper application.

a. Filters should be installed close to the problem areas they are to correct.

b. The mounting area should be free of foreign particles and nonconducting finishes and surfaces to maintain a zero impedance current path through the metal-to-metal contact. This will provide good grounding and bonding, which will enable the design objectives of the filters to be achieved.

c. Filters should not be held with pliers or other gripping tools. Pressure exerted on the filter case may crack the ceramic element.

d. The specified mounting torques should not be exceeded.

e. Isolation should be provided between the input and output terminals of a filter by the use of an rf-tight bulk head.

9.5.3 Thermal considerations. A filter's reliability may be degraded by the improper application of heat. The following guidelines are suggested.

a. A heat sink should be used when attaching leads. Methods such as preheat, slow heating, and uniform heating should be used. The same precautions apply when cooling down the devices.

b. Filter leads or terminals should not be heated for long periods (5 to 10 s maximum).

c. Soldering iron tip temperatures should not exceed 450 °F.

d. Filters should be allowed to cool to room temperature before cleaning.

9.5.4 Equipment EMI requirements. Equipment EMI requirements vary, therefore it is important that the filter parameters be adequately specified on the specification control drawing. Various combinations of inductance and capacitance, as supplied by various vendors, might meet the specified insertion loss requirements as measured per MIL-STD-220, but system EMI characteristics could vary drastically as measured with various combinations of different vendors' filters.

Probably the simplest method of insuring continuing compatibility of filter and system requirements is to specify the filter circuit, minimum inductance, capacitance values, and minimum insertion loss characteristics over the required frequency range.

9. FILTERS, ELECTRICAL

9.6 Environmental considerations. Filter construction should be such that it can meet the shock and vibration requirements of the intended application. Materials used in the construction should be capable of withstanding thermal shock and be capable of resisting solvents and soldering heat. The materials should also be capable of meeting the outgassing and radiation requirements of space application.

9.7 Reliability considerations.

9.7.1 Failure modes and mechanisms. The possible failure modes of interference filters are determined by the number and types of parts making up the filter. The most common failure modes are:

a. Shorts

b. Opens

c. Low insertion loss.

Shorts. Catastrophic failure by shorting of a capacitor is probably the most common failure mode, and the frequency of occurrence is a function of the quality of the capacitors used and the stress to which they are subjected. Many EMI filters are exposed directly to the hazards of power line variations, and the combined effects of ac heating of the capacitors and power line transients can result in early life failure of marginal designs.

Opens. Opens are usually the result of poor solder joints. In addition to marginal joints which are sometimes made by the filter manufacturer, careless assembly techniques by the user can result in remelting of the internal joints and subsequent opens during equipment operation. This problem is particularly important with power line filters, because of the heavy lead wires which are often required for such applications. To minimize this problem, the user should specify that high temperature solder be used by the manufacturer on terminations which will be subjected to solder heat during subsequent user assembly operation.

Low insertion loss. Low insertion loss can be caused by an open capacitor, a shorted inductor, poor solder joint, improper grounding of internal shielding, or a bad capacitor. Insertion loss may also be low at full rated current because of saturation of the inductor, or may be low at temperature extremes due to capacitance temperature coefficient. These latter two faults, however, are design deficiencies rather than true failure modes.

9.7.2 Screening. Screening techniques for EMI filters are essentially the same as those normally applied to the type of capacitor used in the construction of the filter. Thermal shock cycling and operating burn-in have been found to be effective in stressing the filters. For effective screening, limits should be imposed on capacitance change and dissipation factor (at some specified high frequency), after the thermal shock and burn-in tests. Ideally, the burn-in would be conducted at full rated current and full rated voltage, but application of rated current is usually only marginally effective from a cost standpoint. Unless the I^2R losses in the inductors are high, which would be poor design practice, simple voltage burn-in will screen most defects. Most failures in normal operation are the result of capacitor breakdowns. Inductor failures are usually the result of external overloads, rather than degradation of the inductor itself. However, for applications where high reliability is the prime consideration, application of rated current during burn-in is recommended.

9.7.3 Reliability derating. Interference filters should be voltage derated in the same manner as is recommended for the capacitors used. Refer to derating criteria in MIL-STD-975. This is particularly important on filters which are directly across system power lines. Such devices must be capable of withstanding all voltage variations and transient conditions encountered in its application. Derating under normal conditions will insure that transient peaks do not exceed the voltage rating of the capacitors used.

Severe current derating is normally not required, provided that the device is designed such that its internal temperature rise is low. Filters designed to meet the requirements of MIL-F-28861 have an allowable temperature rise of 25 °C maximum, as measured at the case hot spot.

9.7.4 Failure rate. The failure rate of an interference filter is usually taken as the sum of the failure rates of its internal components. For prediction purposes, the latest available data for the individual parts, such as is available in MIL-STD-217, should be consulted.

9. FILTERS, ELECTRICAL

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10. TRANSFORMERS AND INDUCTORS

10.1 General.

10.1.1 Introduction. This section contains information on transformers, inductors, and radio frequency coils. MIL-STD-975 (NASA Standard Electrical, Electronic, and Electromechanical (EEE) Parts List) specifies inductor coils but contains no specific transformers. Instead, it specifies that all transformers be procured to the requirements of MIL-STD-981 (Design, Manufacturing and Quality Standards for Custom Electromagnetic Devices for Space Applications). This section will describe transformers and inductors in terms of the appropriate military specifications and MIL-STD-981.

In its most elementary form, a transformer consists of two inductively coupled wire wound coils. When alternating current at a given frequency flows in either coil an alternating voltage of the same frequency is induced in the other coil. The value of this voltage depends on the degree of coupling and the flux linkages in the two coils. The coil connected to a source of alternating voltage is usually called the primary coil and the voltage across this coil is the primary voltage. Voltage induced in the secondary coil may be greater or less than the primary voltage, depending on the ratio of the primary to secondary turns. Accordingly, a transformer is termed a step-up or a step-down transformer.

Most transformers have stationary iron cores around which the primary and secondary coils are wound. Because of the high permeability of iron, most of the flux is confined to the core, and a greater degree of coupling between the coils is thereby obtained. So tight is the coupling between the coils in some transformers that the primary and secondary voltages bear almost exactly the same ratio to each other as the turns in the respective coils or windings. Thus, the turns ratio of a transformer is a common index of its function in raising or lowering voltage.

Inductors are used in electronic equipment to smooth out ripple voltage in direct current (dc) supplies so they carry dc in the coils. It is common practice to build such inductors with air gaps in the core to prevent dc saturation. The air gap, size of the core, and number of turns depend upon three interrelated factors: inductance desired, current in the winding, and ac voltage across the winding. The number of turns and the air gap determine the dc flux density, whereas the number of turns, applied voltage, applied frequency, and core size determine the ac flux density. If the sum of the two flux densities exceeds the saturation value, then noise, low inductance, and nonlinearity result.

Radio frequency transformers and coils without iron cores or with small slugs of powdered iron are commonly used in electronic circuits. In air core transformers all the current is exciting current and induces a secondary voltage proportional to the mutual inductance. Radio frequency coils are used to pass dc and present high impedance to ac signals of radio frequency.

10.1 TRANSFORMERS AND INDUCTORS, GENERAL

10.1.1.1 Applicable military specifications. Applicable military specifications are listed below:

Mil Specs	Title
MIL-T-27	Transformer and Inductors (Audio, Power, and High-Power Pulse)
MIL-C-39010	Coils, Fixed, Radio Frequency, Molded, Established Reliability
MIL-T-21038	Transformers, Pulse, Low Power
MIL-C-83446	Coils, Radio Frequency, Chip, Fixed and Variable

10.1.2 General definitions.

Air gap. A nonmagnetic discontinuity in a ferromagnetic circuit. The term is used even when the space is filled with such nonmagnetic materials as wood or brass.

Audio frequency. Any frequency audible to the normal human ear. Audio frequencies range from 15 to 20,000 Hz.

Choke. A coil which conducts dc but impedes the flow of ac due to its inductance.

Coil. A conductor wound in helical or spiral shape to form an inductor. Also, a number of turns of wire wrapped around a rod or tube of either ferromagnetic or insulating material. Coils offer considerable opposition to the passage of ac but very little opposition to dc.

Core. A magnetizable portion of a device or component such as an inductor or transformer.

Corona. An electrical discharge into the atmosphere from a high voltage circuit. It can usually be heard as a hiss and seen in the dark as a purplish light near sharp points carrying high voltage.

Degauss. Demagnetize.

Differential transformer. A transformer that connects two or more signal sources to a single transmission line, keeping them isolated from each other and from the line, and with an output proportional to the difference between the signals.

Efficiency. Ratio of the useful power output obtainable from a device to the total input power required by the device.

Ferromagnetic. Capable of being highly magnetized.

Harmonic distortion. The distortion of the shape of the sine wave of the fundamental frequency due to the addition of harmonics of the fundamental frequency.

Hotspot temperature. The highest temperature witnin the coil. It is important because it is necessary to restrict the temperature of the insulation to a safe operating value.

Inductor. A coil inserted in a circuit to supply inductance. It may have a magnetic core, nonmagnetic core, or air core.

Insertion loss. At a given frequency, the insertion loss of an element connected into a system is defined as the ratio of voltage appearing across the line immediately beyond the point of insertion, before and after insertion.

Leakage. Electrical loss due to imperfect insulation. It is the undesired flow of electricity through or over an insulator.

Magnet wire. Insulated copper wire used in the winding of coils. Usually it is solid and enameled and/or covered with cotton.

Permeability. A measurement of the ability of a material to conduct the lines of force of a magnetic field. The permeability of air is considered to be unity and the permeability of other materials is measured in relation to air.

Primary. The current-carrying transformer winding which, through induction, generates a current in the secondary winding.

Q. The ratio of energy stored to energy dissipated in a device. In an inductor, the ratio of reactance to effective series resistance at a given frequency. A measure of frequency selectivity or the sharpness of resonance.

Radio frequency. Any frequency from 10 kHz to 10,000 MHz.

Resonance. The resonant frequency of a circuit is the frequency at which the inductive reactance is equal to the capacitive reactance.

Ripple. The ac component in the output of a dc power supply.

Saturation. The point in magnetic field beyond which the magnetic material cannot be further magnetized.

Secondary. The transformer winding in which voltage is electromagnetically induced by the primary.

10.1 TRANSFORMERS AND INDUCTORS, GENERAL

Shield. A conducting material that provides an electromagnetic barrier between portions of circuits.

Steady state. Pertains to the condition of a circuit or component in which all values remain constant after all transient effects have disappeared.

Toroid coil. A coil of wire wound around a doughnut-shaped core.

Transformer. An electromagnetic device used to increase or decrease ac voltage. If the voltage is increased the current is decreased and vice versa, so that the power is unchanged, except for the losses in the transformer.

Waveform. The shape of an electromagnetic wave or its graphic representation showing the variations in amplitude with time.

Winding. A continuous conducting path, usually wire, generally formed into an electromagnetic coil.

10.1.3 NASA standard parts. NASA standard parts are as listed in MIL-STD-975, section 6 for inductors, and section 12 for transformers. The transformer section contains no specific parts but requires that procurement of transformers be made to the requirements of MIL-STD-981.

10.1.3.1 MIL-STD-981. MIL-STD-981 is the design manufacturing and quality standard for custom electromagnetic devices for space applications. All transformers, and MIL-C-83446 chip inductors if used in Grade 1 applications, shall be procured to the requirements of MIL-STD-981. MIL-STD-981 establishes the requirements for acceptable design, manufacturing, and quality criteria for custom electro-magnetic devices for space applications. It includes provisions for Class S parts intended for critical flight and mission-essential ground support applications as well as for Class B parts for noncritical applications.

10.1.4 General device characteristics.

10.1.4.1 Audio, power, and high-power pulse transformers and inductors. These types of components include transformers and inductors weighing 300 pounds or less, having rms test voltage ratings of 50,000 V or less, or high-power pulse transformers where the peak pulse power is greater than 300 W and the average pulse power is greater than 5 W.

10.1.4.2 Low-power and pulse transformers. Low-power pulse transformers have peak pulse power of 300 W or less and an average pulse power of 5 W or less.

10.1.4.3 Low-frequency transformers. Transformers used in power supplies generally operate at a single frequency that is usually in the lower frequency range of 25 Hz to 400 Hz. In low-frequency applications, the leakage impedance due to Lp is small with respect to the winding resistance (r) and the effect of the capacitive shunt impedance can be neglected when compared with the primary inductance. The equivalent circuit for the low-frequency case can be simplified as shown in Figure 1.

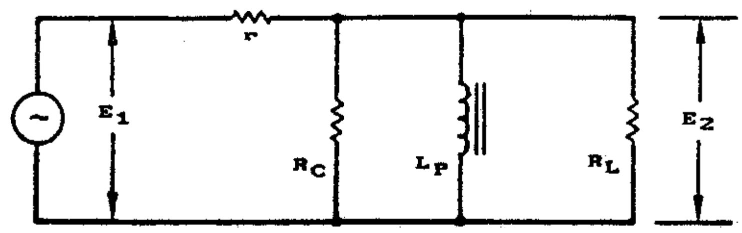

FIGURE 1. Low-frequency transformer equivalent circuit.

The primary current consists of the load current E_2/R_L and an excitation current. The excitation current is actually two out-of-phase currents, a resistive current due to the core losses and a magnetizing current controlled by the shunt inductance. In case of a resistive load, the voltage drop across the series resistor (r) substracts almost directly from the primary voltage E1 (the excitation current is generally small compared with the load current). At low frequencies, the phase angle between input and output voltage is mainly affected by the resistive losses (r) and primary inductance (Lp).

$$\tan \beta = \frac{r}{2 \pi f L_p}$$

10.1.4.4 High-frequency transformers. Transformers used in pulse applications generally operate at much higher frequencies than power transformers. In order to transmit the applied pulse shape with as much fidelity as possible, the transformers must have a relatively wide frequency band response. The low frequency response of the transformer affects the pulse width, whereas the upper frequency response affects the pulse rise and fall time. An acceptable method of estimating the rise time from the upper cutoff frequency (fc_2 - 3 db point) of the transformer is:

$$t_r = \frac{0.35}{fc_2}$$

The equivalent circuit of a high-frequency transformer is shown in Figure 2.

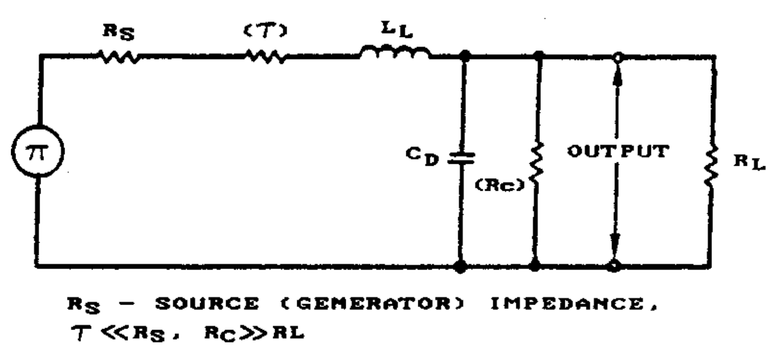

FIGURE 2. High-frequency transformer equivalent circuit.

10.1 TRANSFORMERS AND INDUCTORS, GENERAL

10.1.4.5 Coils. The rf coil is used to pass direct current and to present a high impedance to radio frequency currents. Applications of rf coils include discriminator circuits, oscillator and frequency multiplier tank circuits, and filters.

10.1.4.6 Saturable reactors. Transformers used as saturable reactors in magnetic amplifier circuits generally use cores with square B-H loop characteristics. The magnetic characteristics of the pair of cores, which are usually of toroidal shape, are matched in sets. Each core is individually wound with one or more gate windings. The coils are then stacked together and control windings are wound over both cores. There are many variations of windings and core shapes--single cores, E cores with gate windings on the outside legs, and control windings on the center leg, or other core types and shapes--but the principle of operation is the same. The rule of equal magnetomotive forces requires that the primary and secondary ampere-turn products be equal. The varying ac impedance of the gate winding controls the amount of signal that the load is receiving. The dc current through the control windings saturates or desaturates the core to various degrees and thus controls the impedance of the gate windings.

10.1.5 General parameter information. The following general terms and equations are helpful to understand and evaluate general characteristics of transformers and inductors.

10.1.5.1 DC resistance. Coil dc resistance tolerances vary greatly with the wire size used for winding. On fine wire coils, it is impractical to maintain tight dc resistance tolerances. When specifying Q and dc resistance of the inductor, the values must be compatible or the dc resistance specification should be omitted.

10.1.5.2 Inductance and related parameters. When the flow of electric current through a coil is varied, the resulting change in the magnetic field surrounding the coil causes a voltage to be induced in the coil, which opposes the supply voltage. This results in the coil having "self inductance" or simply "inductance." Inductance can be defined as that property of an electric circuit which opposes any changes in the current flowing in the circuit.

Inductance (L) represents a factor by which the rate of change of current is multiplied to obtain the induced electromotive force (EMF):

$$e = (-L)\ (di/dt)$$

The constant is called the coefficient of self-induction and is measured in henries (H). One henry equals an induced EMF of 1 V for 1 A per second rate of change of current. The minus sign indicates that the self-induced voltage is opposite in polarity to the supply voltage.

10.1 TRANSFORMERS AND INDUCTORS, GENERAL

The amount of inductance is determined by the amount of flux linking a given coil, which depends on the number, size, and arrangement of the turns forming the coil and the presence or absence of magnetic substances in the core of the coil.

Flux linkages represent energy stored in the form of magnetic flux. The amount of such energy depends on the inductance and current.

$$W = LI^2/2$$

Thus, an inductor can be also considered an energy storing device. The term LI^2 establishes the size of the inductor.

The flux (Ø) is defined as the total number of lines of force and is measured in lines or maxwells (Mx). Flux density (B), the number of lines per unit area, is measured in gauss and represents the number of maxwells per square centimeter. The flux density is proportional to the magnetizing force (H), the proportionality factor being the permeability (μ) of the medium, or:

$$B = \mu H$$

The magnetizing force (H) is a measure of the work required to move a unit pole one cm against the field and is measured in oersteds (Oe). The work required to move the unit pole around the total magnetic path is defined as the magnetomotive force and is expressed in Gilberts (Gb). The magnetomotive force is proportional to the product of amperes and turns and does not require that the turns be distributed evenly over the entire magnetic path.

In order to have an inductance, a core of magnetic material is not essential. It is often omitted at high frequencies. At medium and low frequencies, however, a magnetic core is essential for all but the lowest values of inductance.

The ratio of the number of lines in a given medium to the number of lines which the same magnetizing force would produce in air is termed the "permeability" of the medium. In an iron core, the flux density (B) is not a linear function of the magnetic intensity (H). Therefore, the permeability (μ), representing the slope of the B-H curve, is not a constant. Furthermore, the permeability also depends on the "past history" of the iron core, a phenomenon known as core "hysteresis".

Permeability can be further complicated by direct current flowing in the coil. In this case, the incremental permeability is of prime importance in establishing the inductance, i.e., the permeability of magnetic material to alternating currents superimposed on direct current. This is defined as the permeability of the material to small increments of alternating magnetomotive force. Permeability in the concept of flux density and field intensity is analogous to permittivity of dielectric substances in electric fields. While permittivity of dielectrics is usually independent of the magnitude of the electric field intensity, permeabilities of ferromagnetic substances are critically dependent on magnetic field conditions.

10.1 TRANSFORMERS AND INDUCTORS, GENERAL

An inductor usually has ohmic losses which can be represented as a resistance (R) in series with the inductance. When a voltage (V) is applied across that inductor, the current rises gradually to its steady value (V/R), following the logarithmic curve:

$$I_d = (V/R)\ (1 - e^{-t/T}),\ \text{where } t = L/R$$

The term L/R, called the time constant, represents the time in seconds required for the current to reach 63.2 percent of its final value.

The decay of current in an inductor will also follow a logarithmic curve given by the formula:

$$I_d = (V/R)\ (e^{-t/T})$$

The L/R ratio for a given inductor within the winding space factor variation is a constant. For example, doubling the number of winding turns increases the inductance by a factor of 4. However, to fit in the core window space, twice the turns requires half the wire size, which results in a resistance increase by a factor of four.

Inductors are widely used in electronic and electrical equipment. Such coils are generally designed for a specific application whenever the end use is known. The performance of a coil, besides being affected by its shape, size, and core material, can be drastically influenced by the mode of operation. In order to establish the performance of an inductor under actual field conditions, measurements should simulate, as closely as possible, the operating conditions of that coil.

10.1.5.3 Quality factor (Q). In addition to the inductance of a coil, the most important parameter describing the efficiency or quality of the inductor is the quality factor. When alternating current flows through a coil, energy is stored in the coil during a portion of the cycle. Most of the stored energy is fed back into the circuit later in the cycle. The difference between the stored energy and the returned energy is the energy dissipated in the coil. A perfect coil with no losses would return all the energy stored. The Q is the ratio of stored to dissipated energy per cycle. Q can be expressed as the quotient of the inductive reactance of the coil and the resistive losses. For a series representation, $Q = 2\pi fL/R$ (series) while for parallel, $Q = R$ (parallel)$/2\pi fL$.

10.1.5.4 Self-resonant frequency. When an inductor is placed in a circuit or across the terminals of a bridge, it represents a complex network which includes its inductance, resistance, and capacitance. If we neglect flux leakage between turns of the winding, which in most cases is insignificant, we can simplify the coil equivalent circuit to that shown in Figure 3.

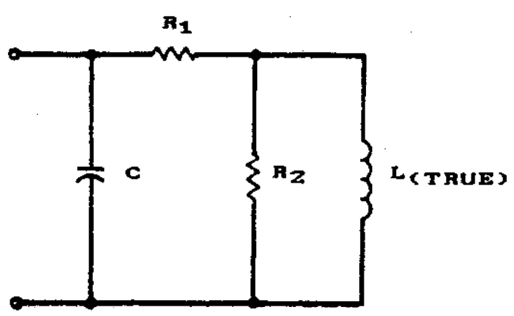

FIGURE 3. Equivalent circuit of a coil.

R1 represents the copper winding resistance and is generally independent of frequency. Only at extremely high frequencies would R1 appear to rise in value due to the "skin effect." R2, representing core losses, is a combination of three frequency-dependent losses: eddy current, hysteresis, and residual losses. These losses increase with frequency and flux level. Capacitor C represents the total shunt capacitance effect of the "between turns" capacitance and the capacitance from each turn to the core or ground. This capacitance forms a parallel circuit with inductance L, which resonates at the self-resonant frequency of the coil.

Due to this self-resonant effect, only those inductance measurements made far below the self-resonance of the coil will give the true inductance value of the coil. As the bridge frequency approaches the self-resonant frequency of the inductor, the apparent inductance measured differs (increases) from the true inductance according to the relationship

$$L\ (\text{Apparent}) = L\ (\text{True})/(1 - (f/f_0)^2$$

where f is the bridge frequency and f_0 is the frequency of the coil self-resonance.

The self-resonant frequency affects the apparent inductance of the coil and adds dielectric losses to it. In addition, it limits the useful frequency range of the coil.

10.1.5.5 Distributed capacitance. The net effective distributed capacitance (CD) of the coil has a direct effect on the self-resonant frequency. This capacitance can be measured directly on some commercial bridges, such as the Boonton "Q" meter. In general, the measuring frequency should be selected far above the self-resonant frequency of the coil.

10.1.5.6 Temperature rise. One important parameter often overlooked in high-current-carrying inductors is the temperature rise of the unit. This is directly related to winding resistance, core losses, and type and size of coil enclosure. Ambient operating temperature plus the self-generated temperature rise determine the operating temperature, life expectancy, and reliability of the inductor.

10.1 TRANSFORMERS AND INDUCTORS, GENERAL

10.1.6 General guides and charts.

10.1.6.1 Considerations when specifying inductors. Most transformers and inductors are designed for specific applications. When ordering these devices and using the military specifications as a baseline, the following information should be specified:

a. Inductance value, tolerance, applied voltage and frequency and dc load current at which it is measured

b. DC resistance and tolerance

c. Q value, tolerance, applied voltage and frequency and dc load current at which it is measured

d. Minimum coil self-resonant frequency

e. Permissible changes in coil parameters over the frequency range, voltage and current ranges, and temperature range

f. Dielectric strength and insulation resistance requirements

g. Static and magnetic shielding requirements

h. Description of inductor application and the associated circuitry

i. Environmental conditions: shock and vibration and maximum altitude

j. Permissible size and shape of inductor package: type of enclosure, (metal case, molded unit), type of termination, mounting method, outside coating (paint) and marking, and the total permissible weight.

10.1.6.2 Trade-off considerations. An existing transformer is frequently required for an application where some conditions are changed. Often the transformer can be used as is. However, at times the new application may require a modification of the design, even to the extent of changing the size and shape.

As the parameters and conditions subject to change are numerous, it is only possible to give some general guidelines for trade-off considerations. The guidelines and formulas referenced in this section still apply, however.

A power transformer, whose input voltage level is lowered, will have a correspondingly lower output power, but will generally not require a change in transformer design, provided the operating frequency is not changed and a slight improvement in regulation (increase of loaded output voltage) is acceptable. However, increasing the power output of a transformer will generally require a corresponding increase in the transformer size and weight. Note that transformer core sizes come in distinct steps. This may cause a slightly larger size increase than the power level would indicate.

Similarly, a reduction in the operating frequency may increase the transformer size. This may occur if the number of turns in the winding or the core cross-sectional area is appreciably increased in order to keep the flux level from going into saturation. An increase of the inductance requirement of winding will generally require an increase in the winding turns, although in some cases a change of core material or the core size can also increase the inductance.

Any dc resistance changes require a change of wire size, number of turns, or the mean turn length (winding location or core size). Interwinding capacitance and leakage inductance are to a great extent dependent on the physical winding configuration (spacing), number of turns, winding traverse and insulation materials. Increasing the spacing between windings reduces the capacitance but increases the leakage inductance between the windings. There are various methods of winding construction to minimize the leakage inductance and the dynamic capacitance.

For a pulse transformer to maintain a flat pulse with a minimum droop requires a given winding pulse inductance (large with respect to the winding and the source resistance). Increasing the pulse width results in a larger pulse droop. The droop can also increase when the pulse amplitude or the pulse repitition rate is increased. This results in an equivalent rise of the dc offset affecting the core permeability, and can even cause core saturation during the end portion of the pulse width.

10.1.7 General reliability considerations. The military-type electronic transformer is potentially one of the most reliable components utilized in electronic equipment. Because of similarity of construction, these general reliability considerations described herein are applicable to transformers, inductors and RF coils, although reference is made only to transformers.

From a dielectric viewpoint transformers have stress levels that are normally low when compared to other component categories. Electronic transformers have completely static parts well suited to adequate structural design techniques. In addition, relatively large thermal capacity generally exists in transformers to absorb unusual conditions of equipment under end use. However, because of many variables involved from the conceptual design stage through the final product stage, transformers sometimes become chronic reliability "offenders".

When trying to obtain maximum reliability of a magnetic component, one should recognize the vital effect of each link in the total chain from concept to use. Some of these links are under the ultimate user's control, some are the responsibility of the equipment manufacturer, and, certainly, a major responsibility rests with the component manufacturer.

In order to improve the reliability of electronic transformers, it is necessary to understand what causes failures before one can act to help prevent them. The following are general considerations of failure patterns and the principal stresses involved:

10.1 TRANSFORMERS AND INDUCTORS, GENERAL

10.1.7.1 Stress. Design safety factors and manufacturing controls should take into account the stresses a transformer will be subjected to in its lifetime. These stresses have an effect on the four basic parts of a transformer; the dielectric system, the conductive system, the structural system, and the magnetic system. Stresses of significance in electronic transformers are:

a. Temperature

b. Vibration

c. Mechanical shock

d. Humidity

e. Dielectric

f. Thermal shock.

In addition to their magnitudes, all of these stresses except dielectric have a significant interaction with time or number of cycles applied. The most important effects of the stresses are shown in Table I.

TABLE I. Effects of primary stress situations on electronic transformers

Stress	Effects
Temperature (long duration, steady state)	Chemically deteriorates insulation materials; weakens solder joints and connections; weakens structural parts; contributes to dielectric breakdown of insulation
Dielectric stress	"Plating" effect deposits conducting ions between parts that should be electrically far apart; deterioration effects as function of time are believed to be negligible in transformers
Vibration and mechanical shock	Contributes to failure of mechanical parts if limits are exceeded; detects weak weld joints; will cause loose electrical parts to move, abrade, and wear out
Thermal shock	Breaks wire, seams, etc., by fatiguing or simple stressing to breaking point; erodes insulation

In summary these stress effects are:

a. Temperature, vibration, mechanical shock, and thermal shock, directly age or degrade the transformer as a function of time; these four stresses interact significantly and are the sole causes of failures in all four transformer parts

b. Dielectric stress accelerates aging effects in the dielectric system.

Because a transformer is a composite of materials with various expansion coefficients, temperature changes establish mechanical stresses. These stresses vary widely as the transformer temperature changes. Therefore, it is important to minimize the mechanical stresses by proper selection of the core, windings, insulation, and impregnation materials, as well as the transformer construction.

Another cause of transformer failure is excessive voltage stress. High voltage stresses between windings, turns, terminals, or to ground (or core) may, if they exceed the dielectric withstanding ability of the insulation barrier, cause a breakdown of the insulation, which will result in transformer failure. Winding configurations, the shape of winding edges, and terminations (electrodes) can intensify electric fields, thus increasing electrical stresses considerably.

10.1.7.2 Failure modes. Failure modes are shown in Table II.

TABLE II. Failure modes in electronic transformers

System	Detection and Interaction
Dielectric	Turn-to-turn or layer-to-layer failures (within a winding) cause radical changes in transformer electrical performance. Heating by excessive current flow may be severe enough to cause failure in the conductive system. Turn-to-turn (between windings) and turn-to-ground failures also cause radical changes in the transformer electrical performance.
Conductive	Failure of current-conducting parts may cause catastrophic or parametric failure.
Structural	Failure of an external structural part may be detected visually, but may also induce failures in the dielectric and conductive systems. Internal structural part failures induce dielectric and conductive system failures.
Magnetic	Failure in the magnetic system is usually characterized by slow deterioration of the magnetic properties.

10.2 TRANSFORMERS AND INDUCTORS, AUDIO, POWER AND HIGH-POWER PULSE

10.2 Audio, power, and high-power pulse.

10.2.1 Introduction. This section covers audio, power, and high-power pulse transformers and inductors for use in electronic and communications equipment. These components are in accordance with MIL-T-27. They have rms test-voltage ratings of 50,000 V or less, and include high-power pulse transformers where the peak pulse power is greater than 300 W and the average pulse power is greater than 5 W.

10.2.2 Usual applications. Transformers are used in applications to optimally couple a load to a source, provide isolation, transform voltages and currents, match impedances, control and shape signals, and to shield and filter signals.

Transformers used to deliver power, whether rectified or not, generally operate at lower frequencies or at a single frequency, and are predominantly governed by different transformer elements than pulse transformers, which operate at much higher and wider frequency bands.

10.2.3 Physical construction.

10.2.3.1 Inductors.

Core materials. The two basic types of cores used in inductors are solid magnetic steel alloys and powder cores.

Magnetic steel cores are obtained in the form of laminations, C-cores, bobbins, sleeves, or toroids. Most magnetic steel alloys are extremely sensitive to mechanical stess from handling, winding pressure, or bending and must be protected to preclude distortion of magnetic properties. For this reason, many designs use cores placed in rigid aluminum or plastic boxes filled with a silicon compound for core cushioning.

Powder cores include molybdenum permalloy (moly-perm), ferrite, and powdered iron cores. Moly-perm cores are made by reducing the magnetic alloy material (nickel/iron/molybdenum) to a very fine powder and are then formed under high pressure and temperature to the desired shape. Ferrites are combinations of various metallic oxides formed into cubic polycrystalline structure by solid state reaction and then pressed and sintered into toroidal cups and other shapes. Powdered iron cores are made in a similiar manner. Powdered iron cores are superior to moly-perm cores at frequencies above 100kHz and are considerable cheaper than either moly-perm or ferrites.

Wire and winding. The most important element in an inductor is its winding. High-frequency toroidal inductors have been wound on "air cores" (that is, nonmagnetic cores) which were machined from wood or plastic merely to serve as a support for the winding.

The winding consists mainly of round insulated copper wire, although copper or aluminum sheet strips and square wires may be used.

10.2 TRANSFORMERS AND INDUCTORS, AUDIO, POWER AND HIGH-POWER PULSE

Due to the high abrasion experienced by the wire during winding, toroids are generally wound with a double (or multiple) insulated wire. Heavy nyleze- and heavy polythermaleze-type insulated wire are used extensively. Nyleze is a wire coating with very high abrasion resistance and is rated for operating temperatures up to 130 °C. Nyleze-coated wire is solderable and has an advantage in production in that it can be soldered directly at the termination. Polythermaleze is a high-temperature wire rated up to 200 °C and it also has a high abrasion resistance. However, it cannot be soldered directly. The insulation must be stripped off, either chemically or mechanically.

Several types of toroidal winding methods are employed. Continuous winding is employed for inductors used at low frequencies. This winding puts the most wire on the core and results in the highest L/R ratio. The wire turns are applied parallel, traversing a multiple of 360 degrees on the core in one direction.

For medium- and high-frequency applications, the effect of distributed capacitance in the coil must be taken into consideration. Consequently, a winding scheme (either bank or progressive) to minimize coil capacitance may be used. They result in somewhat higher winding resistance, as wire one size finer often must be used (compared with a continuous winding) to accommodate the turns required for the inductance. A bank winding consists of several distinct winding sections or segments. Progressive winding is a bank winding with a large (continuous) number of banks; that is, the entire winding is applied in one 360 sweep.

Effect of coil embedment on coil capacitance. The capacitance of the coil is affected not only by the wire insulation and type of winding but also by the coil impregnating and potting compounds. Generally, distributed capacitance is increased by the impregnant, as most of the impregnants have a dielectric constant greater than unity. For low distributed capacitance in a coil, dry air is the best dielectric. Coils operating at high frequencies are often embedded in tiny glass-sealed air bubbles or just sealed in a dry nitrogen atmosphere. Potting compounds vary from waxes and tars to a wide variety of epoxies. The coils are often coated with silicone rubber, which cushions the coil from pressures exerted by the potting compound.

Enclosures. Three types of enclosures (open coil, molded coil, and metal-encased coil) are used for inductors.

Open coils have the least environmental protection. They consist mainly of a winding wound on a core and terminated with plastic insulated leads. Open coils are frequently coated on the outside with plastic, which serves less for environmental protection than for mechanical protection against scraping or breakage of the winding wires during handling. Open coils are normally not recommended for NASA applications.

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For environmental protection, coils must either be molded (encapsulated) or hermetically sealed (metal-encased). Encapsulated units meet stringent requirements of Grade 5 of MIL-T-27 and are generally smaller in size and less expensive than comparable metal-encased coils. Termination of the windings is also simpler and is provided by a variety of solder terminals, printed-circuit pins, or flexible insulated leads. In hermetically sealed coils, termination must be made through a sealed insulated terminal which is soldered into the case.

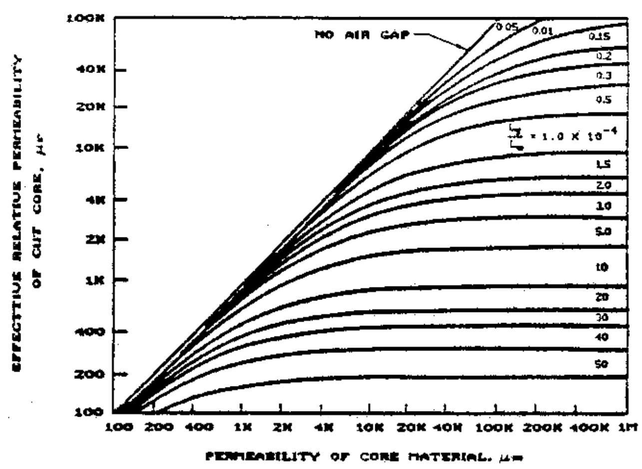
Generally, no mounting provision is made for open coils. Molded units, in addition to solidly embedded terminal pins, can be provided with a variety of mounting hardware, such as brackets, threaded metal inserts, or studs, thus offering inductors that can withstand high shock and vibration levels. Of course, metal-encased units can be supplied with the same mounting provisions and will withstand the most severe environmental stresses. Also, additional magnetic and static shielding can easily be provided for metal-encased units.

10.2.3.2 Transformers.

Cores. Most transformers have stationary cores in various shapes of thin iron alloy sheets, pressed powders, or ferrites. The high permeability of these cores confine the bulk of the flux to the core area and help achieve close coupling between the coils of a transformer.

In selecting the core material, consideration must be given to many core characteristics, such as core losses, saturation flux, magnetizing force, incremental permeability, operating temperature, and others. Some core characteristic information can be obtained from the core B-H (hysteresis) loop. The flux density is proportional to the magnetizing force (H), the proportionality factor being the permeability (μ) of the core material. Thus, the permeability is defined as $\mu = B/H$. The core data indicate that for most core materials the flux density (B) is not a linear function of the magnetic intensity (H). It also depends on the frequency, temperature, and level of operation. Therefore, the permeability (μ) representing the slope of the B-H curve is not a constant. Additionally, the permeability depends also on the core hysteresis. Permeability can be further complicated by a direct current in the coils. In this case, it is the incremental permeability (ie the permeability of the core material to small increments of alternating current superimposed on direct current) which is of importance. The introduction of an air (nonmagnetic) gap in the flux path of a core lowers the effective relative permeability. Figure 4 shows the relation of effective permeability to the core material permeability for various gap ratios.

The ratio of residual flux (B_r) to the saturation flux (B_S) indicates the "squareness" of the core, a characteristic that has a substantial effect on transformer operation, particularly in unidirectional pulse applications or with dc-biased windings (e.g., pulse transformers, saturable reactors, and magnetic amplifiers).



$$\mu r = \frac{\mu m}{1 + \frac{L_g}{L_m}\mu m}$$

WHERE: L_g = EFFECTIVE AIR GAP
L_m = MEAN CORE LENGTH

NOTE: CURVES NEGLECT STACKING FACTOR AND FRINGING FLUX. AIR GAP AND MATERIAL CROSS-SECTIONS ASSUMED TO BE EQUAL.

FIGURE 4. Effective permeability of cut core vs permeability of the material.

Cores are available in soft magnetic steels, ferrites, and powdered iron materials. The most significant advantage of ferrite over laminated and powdered iron cores is its high resistivity, which affords a dense homogeneous magnetic medium with high permeability, stable with respect to both temperature and time, but without the high eddy current losses inherent in conventional core materials.

10.2.4 Military designation. The designation of MIL-T-27 units is in the form depicted below. Note that MIL-STD-975 contains no transformers, all transformers must be procured to the requirements of MIL-STD-981.

TF	4	R	03	GA
Component	Grade	Class	Family	Envelope and mounting dimensions

a. Component. Transformers and inductors are identified by the two-letter symbol "TF."

b. Grade. The grade is identified by a single digit.

Grade 4. These units are metal encased, including such constructions as those having a metal shell, with separately fabricated headers which provide a hermetic seal.

Grade 5. These units are encapsulated, including molded or embedded constructions, or are units with a metal shell, open at one or both ends and filled with encapsulant material.

Grade 6. These units are open type and are generally intended for subsequent potting, molding, or embedment in an assembly with or without component parts.

c. Class. The class is identified by a single letter denoting the maximum operating temperature (temperature rise plus maximum ambient temperature).

d. Envelope and mounting dimensions. The envelope and mounting dimensions are identified by a two-letter symbol in accordance with MIL-T-27.

10.2.5 Electrical characteristics. Transformers and inductors are usually intended for custom applications and as such, MIL-T-27 provides provisions for specifying parameters. The following are typical ratings which should be specified:

10.2.5.1 Power transformers.

a. Nominal primary voltage and possible variation (taps on winding clearly defined)

b. Operating frequency range

c. Secondary rms load voltages with allowable tolerance at nominal input voltage and rated loads

d. Secondary rated rms and dc load currents and possible variations

e. Allowable regulation the basis for which shall be clearly stated; e.g., 5 to 100 percent load, over temperature range, etc.

f. Electrostatic shielding

g. Polarity of windings

h. Surge conditions and transient peaks

i. Corona limits, if absolutely necessary

j. Capacitive or inductive input if used in a rectifier or filter circuit.

k. Allowable dc resistance of each winding

l. Self-resonant frequency

m. Dielectric withstanding voltage limit.

10.2.5.2 Inductors.

a. Rated inductance and required limits at nominal rms voltage and frequency, and dc current

b. Allowable dc resistance

c. Quality factor (Q) at the specified voltage and frequency.

10.2.5.3 Audio transformers.

a. Source and load impedances

b. Allowable variations in primary impedance when operating at rated load on secondaries and at the specified frequency

c. Primary and secondary dc currents

d. Frequency response at the specified power level

e. Harmonic distortion

f. Insertion loss at the specified frequency

g. Self-resonant frequency

h. Electrostatic shielding

i. Magnetic shielding

j. Polarity

k. Phase shift

l. Resistive, inductive, and capacitive unbalances, if applicable

m. Allowable insulation resistance

n. Dielectric withstanding voltage limit.

10.2 TRANSFORMERS AND INDUCTORS, AUDIO, POWER AND HIGH-POWER PULSE

10.2.5.4 Winding inductance. The inductance of a winding is proportional to the square of the number of turns and the effective permeability of the magnetic medium, and inversely proportional to the total magnetic path length. With an air gap present in the magnetic path, the inductance (L) of a coil can be calculated as:

$$L = \frac{0.4\ \pi\ N^2 \times 10^{-8}}{\frac{L_m}{\mu A_m} + \frac{L_g}{A_g}}$$

where

L = coil inductance in henries
N = number of turns in the coil
L_m = magnetic length of the core in cm
L_g = length of the air gap in cm
A_m = core cross-sectional area in cm2
A_g = effective gap area in cm2
μ = core .ermeability.

10.2.5.5 Induced voltage. Most transformers have stationary cores in various shapes of laminations, pressed powders, or ferrites. The high permeability of these cores confine the bulk of the magnetic flux to the core area and help achieve close coupling between the coils of a transformer. The close coupling enables the primary and secondary voltages to have almost the same voltage per turn. Thus, an alternating voltage applied to the primary winding of a transformer induces in the secondary winding a voltage directly proportional to the winding turns ratio. The induced voltage is proportional to the rate of flux change and the number of secondary turns:

$$E = - \frac{Nd\emptyset}{dt} \times 10^{-8}$$

10.2.5.6 Flux density. Flux density (the number of flux lines per unit area of the core cross-section) is an important parameter that characterizes the ability to contain the flux within the magnetic core. For a sinusoidal voltage applied to a winding, the flux density is:

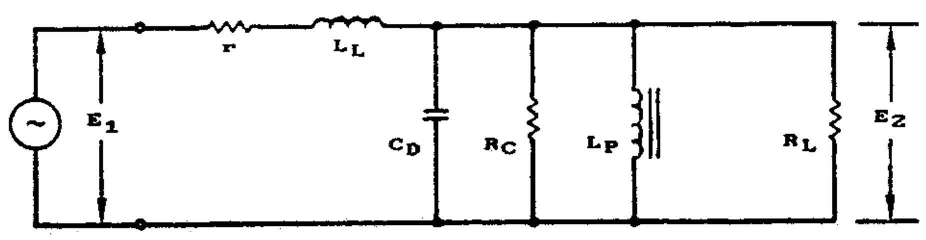
$$B = \frac{E \times 10^8}{4.44 \times f \times N \times A}$$

where

B = flux density (gauss)
E = voltage (rms)
f = frequency (Hz)
N = number of turns in winding
A = effective core cross-section area in square centimeters.

10.2.5.7 Equivalent circuit representation. Most transformers are not ideal. They have finite inductance (permeability), winding resistance, core losses, leakage inductance, and dielectric losses, and the core flux capacity is limited. Therefore, the induced voltages and the output voltages do not exactly correspond to the winding turn ratios and the regulation of a transformer usually cannot be neglected.

A transformer can be represented in an equivalent circuit (shown in Figure 5) with all important transformer elements represented as lumped parameters and reflected to one side (e.g. primary), including the load impedance (R_L). All impedances are reflected by the square of the turns ratio.



where

r = primary and reflected secondary winding resistances
L_L = primary and reflected secondary leakage inductances
C_D = distributed capacitance represented as a total shunt capacitor
R_C = shunt resistance equivalent to the core losses
L_p = primary open circuit inductance
R_L = load impedance.

FIGURE 5. Transformer equivalent circuit.

10.2.6 Environmental considerations. The major environmental conditions affecting transformer and inductor life and performance and influencing the methods of construction and protection of such devices are as follows:

10.2.6.1 Temperature. Temperature has the following effects on transformer construction.

a. Magnetic materials. These materials must be selected so that their variations with temperature will not result in appreciable variations in circuit performance.

b. Insulation. Class of insulation material and allowable winding temperature rise must be selected to give the required life at maximum operating temperature.

10.2 TRANSFORMERS AND INDUCTORS, AUDIO, POWER AND HIGH-POWER PULSE

c. Sealing. Materials and type of construction must be such that wide temperature range and rapid cycling over this range will not degrade the moisture seal.

d. Regulation. When regulation is critical, design techniques must be applied to minimize copper losses and to deliver normal secondary voltage at rated load and at design center temperature.

10.2.6.2 Altitude. High-altitude, low-pressure operation affects the dielectric properties of insulation and the temperature rise. Because voltage breakdown strength and the corona-inception voltage of air are affected by the air density, internal insulation and spacing must be designed for the lower pressure at higher altitudes.

Another factor in high-altitude operation is the temperature rise in the transformer where significant power is dissipated. At ground-level altitudes under 10,000 feet, much of the heat dissipated in the transformer can be carried away by conduction, convection and radiation. As the altitude is increased and air density decreased, the rates of conduction and convection are reduced and the heat must be almost entirely removed by radiation. As a result, the temperature rise of a transformer with a given power loss increases substantially with altitude. Care must be taken in locating the transformer within a package, considering the effect its temperature rise may have on other components.

10.2.6.3 Vibration, shock, and acceleration. Power transformers and inductors usually have a higher mass to size ratio and are unusually susceptable to vibration and mechanical shock. Mountings may be damaged as may winding and lead wires if they are not properly secured.

10.2.6.4 Explosive atmosphere. Explosive atmospheres generally do not cause deterioration of transformer parts. However, a spark which could be the result of a failure from some other cause could be disastrous. For this reason, transformers used in explosive atmospheres should be hermetically sealed.

10.2.6.5 Radiation. Some insulation materials used in transformers and inductors may deteriorate when exposed to radiation. Magnetic properties, however, are not affected.

10.2.7 Reliability considerations. The following failure mechanisms are common causes of transformer and inductor failures.

10.2.7.1 Excessive primary voltage. Excessive primary voltage induces excessive voltage in the secondary windings. The overvoltage may lead to immediate puncture of the insulation or to premature breakdown. The overvoltage on the primary will saturate the core and increase the input current, which increases the core and copper heat losses. This results in excessive temperature and rapid deterioration of the insulation system.

10.2.7.2 Excessive secondary currents. Excessive secondary currents will result in a corresponding increase in primary current which will cause over-heating in both windings. This will cause a rapid deterioration of the insulation system, open or short circuited windings, or misshapen or broken containers, as a result of rapid expansion of the potting or filling materials.

10.2.7.3 Input frequency fluctuations. Operating frequencies below the lower design range limit will result in low reactance due to core saturation and higher than rated input current. This will result in overheating of the transformer and rapid deterioration of the insulation system.

10.2.7.4 Corona. This phenomenon occurs at points of high voltage stress and causes accelerated aging of the insulation by the liberation of ozone and by increasing temperatures. It creates weak spots in the insulation that eventually lead to insulation breakdown.

10.2.7.5 Other causes. Most transformers and inductors fail as a result of insulation breakdown resulting from insulation embrittlement and degradation of insulation resistance due to exposure to excessive hotspot temperatures. Open circuits occur in some instances because of poor wire terminations and mechanical structures that are inadequate to support the unit. Poor workmanship in coil winding and inadequate location of insulation contribute to failures because of opens resulting from broken wires and short circuits between uninsulated current-carrying parts. Poor workmanship in soldering connections and incorrect techniques of making wire joints are also common causes of failures.

10.2.7.6 MIL-STD-981. MIL-STD-981 establishes the requirements for acceptable design, manufacturing, and quality criteria. Transformers and inductors must meet the criteria and quality assurance provisions identified in that Military Standard.

10.3 TRANSFORMERS AND INDUCTORS, PULSE TRANSFORMERS

10.3 Pulse transformers.

10.3.1 Introduction. This section covers low-power pulse transformers used in electronic and communications equipment. These components are manufactured to meet the requirements of MIL-T-21038 and are transformers where the peak pulse power is 300 W or less and the average pulse power is 5 W or less.

10.3.2 Usual applications. Low-power pulse transformer applications fall into two categories:

a. Those applications which may be characterized as coupling or impedance matching

b. Those applications in which the transformer acts in conjunction with some nonlinear element such as a transistor to form a pulse-generating circuit. Most applications in this category are blocking oscillator circuits.

All applications which can be discussed in terms of generator constants, load impedances and desired pulse responses fall into the first category defined above. All others are in the second This distinction between the two categories is emphasized because in a pulse generating circuit, the dynamic characteristics of other circuit elements have as much to do with the pulse shapes as the parameters of the transformer itself.

Some common applications of low-power pulse transformers are described below.

10.3.2.1 SCR circuits. Pulse transformers find broad application in silicon-controlled rectifier (SCR) speed and load control circuits. Commonly, they supply between 30 mA and 1 amp of current to an SCR gate. Although 1:1 is the most common transformer turns ratio in SCR circuits, often it is more convenient and economical to use a step-up transformer. Its voltage gain is especially useful in servo controlled motors and in speed-control applications where a transducer signal must be applied.

10.3.2.2 Blocking oscillator circuits. Another valuable use of pulse transformers is in blocking oscillator circuits. The transformer should have an in-circuit saturation time at least double the required pulse width. Then, by carefully selecting the values of components, the pulse width of the circuit may be reduced. The resulting circuit will be relatively unaffected by changes in transistor parameters or temperature.

10.3.2.3 Low power data bus coupling pulse transformers. Data bus coupling transformers provide signal coupling and fault isolation between the stub and the main data bus. Terminal interfaces must be designed to guarantee proper signal level and minimum distortion to achieve the desired bit and word error rates.

10.3.3 Physical construction. Low-power pulse transformers are generally small in size because of the low-power requirements. The outer surface of the transformer may be a metal shell for magnetic shielding or it may be the potting material in its normally molded shape or conformally coated configuration. These small parts are usually mounted by their lead wires. Many designs are used in printed circuit construction, where they are mounted by their lead wire pins. Figure 6 demonstrates a typical outline drawing.

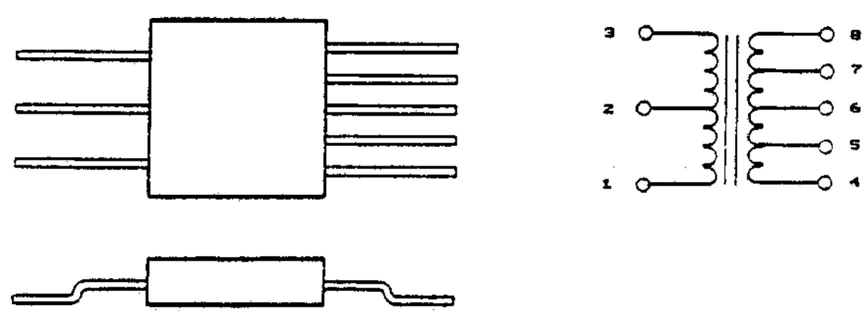


FIGURE 6. Typical outline drawing and schematic.

The internal construction of a low-power pulse transformer consists of a magnetic core with two, three, or four coil windings wound on the core which are insulated from each other. The ends of the coil windings are soldered to lead wires which serve as external electrical connections to the transformer. The core and coil windings are encapsulated with an insulation potting material, which adds additional insulation, serves as a protection from moisture, and provides mechanical support for the core and coils.

10.3.4 Military designation. The type designation specified in MIL-T-21038 is in the form depicted below. Note that MIL-STD-975 contains no transformers. All transformers must be procured to the requirements of MIL-STD-981.

TP	4	Q	X	1100	B	C
Component	Grade	Class	Life expectancy	Turns	Style	Envelope dimensions

10.3 TRANSFORMERS AND INDUCTORS, PULSE TRANSFORMERS

Component. Low-power pulse transformers are identified by the two-letter symbol "TP."

Grade. The grade is identified by a single digit.

Class. The class is identified by a single letter denoting the maximum operating temperature (temperature rise plus maximum ambient temperature).

Life expectancy. The life expectancy is identified by a single letter.

Turns ratio. The turns ratio for the first four windings is identified by a four-digit number.

Style. The style is identified by a single letter, in accordance with MIL-T-21038.

Envelope dimensions. The envelope dimensions are identified by either a single letter or two letters, in accordance with MIL-T-21038.

10.3.5 Electrical characteristics. Pulse transformers are usually intended for custom applications in which parameters are tailored to the circuit. MIL-T-21038 has provisions for specifying these parameters. Following are typical ratings which should be specified.

a. ET constant
   E is pulse amplitude (in volts)
   T is pulse width (in microseconds)

b. Power level

c. Pulse waveform characteristics

d. Number of windings

e. Winding dc resistance

f. Turns ratio

g. Winding-to-winding capacitance

h. Open circuit inductance

i. Leakage inductance

j. Core material description

k. Magnetizing current

l. Winding structure

m. Dielectric strength test voltage

n. Induced test voltage

o. Insulation resistance test voltage

p. Environmental conditions

q. For coupling transformers, specify the source and load impedance and describe the input pulse and the desired output pulse.

10.3.6 Environmental considerations. The environmental considerations for low-power pulse transformers are essentially the same as those described for power devices (section 10.2.6). The low-power pulse transformers are usually small because of their low power requirements and thus are usually adequately designed to meet the requirements of shock and vibration. Units which are mounted by their terminal lead wires should be provided with additional mechanical support for the body.

Temperature cycling and thermal shock environments are the most severe environments for these parts. When adjacent materials have different rates of expansion with temperature changes, there are often stresses applied to the fine wire in the coil windings. If materials separate or crack during temperature change, the coil wires may break and cause an open coil winding.

10.3.7 Reliability considerations.

10.3.7.1 Usual failure mechanisms. The usual failure mechanisms for low-power pulse transformers fall into one of the following categories:

a. Broken coil wire

b. Insulation failure

c. Change in core characteristics.

Broken coil wire occurs most often where small diameter wire is used because of the low power requirement, and where the mechanical construction of the part is not adequate to withstand the mechanical stresses encountered in normal handling, or when exposed to normal environments. Circuit discontinuities also occur at failed solder joints where the wire is soldered to the terminal. These failures are due to faulty solder joints or excessive mechanical stress.

Insulation failures may occur between coil windings or between the current-carrying coils and the core, mounting structure or metal cases. These failures are caused by overvoltage stress on the insulation or the use of inadequate insulation, and when insulation is damaged by excessive mechanical stress on the insulation materials. Generally, the dielectric withstanding voltage and induced voltage tests are adequate to assure that insulation failures will not occur during normal operation.

10.3 TRANSFORMERS AND INDUCTORS, PULSE TRANSFORMERS

Change in core characteristics can be caused by mechanical forces on the core, high ambient temperature, exposure to magnetic fields and dc saturation of the core during dc resistance measurements of the coil windings. A change in the core characteristics will cause a detrimental change in the transformer pulse waveform parameters. Special consideration of the design, construction, handling, and testing of pulse transformers is essential for the preservation of the waveform parameters.

10.3.7.2 MIL-STD-981. MIL-STD-981 establishes the requirements for acceptable design, manufacture, and quality criteria. Pulse transformers must meet the criteria and quality assurance provisions identified in that military standard.

10.4 Coils and chip inductors.

10.4.1 Introduction. This section covers coils and chip inductors for use as inductive elements in radio frequency circuits. They are low profile, miniature devices suitable for use on printed wiring boards and in hybrid circuits.

10.4.2 Usual applications.

10.4.2.1 Coils. A radio frequency coil is used to pass direct current and present a high impedance to radio frequencies. The coil may have high radio frequency voltage across it. Typical applications are in oscillators, amplifiers, converters, and exciters. High stability and high Q characterize these inductors, which operate up to 200 MHz. Inductance values from 0.1 microhenries through 100 millihenries are available. Typical Q ranges from 50 to 80. These devices meet the requirements of MIL-C-39010 for established reliability coils.

10.4.2.2 Chip inductors. Fixed and variable chip inductors are primarily intended for use in hybrid microelectronic circuits and have termination systems suitable for solder attachment to alumina substrates. These devices are manufactured to meet the requirements of MIL-C-83446.

10.4.3 Typical construction.

10.4.3.1 Coils. Fixed radio frequency coils consist of a coil of insulated copper wire wound on a coil form. Two terminal wire leads are anchored in the coil form and the wire coil ends are soldered to the terminal lead wires. This internal assembly is encapsulated with a molded jacket of plastic insulating material or conformally coated with a protective coating such as varnish.

RF coils may be enclosed in housings of magnetic or conducting material to form electromagnetic shielding. Considerations of economy and good practice indicate that shielded coils should be used only in applications where the environmental and service conditions are severe and where space is at a premium. Advantages of shielding are the exclusion of unwanted pickup from random internal and external sources, the prevention of feedback which may cause oscillation, and the confinement of the magnetic and electrostatic fields generated by the coil itself.

Coil forms may be powdered iron, ferrite, ceramic or phenolic. Powdered iron and ferrite coil forms are used when high inductance values are required. The ceramic and phenolic forms are used for lower inductance values. The phenolic form is used where environmental conditions are not so severe as to require ceramic forms. Figure 7 shows a typical coil.

10.4 TRANSFORMERS AND INDUCTORS, COILS AND CHIP INDUCTORS

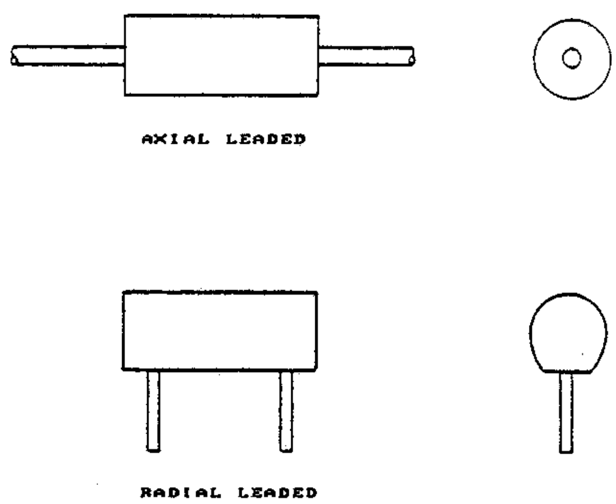
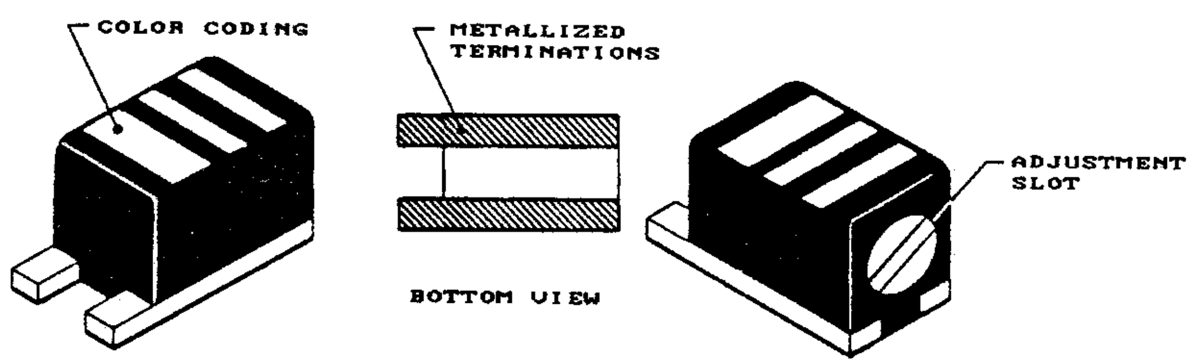


FIGURE 7. Typical outline drawing for RF coils.

10.4.3.2 Chip inductors. Chip inductors are miniature coils molded onto alumina substrates having metallized termination pads compatable with standard hybrid attachment techniques, as shown in Figure 8.



A. Fixed B. Variable

FIGURE 8. Typical outline drawing for chip inductors.

10.4.4 Military designation.

Coils per MIL-C-39010. MIL-C-39010 is an established reliability specification. It designates parts as follows:

M	39010/01	A	1R0	K	M
Military designator	Document sheet	Class	Inductance	Inductance tolerance	Failure rate level

a. Class. A single letter denoting the maximum operating temperatures

b. Inductance. nominal inductance expressed in microhenries

c. Tolerance. single letter denoting tolerance

d. Failure rate level. letter denoting failure rate level.

Chip inductors per MIL-C-83446. The designation specified in MIL-C-83446 is in the following form:

M83446/05-	04	B
Detail specification	Dash number	Termination finish

a. Detail specification. The specification slash sheet

b. Dash number. Sequentially assigned number

c. Termination finish. A single letter denoting finish.

10.4.5 Electrical characteristics. Due to their small physical size, radio-frequency coils have low inductance values, ranging from 0.1 to 33 microhenries for all but the largest size (M39010/03). This device has inductance range up to 100 millihenry.

Chip coils have inductance ranges up to 1 millihenry for fixed inductors and 0.1 millihenry for variable inductors.

10.4.6 Environmental considerations. The environmental considerations for radio frequency coils are essentially the same as those described in the section "Transformers, power."

10.4 TRANSFORMERS AND INDUCTORS, COILS AND CHIP INDUCTORS

Radio frequency coils are small in size and, as a result, are usually adequately designed for shock and vibration requirements without special considerations. Generally, the voltage level of radio frequency coils is low and insulation problems do not exist, except where the voltage level above ground requires special insulation between the coil and ground.

Molded jacket coils are well protected from moisture and contaminants. Open type coils with only a varnish coat should be used in more protected applications.

10.4.7 Reliability considerations. Molded rf coils tend to fail because of degradation of Q, shorted turns, and open terminations. In the instances where Q degrades, there will be a higher incidence of failures in coils with powdered iron cores because the powdered iron slug, if overheated, will degrade. The maximum operating temperature of coils with powdered iron cores should be limited to 105 °C by suitable derating and adequate cooling. Compression molding of insulating jackets can produce coil failures due to pressures which crush the coil or push it to one side of the molded jacket. This condition produces open circuits, short circuits, core characteristic changes, broken cores, or dielectric strength failures. Shrinkage of epoxy as it cures can place mechanical stress on the coil winding and the wire terminations and can cause an open circuit, which is the most predominant failure mode in units with encapsulated coils.

Failure mechanisms for variable rf coils are similar to those for fixed rf coils. An inability of the tunable slug to stay in position or to adjust as required is caused by mechanical failure. Tunable slugs are frequently broken by excessive force applied during adjustment.

11. DELAY LINES

11.1 General.

11.1.1 Introduction. This section discusses delay lines for NASA applications. These devices are not included in MIL-STD-975. The delay line is a versatile device, the basic function of which is to introduce a time delay in the transmission of an electrical signal. This delay phenomenon can be achieved by electromagnetic devices (e.g., lumped constant and distributed constant delay lines) or by electromechanical devices (e.g., metal and quartz media delay lines). Some of the applications of a delay line are:

a. Phase shifting
b. Triggering
c. Time interval measurement
d. Event synchronization
e. Phase angle measurement
f. Pulse train positioning
g. Pulse storage.

An ideal delay line would perform the above functions without distorting or modifying the information contained in the signal. However, depending upon the design and the application, delay lines induce various types of losses.

11.1.2 Definitions. The large variety of delay lines technologies has given rise to an equally large vocabulary of delay definitions. However, all delay lines regardless of their physical construction share certain characteristics. These shared characteristics and their corresponding definitions are listed below and are depicted in Figure 1.

Characteristic impedance (Z_0). The value of terminating impedance that will produce a minimum reflection to the input.

Crosstalk (C_S). The amount of input pulse reflected directly into the output pulse.

Delay time (T_0). The time duration between the 50 percent point on the leading edge of the input pulse and the 50 percent point on the leading edge of the output pulse.

Dispersion. The variation of delay as a function of frequency.

Feed through. A spurious signal which arrives at the output by electrical coupling.

Frequency response. The insertion loss or voltage attenuation as a function of frequency normalized to a maximum of 0 dB.

Input fall time (F_{t1}). The time duration between the 90 and 10 percent points on the decreasing edge of the input pulse.

Input rise time (T_{r1}). The time duration between the 10 and 90 percent points on the increasing edge of the input pulse.

11.1 DELAY LINES, GENERAL

Output fall time (F_{t2}). The time duration between the 90 and 10 percent points on the decreasing edge of the output pulse.

Output rise time (T_{r2}). The time duration between the 10 and 90 percent points on the increasing edge of the output pulse.

Output voltage (E_{out}). Amplitude of the output voltage.

Postpulse spurious (P_{ps2}). The output pulse excursions following the main pulse.

Prepulse spurious (P_{ps1}). The output pulse excursions prior to the main pulse.

Pulse attenuation (a). The difference in voltage of the input and output pulses.

Pulse distortion (S). The magnitude of the largest peak amplitude of all spurious responses in either a positive or negative direction relative to pulse amplitude.

Pulse overshoot (P_{os}). The amplitude of the overshoot on the leading edge of the output pulse.

Pulse top ripple (P_r). A measure of the deviation from the average amplitude in the output pulse top.

Pulsewidth (P_w). The time duration on the input pulse between the 50 percent point on the increasing edge and the 50 percent point on the decreasing edge.

Sonic delay line. A device that uses electroacoustic transducers and the propagation of an elastic wave through a medium to achieve a signal delay.

Spurious level. The ratio of a spurious signal to the desired signal, measured at a specific frequency over a band of frequencies.

Tapped line. A delay line having more than one terminal pair associated with a single delay channel.

Temperature coefficient of delay. The variation of delay with temperature measured in parts per million per degree centigrade (PPM/°C.), microseconds per microsecond per degree centigrade (μs/μs/°C.) or percent per degree centigrade (%/°C.).

Terminal impedance. The impedance at specific terminals and specific frequencies under conditions of negligible incident acoustic energy.

Terminal inductance. The imaginary part of the terminal impedance at a specified frequency divided by twice that frequency.

Terminal resistance. The reciprocal of the real part of the effective terminal admittance.

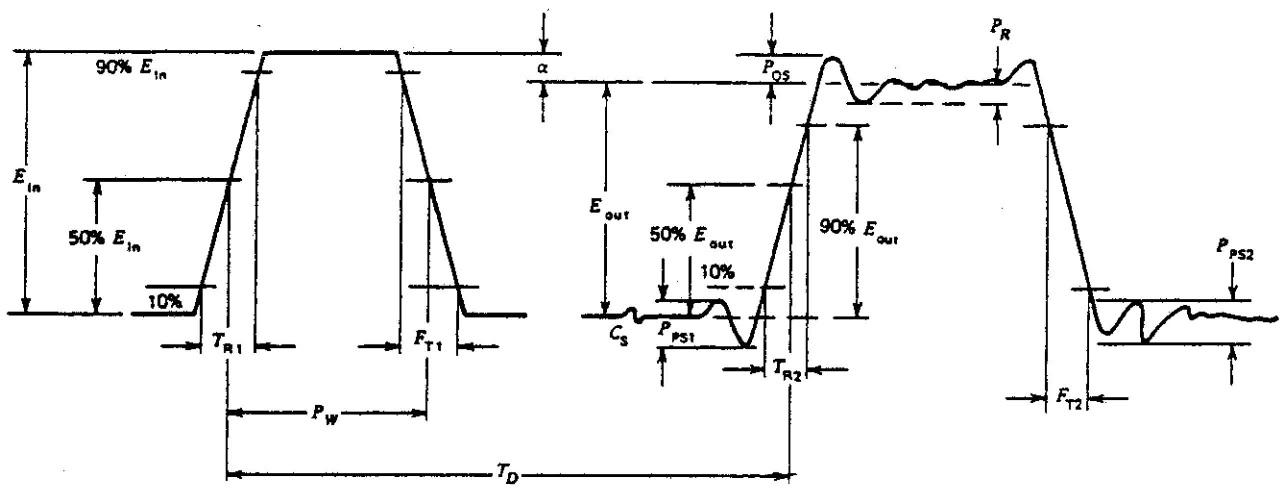


FIGURE 1. Pulse characteristics.

11.1.3 NASA standard parts. No delay lines appear in MIL-STD-975 NASA Standard Electrical, Electronic, and Electromechanical (EEE) Parts List.

11.1.4 General device characteristics. Delay lines are essentially of two types: electromagnetic and sonic.

An electromagnetic delay line is a device that uses the inherent characteristics of electrical components to provide precise pulse delays. This is accomplished by designs that use relatively high values of inductance and capacitance in miniature packages.

Electromagnetic line designs can take the form of coaxial cables, distributed capacitance-inductance circuits, and lumped' capacitance-inductance circuits. Lumped devices provide the best overall electrical characteristics of the electromagnetic delay lines. However, they are also the most expensive.

The second class of delay lines is designated as sonic because it converts electrical signals into mechanical energy in the form of acoustic waves. These acoustic waves are injected into a metal or quartz/glass medium and propagate at a velocity much slower than electrical energy. The acoustic signal is then reconverted into an electrical signal. This design has the advantage of affording very long delay times. Electromagnetic and sonic delay lines with their subsequent derivations are depicted in Figure 2.

11.1 DELAY LINES, GENERAL

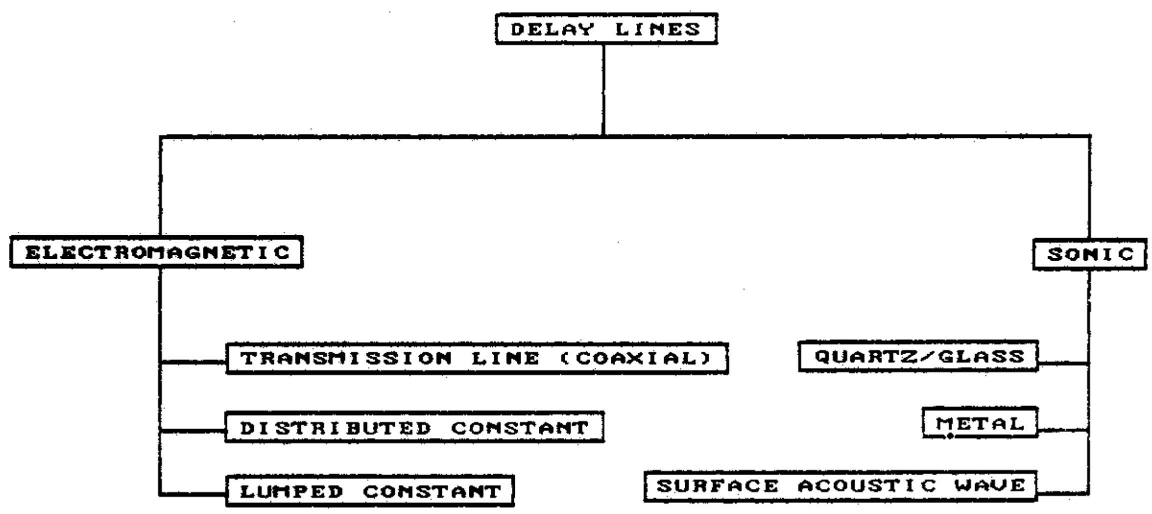


FIGURE 2. Types of delay lines.

11.1.5 General parameter information. Delay line parameters consist of the following. However, not all delay lines utilize the same parameters and specifications because there are many diverse delay line technologies.

a. Delay time
b. Delay tolerances
c. Tap delay times
d. Tap delay tolerance
e. Impedance
f. Maximum rise time (or bandwidth)
g. Attenuation
h. Output loading
i. Temperature coefficient of delay
j. Distortion
k. Operating temperature range
l. Storage temperature range
m. Maximum operating voltage
n. Package size.

11.1.6 General guides and charts. Table I outlines the various delay line technologies and their typical performance characteristics. This table should be used as a first step in device application. It should also be noted that these are typical characteristic values and individual vendors may offer delay lines whose performance can exceed those given in Table I. This is because delay lines are essentially custom devices and devices that appear to be similar can exhibit wide variations in internal design.

TABLE I. Guide to delay line application

Electrical Requirement	Limits	Select
Delay time (T_d)	<= 10 ns	Coaxial
	< 6 μs	Distributed
	0.1 μs-200 ms	Lumped
	Custom	Quartz
	Custom	Metal
	Custom	SAW
Delay to rise time (T_d/T_r)	< 20	Coaxial
	< 10	Distributed
	< 150	Lumped
	Custom	Quartz
	Custom	Metal
	Custom	SAW
Characteristic impedance (Z_0)	25 - 1 KΩ	Coaxial
	100 - 2 KΩ	Distributed
	50 - 10 KΩ	Lumped
	Custom	Quartz
	Custom	Metal
	Custom	SAW
Temperature coefficient of delay	>100 PPM/°C.	Coaxial
	>150 PPM/°C.	Distributed
	> 50 PPM/°C.	Lumped
	Custom	Quartz
	Custom	Metal
	Custom	SAW

11.1.7 General reliability considerations. Delay lines are not true components but are assemblies of components that are more electrically complex (and less reliable) than stand-alone components such as resistors and capacitors. They also tend to have complex responses to environmental conditions. In addition, delay lines are made using a variety of diverse technologies to achieve desirable delays with acceptable levels of distortion.

Delay lines are also labor intensive devices and must have numerous in-process checks and controls imposed during their fabrication to ensure acceptable levels of quality and reliability. Subsequently, delay lines require rigorous reliability screening prior to installation in the end application.

11.1 DELAY LINES, GENERAL

Continuously variable delay lines should be avoided because their mechanically complex construction is often susceptible to environmental hazards such as shock and vibration. Tapped delay lines such as LC devices tend to be relatively immune to their environment in comparison to continuously variable designs.

All delay lines regardless of technology or construction should undergo screening prior to assembly, packaging, and installation into a high reliability application. The nature and scope of such screening will depend upon contractual requirements and the component engineering function.

11.2 Coaxial.

11.2.1 Introduction. The passage of an electromagnetic signal through any medium other than free space introduces a delay phenomenon. The simplest device using this effect is the coaxial delay line. Several attributes that make coaxial cable delay lines attractive to noncritical applications are their wide bandwidth, fast rise times, low cost, and ease of replacement.

11.2.2 Usual applications. The two most common applications of coaxial cable delay lines are video pulse processing and radio-frequency (rf) pulse envelope processing. However, coaxial delay lines in video applications have draw backs such as dribble-up. In an rf application, there can be a tendency for the attenuation of the cable to vary at the band limits. Dribble-up and attenuation variation are discussed further in section 11.2.5.

Another consideration in the application of coaxial delay lines is availability. Diameters less than 0.013 in. may not be available in more than 8-ft lengths and diameters less than 0.034 in. in more than 10-ft lengths. Cables with diameters of 0.034 in. are available in 15-ft lengths and larger diameters are available in 20-ft lengths. Consequently, splicing is sometimes necessary to meet the application requirements. The implications of splicing coaxial cable are discussed further in paragraph 11.2.7, Reliability considerations.

11.2.3 Physical construction. Typical flexible coaxial cable construction is shown in Figure 3. The center conductor is usually copper, copper-plated high-resistivity base material, or silver-plated high-resistivity base material. A sheath of dielectric material (e.g., polyethylene, Teflon TFE, or Teflon FEP) separates the center conductor from the outer conductor. The outer conductor typically consists of a braid of copper or silver-plated copper. This braid is then sheathed in a protective cover of vinyl or fiberglass.

In addition to the typical construction, several variations are common. These variations include:

a. The use of a secondary layer of conductive braid added either underneath or above the protective cover to provide more shielding

b. A layer of protective armor added above the protective cover

c. The inner and outer surfaces of the dielectric made conductive to reduce electrical noise caused by mechanical motion of the cable.

A form of high impedance coaxial cable is shown in Figure 4. This construction is the same as flexible cable construction described above except a nylon insulating thread is wound around the center conductor which results in air gaps in the nylon winding. The air gaps are used to lessen the overall dielectric constant of the sheath. Consequently, the capacitance per unit length is also lessened. Although the resultant higher impedance is often attractive in delay line applications, the propagation velocity also increases and greater cable length is required to maintain the same delay.

11.2 DELAY LINES, COAXIAL

The effective inductance of the center conductor is increased as shown in Figure 5 by winding the center conductor in the form of a coil. This inductive effect can be further enhanced by making the core of the coil magnetically loaded. A dielectric sheath insulates the coiled center conductor from a continuous wrap of alternatingly insulated and bare wires. This continuous wrap of wire is used instead of conventional coaxial cable braid because it yields an increase in line impedance and line delay. A conventional braid for the outer conductor would place a shorted turn adjacent to the inductor, thus decreasing the inductance and increasing overall cable losses. The outer wires are connected together at only one end to prevent ground loops also acting as shorted turns.

The lack of magnetic shielding on this type of cable makes it more susceptible to stray fields than any of the more conventional cables. Part of these stray fields are self-generated and it is advisable not to attempt to crowd the cable or place it in the vicinity of similar cables unless the application can tolerate considerable feedthrough and spurious signals.

Semirigid cable construction is shown in Figure 6. The center conductor consists of either solid or stranded material. A sheath of dielectric material (polyethylene, Teflon TFE, or Teflon FEP) separates the center conductor from the outer conductor which consists of seamless tubing. Semirigid cable is available in smaller diameters than typical flexible cables. However, small cable sizes usually mean greater losses over frequency.

Continuously variable coaxial delay lines are also available. Two common configurations are the "line stretcher" and the "trombone" in which sections of the inner and outer conductors slide into and out of corresponding sections of an adjacent assembly.

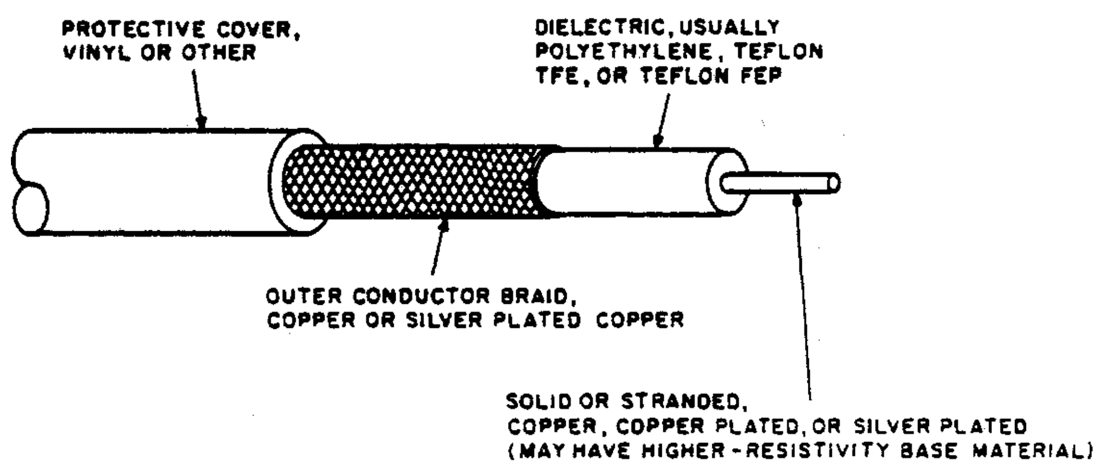


FIGURE 3. Flexible coaxial cable construction.

11.2 DELAY LINES, COAXIAL

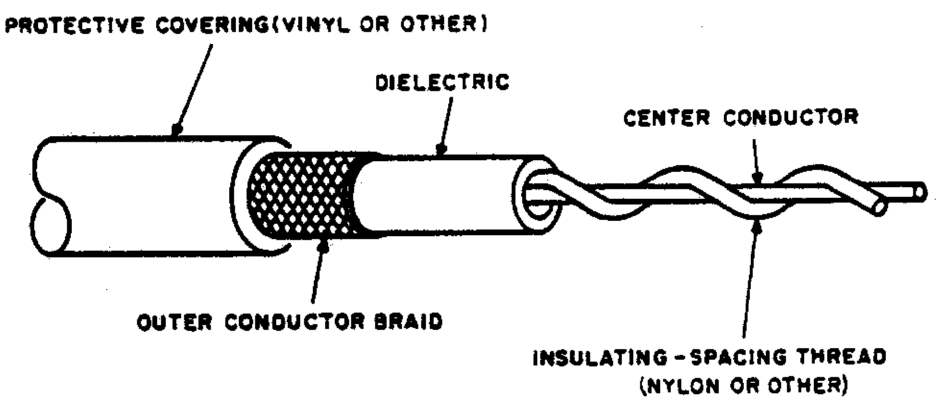


FIGURE 4. Low-capacitance/high-impedance cable construction.

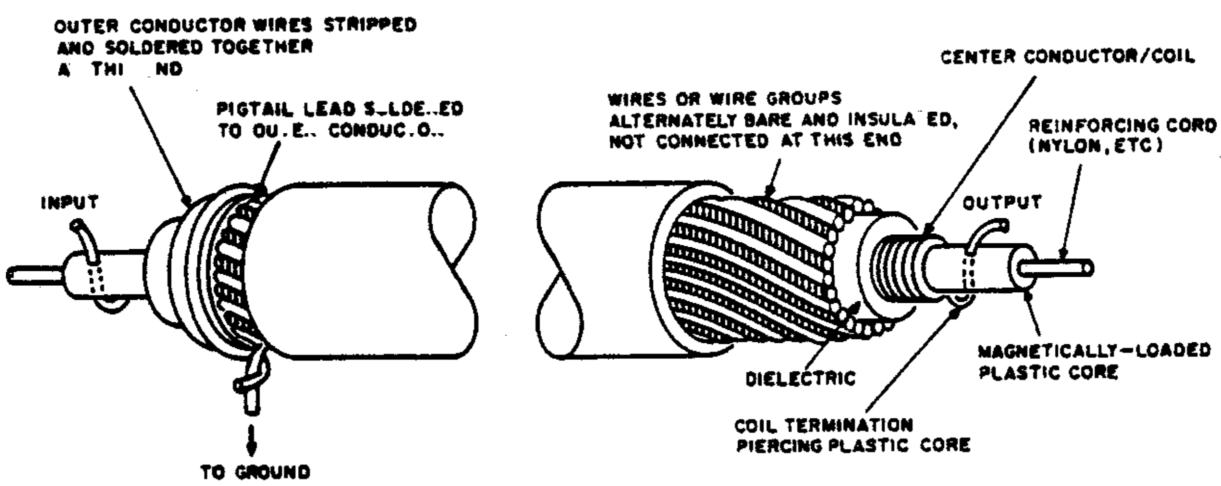


FIGURE 5. High-inductance/high-impedance cable construction.

11.2 DELAY LINES, COAXIAL

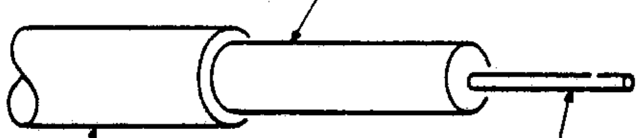


FIGURE 6. Semirigid cable construction.

11.2.4 Military designation. There are no military specifications directly applicable to the application of coaxial cable delay lines. However, there are several military specifications for coaxial cable in general. These are:

MIL-C-17	Cable, Radio Frequency, Flexible and Semirigid, General Specification for
MIL-C-22931	Cable, Radio Frequency, Semirigid, Coaxial, Semi-Air-Dielectric, General Specification for
MIL-C-23806	Cable, Radio Frequency, Coaxial, Semirigid, Foam Dielectric, General Specification for
MIL-C-28751	Cable, Radio Frequency, RG-373/U

There are no delay lines included in MIL-STD-975.

11.2.5 Electrical characteristics. One of the most common applications for coaxial cable delay lines is for the processing of video pulses. In this application however, long lines can exhibit what is called dribble-up. Dribble-up occurs when the rise time from the 10 to 50 percent point may be fast but the rise time from the 50 percent point to the full pulse height may be several times as long.

Rf pulse envelope processing, the second common application of coaxial cable delay lines, can exhibit an undesirable variation of cable attenuation as a function of frequency. This is not a particularly serious effect if phase stays proportional to frequency. This effect can be explained by the equation for the characteristic impedance of a transmission line shown below.

$$Z_0 = \sqrt{(R + j2\pi fL)/(G + j2\pi fC)}$$

where

R and L = the equivalent series elements
G = equivalent shunt conductance
C = capacitance

Not only does the ratio of L/C have to remain constant, but it must also equal the ratio R/G if the line characteristics are not to change as a function of frequency. When cable attenuation varies as a function of frequency, the ratios do change but the condition is so gradual that changes of amplitude and phase may not be significant over wide bandwidths. It is advisable to check this factor, especially at the higher frequencies.

Some types of lines, such as the high-inductance and high-impedance design shown in Figure 5, exhibit the best characteristics if not bent, or if bent, done so on a large radius. This is due in part to changes in cable inductance resulting from handling and in part to feed-through if the bend approaches or exceeds 360 degrees. The semirigid cable of Figure 6 is recommended as probably more constant in characteristics after strenuous handling.

Flexible coaxial cable lines are susceptible to degradation from mounting in addition to bending. Tight mechanical clamps can cause spurious reflections that can result in signal degradation.

11.2.6 Environmental considerations. The environmental considerations associated with coaxial delay lines are:

a. Electromagnetic environment

b. Reduced barometric pressure

c. Humidity

d. Operational temperature range

e. Shock and vibration.

In the case of high leakage coaxial designs, such as shown in Figure 3, the delay line should be dressed well away from susceptible circuits or circuits that generate high electrical or magnetic fields. Even other coaxial cables can present a hazard due to rf leakage through the outer conductor braid of the cable.

Altitude also affects delay line performance. Certain materials have the tendency to outgas at reduced barometric pressure. This outgassing can eventually lead to degradation of the part. The degradation can be physical or electrical in nature, or a combination of both.

11.2 DELAY LINES, COAXIAL

Flexible cables are not particularly suitable for exposure to conditions of high humidity. Braid and other forms of multiple wire conductors can act as moisture traps which cause corrosion. Condensation occurring in the construction of devices similar to Figures 4 and 5 can cause immediate (although sometimes temporary) changes in performance characteristics.

At low temperatures flexible cables tend to become stiff. For this reason, it is advisable to provide mechanical support for coaxial cable delay lines. Coaxial designs tend to be relatively immune to the high end of the operating temperature range (-55 to +125 °C.)

Properly dressed and mounted coaxial cables are usually insensitive to the effects of shock and vibration. However, improperly installed cables that undergo shock and vibration can generate spurious signals and sustain mechanical fatigue.

11.2.7 Reliability considerations. Because cable splicing is inevitable due to limited cable selection and demands for longer delay times, it is advisable to have the cable manufacturer make the assembly. If some adjustment is necessary on the part of the user, a portion of the outer layer of the cable assembly can be left unbound or unpotted for trimming after delivery.

After a coaxial delay line has been assembled, the number of reliability screening options is limited. Radiographic inspection is useful only in locating gross mechanical defects in the assembly. For electrical integrity, radiographic inspection is usually not an advisable screen.

The electrical integrity of a coaxial cable delay line can be further assured by the use of time domain reflectometry (TDR). The TDR screening process injects a pulse down the line under inspection and the resultant type and magnitude of any reflections can be recorded and examined. This is especially important when the cable has been spliced or trimmed.

Final trimming of the cable should not be made until after the assembly has been subjected to several cycles of thermal shock. Thermal shock has a tendency to promote dimensional changes in the cable. These dimensional changes can alter electrical performance characteristics.

11.3 DELAY LINES, DISTRIBUTED CONSTANT

11.3 Distributed constant.

11.3.1 Introduction. Distributed constant (dc) delay lines were developed to provide larger induced signal delay times than are obtainable from coaxial delay lines. The delay lines are either inductive designs with incidental capacitance or capacitive designs with incidental inductance. The capacitance and inductance arise from magnetic and electric fields set up in the structures and, therefore, the effect is distributed over a considerable part of the structure of the device.

11.3.2 Usual applications. DC delay lines can be utilized for a conventional delay function. In addition, they can be used to invert the polarity of a pulse so the output of a delay line may be shorted and the inverted pulse will emerge from the input terminals after a period equal to twice the delay of the line.

Another application is to derive a train of pulses from a single pulse with a line having several taps. A single input pulse will appear, in turn, at each successive tap. The pulses are then summed to form a binary word. It should be noted that each tap will reflect some energy back to the input and likewise deduct some energy from the single traveling pulse. There has to be some compromise between the amount of tap loading and characteristics of the output waveform.

11.3.3 Physical construction. The most common form of the distributed delay line is a coil wound on an insulating mandril with conductive longitudinal stripes (Figure 7). The longitudinal stripes are joined with a broken circle at one end to provide the ground connection. The circle is broken to keep the ground connection from looking like a shorted turn in the magnetic field of the coil.

The above method of construction can be reversed. The coil can be placed on the inside and wound on a magnetic core (Figure 8). The ground plane of the capacitor is a sheath of insulated wires wrapped around the outside of the coil on a relatively long pitch. In some configurations only every other wire is insulated and the alternate wires are bare.

The advantage of this form of construction is that higher characteristic impedances can be obtained. The disadvantages are that external electrical field problems tend to increase and the device is a harder to protect from a hostile electromagnetic environment.

DC delay lines can also be made in the form of a modified capacitor (Figure 9). The inductor is formed by winding a copper conductor on a continuous strip of magnetically permeable material. The distributed capacitance is achieved by placing conductive foil strips between two layers of dielectric sheathing. This insulated conductive screen (ground plane) provides one plate of the distributed

11.3 DELAY LINES, DISTRIBUTED CONSTANT

capacitor whereas the individual turns of the inductor strip form the other. When combined with the inductor the ground plane also provides shielding between successive turns of the spiral when wound.

Variable dc delay lines are also available. A common design uses a slider that runs along a coil wire from which the insulation has been removed. A second slider electrically connected to the first transfers the signal from the tap connections to a rail (Figure 10).

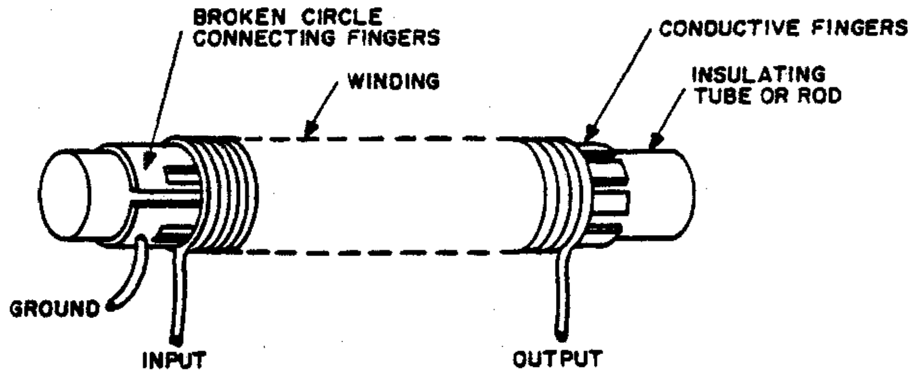


FIGURE 7. Distributed constant delay line mandril construction.

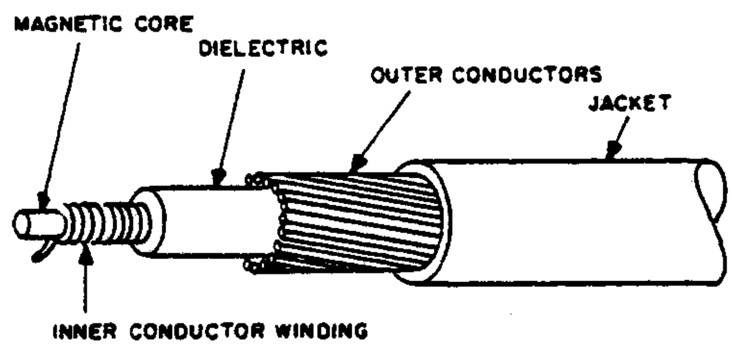


FIGURE 8. Distributed constant delay line construction.

11.3 DELAY LINES, DISTRIBUTED CONSTANT

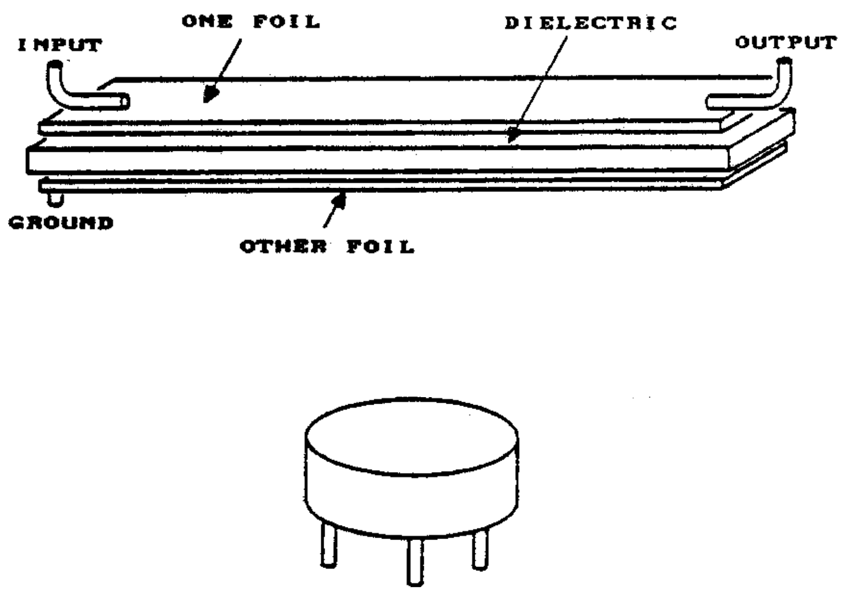


FIGURE 9. Distributed constant delay line cylindrical construction.

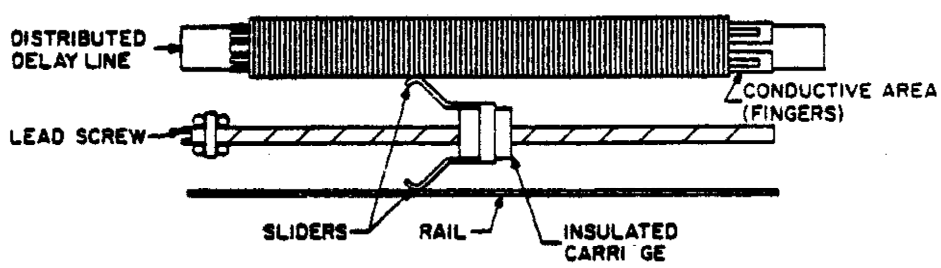


FIGURE 10. Variable distributed constant delay line.

11.3.4 Military designation. The applicable military specification for distributed constant delay lines is MIL-D-23859, Delay Line, Electromagnetic and Fixed. There are no delay lines included in MIL-STD-975.

11.3.5 Electrical characteristics. Distributed delay lines are generally limited to modest delays, lower T_d/T_r ratios, higher attenuations, and higher temperature coefficients than coaxial delay lines as well as low operating voltages (100 V or less) and a modest range of impedances. Low impedances require high capacitance-low inductances and high impedances require very low capacitance-high inductance. Both cases are difficult to obtain in a distributed delay line design.

11.3 DELAY LINES, DISTRIBUTED CONSTANT

Distributed delay lines are usually more likely to generate external fields than lumped constant delay lines. Distributed delay line also tend to be more susceptible to external fields created by other components. Care is required in specifying, positioning, and shielding the distributed line. The cable type delay line (Figure 8) is not shielded against magnetic fields and although it appears to be like a coaxial cable, it has very few of the coaxial cable's immunities to the electromagnetic environment.

11.3.6 Environmental considerations. The environmental considerations associated with distributed delay lines are:

a. Electromagnetic environment
b. Reduced barometric pressure
c. Humidity
d. Operational temperature range
e. Shock and vibration.

Due to inherent design configurations of the cable type distributed delay line, susceptibility to the electromagnetic environment is a possibility. This interaction can be inductive leakage to, or pickup from, other portions of adjacent circuitry or stray capacitance.

Altitude also affects delay line performance. Certain materials (electrical and packaging) have the tendency to outgas at reduced barometric pressure. This outgassing can eventually lead to the degradation of the part which can be physical or electrical in nature or a combination of both.

Properly packaged delay lines are relatively immune to the effects of humidity. However, potted or encapsulated devices can develop cracks and fissures if the materials used are incorrect for the application or if the correct materials are applied incorrectly by the vendor.

Because dc delay lines are assemblies of many components and their interconnections, the operational and storage temperature range is an important consideration. The inductance and capacitance values can change as a function of temperature. This change can range from 50 to 200 parts per million and may not be a linear function of temperature.

Packaging is also affected by temperature. Molded cases, which are formed with elevated temperature and pressure are immune to degradation over the temperature range of -55 to +125 °C. However, potted and encapsulated devices can experience degradation at elevated temperatures especially when coupled with reduced barometric pressure.

11.3 DELAY LINES, DISTRIBUTED CONSTANT

The mandril and capacitor designs of distributed delay lines are relatively immune to the effects of shock and vibration when properly packaged and mounted. Because vibration can introduce spurious signals into the line and cause the cable to undergo mechanical fatigue, cable applications require careful dressing and mounting.

11.3.7 Reliability considerations. After a dc delay line has been assembled, the number of reliability screening options is limited. Radiographic inspection is usually not an advisable screen. Unless the internal construction of the delay line consists of a few macroscopic component parts with simple interconnections, the resultant radiographs will only exhibit indiscernable clutter.

Burn-in under voltage is an inexpensive and relatively fast reliability screen. Thermal shock under voltage is another inexpensive and relatively fast reliability screen. Both tests should be preceded and followed by functional electrical testing.

11.4 DELAY LINES, LUMPED CONSTANT

11.4 Lumped constant.

11.4.1 Introduction. Distributed constant delay lines tend to be more space efficient, less environmentally susceptible, offer a wider range of impedances, and modest signal delay.

Lumped constant (LC) delay lines using discrete inducting and capacitors, were developed to provide the electrical advantages of both coaxial and distributed constant delay lines.

The accuracy of the approximation to coaxial or distributed constant delay lines depends on the length of the equivalent line increment. As the length of the line modeled becomes shorter, the approximation becomes closer if the resistance and parasitic reactance of the inductors and capacitors are low.

Where the length of the coaxial line is a small fraction of the wavelength, the increment can be characterized by two resistors, one inductor, and one capacitor. If the line has low loss, the resistors can be ignored entirely. The line increment can then be equated to a series inductor (L) and a shunt capacitor (C). The impedance (Z) of the line increment can be expressed as:

$$Z = \sqrt{L/C}$$

and time delay (T_d) can be expressed as:

$$T_d = \sqrt{LC}$$

Note that both equations are independant of frequency. This is the basic advantage for using a coaxial cable to achieve a delay. Therefore, the LC delay line which is an approximation of the coaxial design with the augmented inductances and capacitances of the distributed design exhibits longer signal delays, but is limited by frequency. However, the LC delay line is more space efficient, can have a variety of impedances, and exhibits large delays due to relatively larger inductive and capacitive elements.

11.4.2 Usual applications. LC delay lines can be used in essentially the same applications as distributed constant delay lines. One such application is pulse inversion. LC devices can be used to invert the polarity of a pulse. The output of a line can be shorted and the reflected (and inverted) pulse will emerge from the input terminals of the delay line after a period equal to twice the delay of the line.

It is also feasible to derive a train of pulses from a single pulse with a line having several taps. A single input pulse will appear, in turn, at each successive tap. The summed pulses form a binary word. It should be noted that each tap will reflect some energy back to the input (and likewise deduct some energy from the single traveling pulse) so there must be some compromise between the amount of tap loading and the characteristics of the output waveform.

11.4.3 Physical construction. LC delay lines consist of discrete multilayer capacitors and core inductors in a ladder configuration. Capacitors are chosen that exhibit negative temperature coefficients and inductors are selected that exhibit a positive temperature coefficient. The resulting cancellation yields a device which is relatively stable over the temperature range of -55 to +125 °C.

Digital integrated circuits that use transistor-to-transistor logic (TTL) or emitter coupled logic (ECL) can also be incorporated into LC delay line design. The delay line assembly compensates for the inherent propagation delay of the integrated circuit (IC) and enables the delay line to process digital information.

Delay line packaging consists of three types: molding, potting, and encapsulation. Consideration should be given to outgassing characteristics. Molding utilizes high pressure and elevated temperature resins to package the assembly. Potting usually consists of housing the assembly in a mold. A resin is then introduced which completely surrounds the assembly. When the resin has cured the mold is removed. Encapsulation involves the dipping of the assembly in a high viscosity thixotropic resin to give a conformal coating of 10 to 50 mils on the surface. Dual in-line packages (DIPs) and single in-line packages (SIPs) are most common. Their popularity arises from their ability to be machine inserted onto printed circuit boards (Figure 11).

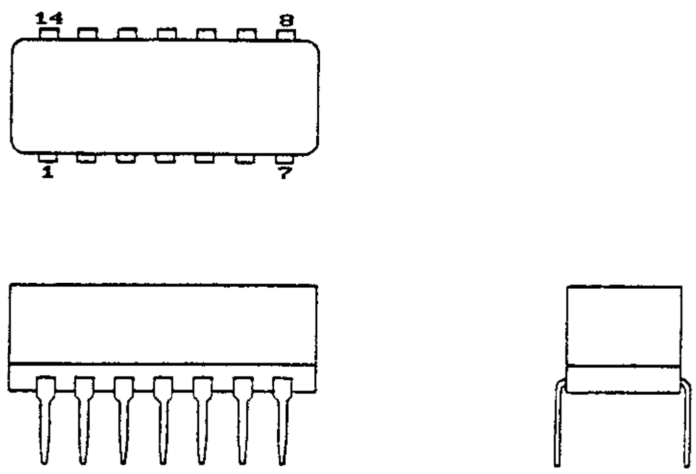


FIGURE 11. Lumped-constant delay line dual in-line package.

11.4 DELAY LINES, LUMPED CONSTANT

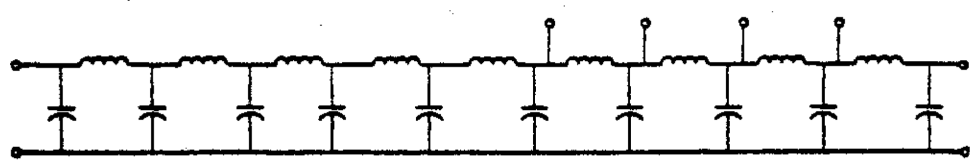
Variable LC delay lines are also available. In Figure 12A taps are at the position of shunt capacitors to achieve delay variation in incremental steps and because an external shunt capacitance does not degrade electrical performance as much as when the tap is placed in the coil.

A signal impressed at the input terminals will proceed to the loaded tap where a part of it will leave the line, part of it will be transmitted, and part will be reflected back to the input. The reflected signal will modify the signal appearance at previous taps. The reflection occurs whether power is withdrawn or only stored and then discharged by a pure reactance.

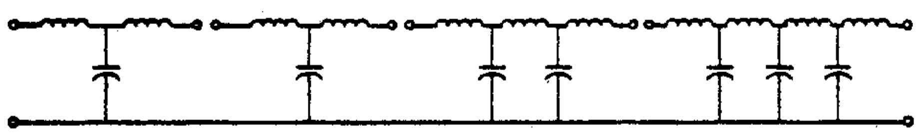
Figure 12B, shows an example where only the last few sections of a line are tapped in order to trim the delay line length to a desired value. Figure 12C shows several lines (usually within a single enclosure) designed to be electrically connected in cascade. A number of the mismatch and reflection problems are avoided, although a delay line is not necessarily a good termination for another delay line.

Figure 12D shows a way to avoid the effects of tap loading by using the tap as the input point. The two disadvantages to this configuration are: First that the insertion loss is a minimum of 3 dB and the input impedance is 0.5 of the line impedance; the second is that the reflections will still occur if several intermediate taps are used simultaneously.

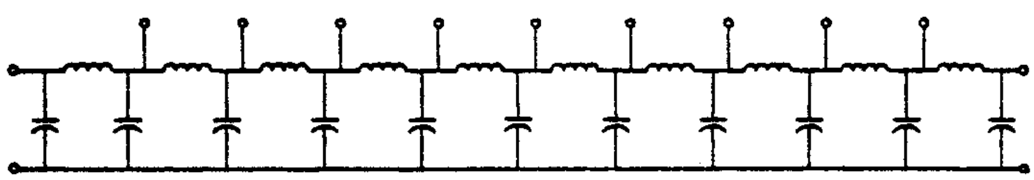
Electronically variable versions of LC delay lines are also available. Figure 13A shows the simplest form wherein a change in a direct current voltage bias causes a change in the capacitance of semiconductor varactor diodes. A disadvantage of this type of line over that made of passive components is that the signal can only be a small part of the bias level if the signal is not to be affected. Figure 13B shows an electronically variable LC delay line using both semiconductor varactor diodes (as capacitors) and saturable reactors. It is possible to devise a control system that will give variable delay while keeping the ratio L/C (impedance) constant. This design also requires a relatively small signal to avoid distortion.



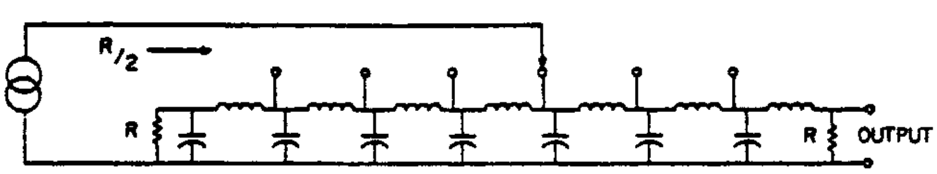
A. Lumped-constant line with trimming tap increments



B. Segmented lumped-constant line



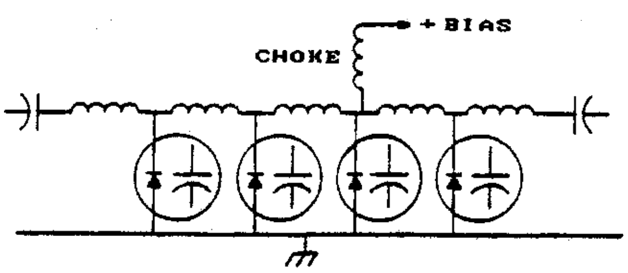
C. Lumped-constant line with equal tap increments



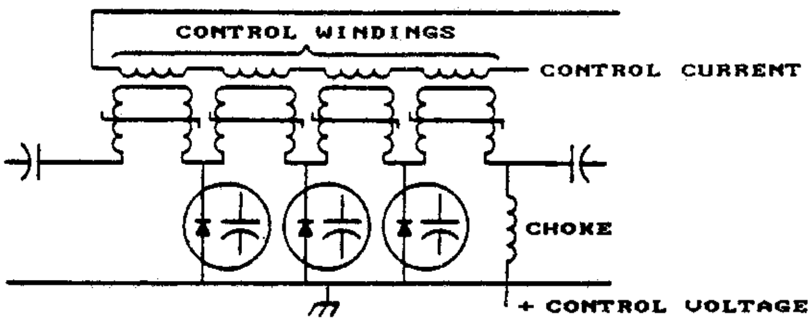
D. A tap used as input to avoid reflections

FIGURE 12. Variable lumped constant delay line configurations.

11.4 DELAY LINES, LUMPED CONSTANT



A. Nonconstant-impedance electronically-variable line



B. Constant-impedance electronically-variable line

FIGURE 13. Electronically variable lumped-constant delay line.

11.4.4 Military designation. The applicable military specification for lumped constant delay lines is MIL-D-23859. There are no delay lines included in MIL-STD-975.

11.4.5 Electrical characteristics. All delay lines will degrade the response of the input pulses because these devices function as low-pass filters that attenuate the higher frequencies. This is especially true with the relatively high inductances and capacitances encountered in lumped delay lines.

When observing the response of the delay line to an input signal, the input waveform rise time, the oscilloscope rise time, and the output rise time degradation (due to the delay line) must be considered. If the delay line rise time characteristics are to be referred to the ideal rectangular pulse, the following relation applies.

$$T_{r(ob)} = \left[T_{r(i)}^2 + T_{r(osc)}^2 + T_{r(o)}^2 \right]^{0.5}$$

where

$T_{r(ob)}$ = observed output rise time

$T_{r(i)}$ = input pulse rise time

$T_{r(osc)}$ = rise time of the oscilloscope

$T_{r(o)}$ = output pulse rise time.

In video applications, the LC delay line is usually used in group delay. It is expected that the output pulse will be a faithful reproduction of the input, and usually a band of frequencies is involved. Pulse fidelity is obtained

when

$$\frac{\emptyset}{F} = K$$

where

$\emptyset$ = radians

F = radians/second.

A similar condition applies to passband delay for faithful reproduction of a waveform envelope within the passband,

$$\frac{d\emptyset}{dF} = K$$

In each of these cases (zero dispersion), not only is the relation of $\emptyset/F = K$ required, but the attenuation must be constant also. Attenuation arises from two factors: those that are internal to the delay line and those external to the delay line. Internal factors are primarily the dc resistance of the inductors, losses in the dielectric of the capacitors, and losses in the ground planes. External factors consist of termination mismatch and tap loading.

11.4.6 Environmental considerations. The environmental considerations associated with LC delay lines are:

a. Electromagnetic environment

b. Reduced barometric pressure

11.4 DELAY LINES, LUMPED CONSTANT

c. Humidity

d. Operational temperature range

e. Radiation hardness.

Passive and digital LC delay lines are usually furnished in molded, potted, or encapsulated packages. For this reason, the device is susceptible to various types of interaction with the electromagnetic environment. This interaction can be inductive leakage to, or pickup from, other portions of adjacent circuitry, stray capacitance from a nearby chassis or shield, or waveform changes from the effect of a hand used to hold the delay line in a test jig.

Altitude also affects delay line performance. Certain materials (electrical and packaging) have the tendency to outgas at reduced barometric pressure. This outgassing can eventually lead to the degradation of the part. The degradation can be either physical or electrical.

Properly molded, potted, or encapsulated delay lines are relatively immune to the effects of humidity. However, molded, potted, or encapsulated devices can develop cracks and fissures if the materials used are incorrect for the application or if the correct materials are applied incorrectly by the vendor. Of particular concern is the lead egress area of the package. Incorrectly applied potting or encapsulation can separate from the lead material creating an entry point for moisture.

Because LC delay lines are assemblies of many components and their interconnections, the operational and storage temperature ranges are an important consideration. The value of inductors and capacitors will change as a function of temperature. This change can range from 50 to 200 parts per million and may not be a linear function of temperature.

Discrete passive LC delay lines are relatively insensitive to nuclear radiation effects. Semiconductors used in adjacent circuitry will usually fail before a discrete passive delay line. However, digital delay lines use ICs that reside in the same package as the passive components. If radiation hardness is called for, radiation-hardened versions of ICs are available.

11.4.7 Reliability considerations. After an LC delay line has been packaged, the number of reliability screening options decreases. For this reason preassembly screening of the lumped components (inductors and capacitors) is advisable. In digital LC designs, preassembly screening of the IC used is also recommended.

11.4 DELAY LINES, LUMPED CONSTANT

After a design has been assembled and packaged, only certain screening tests are advisable. For example, radiographic inspection is usually not a conclusive screen. Unless the internal construction of the delay line consists of a few macroscopic component parts with simple interconnections, the resultant radiographs would only exhibit indiscernable clutter.

Burn-in and thermal shock under voltage are inexpensive and relatively fast reliability screens. Both of these screen tests should be preceded and followed by functional electrical testing.

Where digital delay lines are utilized, it is advisable that radiation hardened ICs with high mean time between failures (MTBFs) be used.

11.5 DELAY LINES, QUARTZ-GLASS SONIC

11.5 Quartz-glass sonic.

11.5.1 Introduction. Delay in electrical circuits does not have to be confined to electromagnetic delay phenomena. One technology utilizes the transformation of an electrical signal to a sonic signal. The sound wave then passes through a mechanical medium and the resultant delayed signal is transformed back into an electrical signal.

It should be noted that the use of the term "sonic" is a misnomer. In actuality the signal is ultrasonic and can extend into the gigahertz region. Ultrasonic frequencies are utilized because of the greater information handling capabilities of that portion of the spectrum. This section is concerned with the utilization of fused quartz or glass as a bulk medium to achieve delay.

11.5.2 Usual applications. The applications of quartz-glass delay lines can be divided into analog information processing and digital information processing categories.

Analog information can be processed in the form of a modulated carrier centered in the passband of a nondispersive line. One such application is in moving target indicator radars where the stored result of one sweep is subtracted from the result of a subsequent sweep. Only those targets not appearing in the same position of the subsequent sweep are displayed by the radar.

Another application is passing a narrow signal envelope through a quartz-glass delay line so that it emerges as a longer (and lower in amplitude) frequency modulated (fm) pulse. In a radar system, this pulse can be amplified and transmitted at relatively high average power with the reduced possibility of insulation and parts overload. This wider fm pulse is received and inverted by passage through a delay line and the received pulse is narrowed once again. This permits the display of, and discrimination between, many small targets that might otherwise be undetectable or indistinguishable.

A common digital application of quartz-glass delay lines is as memory devices. The delay line is used as a storage device in which the input signal is injected into the medium, extracted at the output side of the delay line, and then externally rerouted to the input side multiple times. This signal recirculation can be achieved with or without the benefit of external pulse shaping circuitry to preserve its integrity.

Signal recirculation can also be accomplished internally to the delay line itself. A signal can be injected into the input side of the delay medium, reach the output side, and be reflected back to the input side for another pass through the medium. This is referred to as an echo line. The echo line is very often used to create a train of pulses differing in amplitude from the previous pulse by a few decibels. Usually the signal is inserted into the echo line by a single burst of a few cycles of the nominal operating frequency and the input transducer is used as a detector to ascertain the number of pass throughs.

11.5.3 Physical construction. Material for the delay medium of this class of device falls into two categories: amorphous and single crystal. The material called amorphous may not be truly amorphous but actually polycrystaline. However, because the crystals are usually very small and of random orientation they can be regarded as amorphous for practical purposes. The single crystal delay media are usually quartz and the amorphous media are fused quartz or "delay line glass."

Single crystal material has the advantage of low attenuation. However, single crystal media as a category have different propagation velocities and temperature coefficients depending on orientation. The orientation of the crystal right handed or left handed) will also give rise to performance variations.

Amorphous material tends to be less critical than single crystal material of direction of propagation but does exhibit more attenuation. Moreover, various latent material faults and variations may make a quartz-glass blank undesirable in some applications. Adverse effects are noted in lines designed to furnish the greatest delay as these lines require the greatest and most complex paths.

Regardless of the medium, transducer positioning is critical to delay line function. The transducer is attached to the surface of the delay medium by means of a bonding agent (Figures 14 and 15). After the transducer is attached, the bonding agent is applied to the rear of the transducer and a backing is attached to it. The transducer, the bonding agents, the backing, and the delay medium form an acoustical system that provides the efficient transfer of power to and from the delay medium over a broad bandwidth.

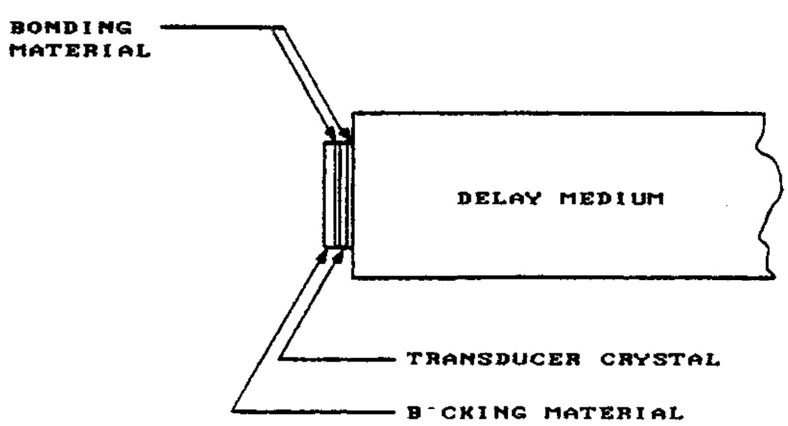


FIGURE 14. Transducer attachment.

11.5 DELAY LINES, QUARTZ-GLASS SONIC

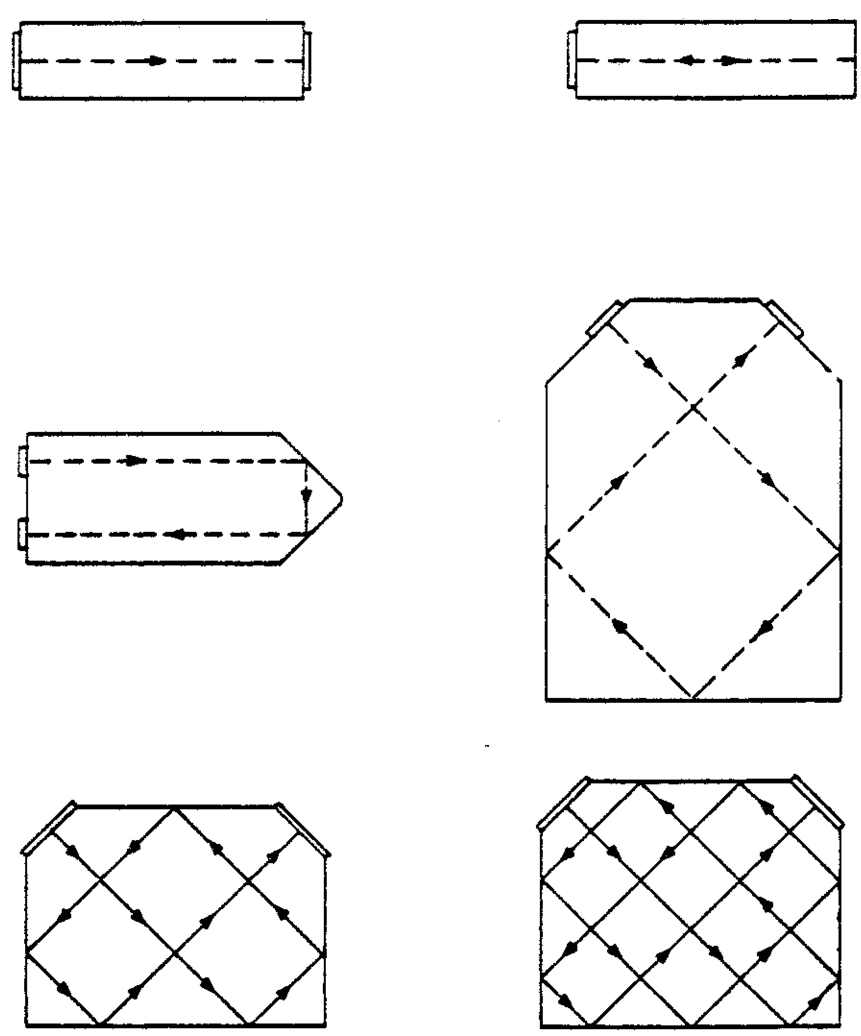


FIGURE 15. Basic quartz and glass delay line construction.

Variable quartz delay lines are also available (Figure 16). The moving delay medium can be adjusted either manually or by external control circuitry. This configuration permits variation of delay up into the microsecond region. To a lesser extent, a fixed delay line can also be used to obtain a variable delay. Variation of delay is achieved by the relative movement between an optical pickup system and the quartz/glass delay medium (Figure 17).

11.5 DELAY LINES, QUARTZ-GLASS SONIC

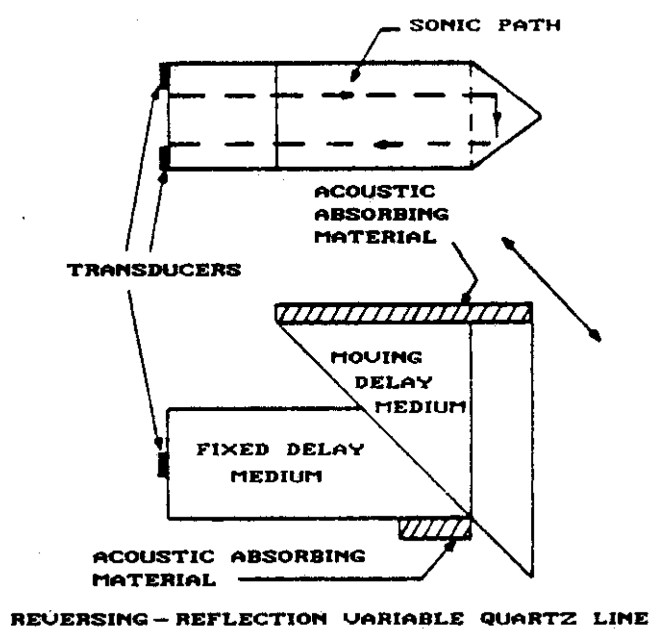


FIGURE 16. Variable quartz/glass delay line.

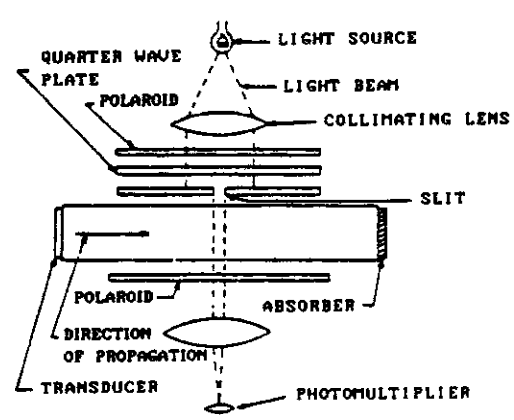


FIGURE 17. Variable quartz/glass delay line with optical pickup.

11.5 DELAY LINES, QUARTZ-GLASS SONIC

11.5.4 Military designation. There are no directly applicable military specifications or standards for quartz/glass delay lines. Some relevant military documents are:

MIL-C-3098	Crystal Units, Quartz, General Specification for
MIL-F-18327	Filters; High Pass, Low Pass, Band Pass, Band Suppression, and Dual Functioning, General Specification for.

There are no delay lines included on MIL-STD-975.

11.5.5 Electrical characteristics. Three techniques in making glass-quartz media are used to improve electrical performance by minimizing the effects of spurious signals. One uses wide apertures to minimize the generation of spurious lobes in the reflection pattern. Another uses large reflection angles which cause spurious lobes to strike subsequent facets at less than optimal angles. The third uses long propagation paths in high attenuation media. Such long paths expose spurious lobes to greater attenuation as they traverse the delay medium.

11.5.6 Environmental considerations. The environmental considerations associated with quartz-glass delay lines as a whole are:

a. Electromagnetic environment
b. Reduced barometric pressure
c. Humidity
d. Operational temperature range
e. Shock and vibration
f. Radiation hardness.

Virtually all of the environmental considerations associated with quartz-glass delay lines are concerned with the transducer components rather than the delay medium used in an application. The two exceptions to this are temperature and nuclear radiation.

Quartz-glass transducers can exhibit sensitivity to the electromagnetic environment, reduced barometric pressure, humidity, temperature excursions, shock-vibration and nuclear radiation. However, transducer sensitivity to the environment is no greater than that of associated electrical and electronic components.

Temperature coefficient problems can be avoided by using an oven to stabilize the delay medium. The high temperature inertia of a large blank and the general requirements for high stability temperature control mean that critical lines are usually within two or more nested ovens. The outer oven provides the rougher temperature control and the inner oven, the finer temperature control.

Amorphous delay media are relatively insensitive to nuclear bombardment. The transducer used in the application will most likely fail first. Single crystal delay media will usually exhibit a much greater susceptibility to nuclear effects. It should be noted that these are generalizations and that specific media must be evaluated for specific behavior in this kind of environment.

11.5.7 Reliability considerations. Once a quartz-glass delay line has been packaged, the number of reliability screening options is limited. Radiographic inspection is usually not an effecitve screen. Unless the internal construction of the delay lines consists of a few macroscopic component parts with simple interconnections, the resultant radiographs will only exhibit indiscernable clutter.

Burn-in and thermal shock under voltage are inexpensive and relatively fast reliability screens. Thermal shock is especially important as it provides a means of ensuring the integrity of the transducer attachment. Both of these screen tests should be preceded and followed by functional electrical testing.

Vibration is also a recommended reliability screen. By their very nature, these devices are physically massive and their fabrication is labor intensive. Vibration reveals the mechanical integrity of the basic design and the transducer attachment.

11.6 DELAY LINES, METAL SONIC

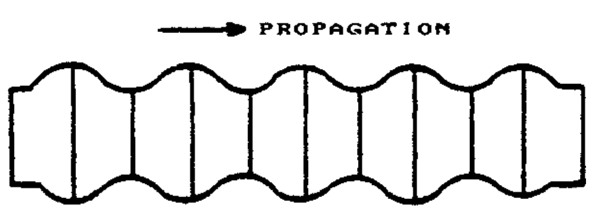
11.6 Metal sonic.

11.6.1 Introduction. The delay of electrical signals may be accomplished by propagation of an electromagnetic wave through a dielectric medium or by translating the electrical wave to some other form (i.e., sonic waves) where it can pass through an appropriate delaying medium and be retranslated back to electrical signals after the delay. This section deals with use of metals as sonic delay media.

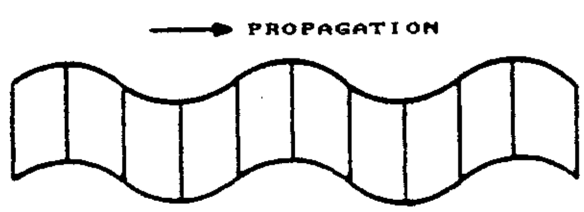
The most common propagation modes in metals are longitudinal and shear (Figure 18). These modes can be excited either with direct electrical to mechanical transducers or by magnetostriction. Nickel is a particularly good magnetostrictive material exhibiting longitudinal and shear distortion when subjected to a longitudinal magnetic field.

11.6.2 Usual applications. The most common application for a metal sonic delay line is for digital memories which can be used as buffer memories for teletype, process control, and numerically controlled machines. They can also be used as main memories for special purpose computers, main frame computers, differential analyzers, and shift registers.

A number of the applications of metal sonic delay lines have been superseded by surface acoustic wave delay lines operating in higher frequency ranges. While such lines are obviously attractive for equipment operating in these ranges (such as the intermediate or signal frequencies of radar), data processing equipment can likewise benefit from the wider bandwidths available in metal sonic delay lines.



A. Compression wave



B. Metal sonic delay line propagation modes

FIGURE 18. Metal sonic delay line propagation modes.

11.6.3 Physical construction. The simplest forms of metal sonic delay lines consist of the delay medium and a transducer at each end of the sonic path (Figure 19). Absorptive material is used at the ends of the line to prevent unwanted reflections of the sonic wave.

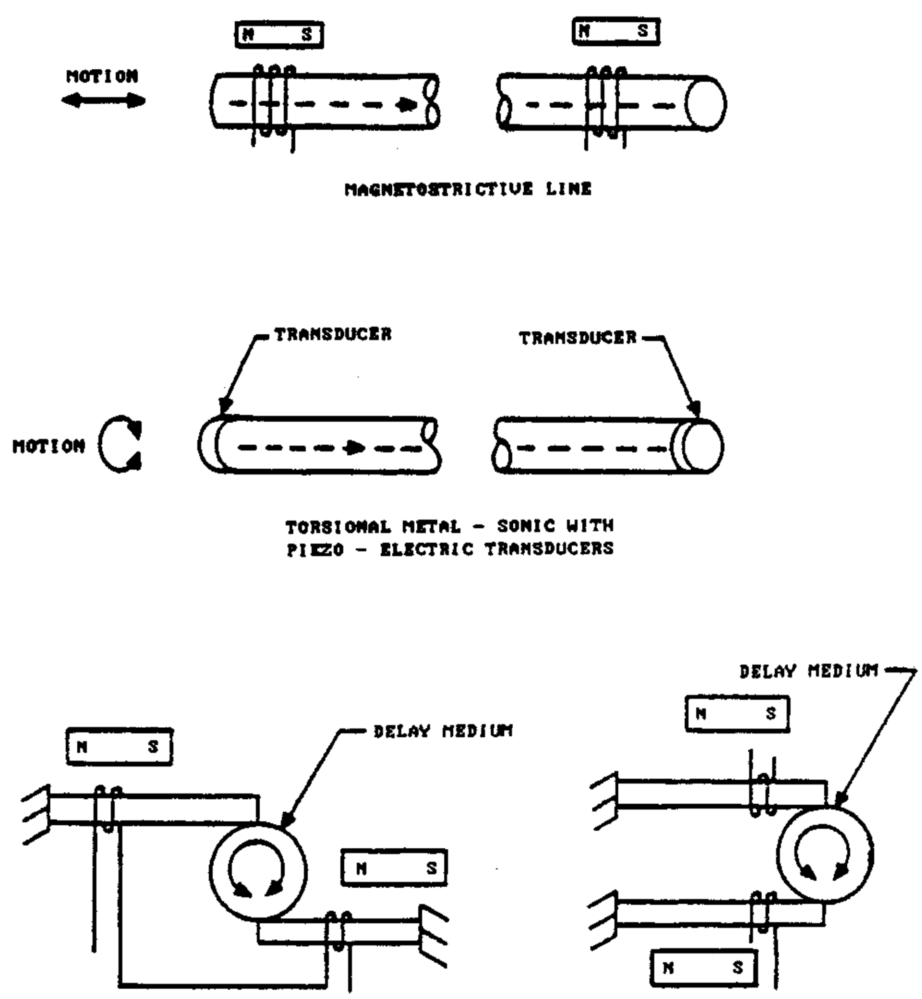
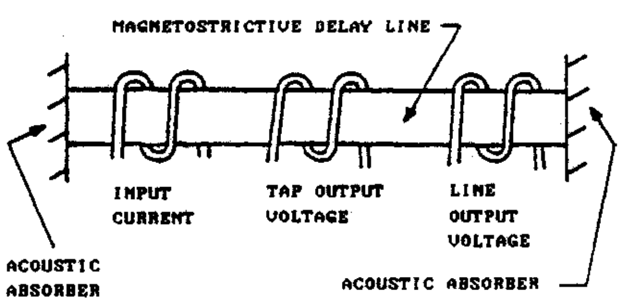


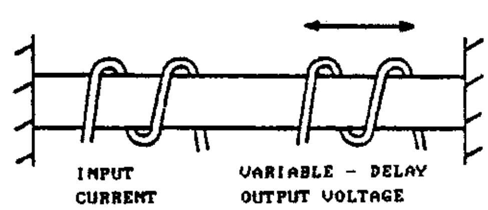
FIGURE 19. Metal sonic delay line magnetostrictive transducers.

An attractive feature of metal sonic delay lines with magnetostrictive transducers is that it is possible to change the position of one or both transducers without major difficulty and thus adjust the length of the line by as much as several microseconds. In order to achieve a variable delay, metal sonic devices can be tapped by the addition of a magnetostrictive transducer (Figure 20).

11.6 DELAY LINES, METAL SONIC



A. Tapped magnetostrictive delay line



B. Variable magnetostrictive delay line

FIGURE 20. Variable metal sonic delay line with magnetostrictive tap.

11.6.4 Military designation. There are no directly applicable military specifications or standards.

11.6.5 Electrical characteristics. The nature of the disturbance propagated through metal delay media and the nature of the transducers used cause considerable alteration in the form of the transmitted signal. For this reason metal sonic delay lines are more suitable to the processing of digital rather than analog information because digital signals lend themselves more to reshaping after the delay phenomenon has been accomplished.

There is also considerable attenuation in metal media devices, making pre- and postamplification desirable. Combining amplifiers and signal shaping circuits in the sealed delay line package make unity gain delay lines possible.

11.6 DELAY LINES, METAL SONIC

The longer lines, relying upon sonic propagation due to a torsional stress, pose special problems. A considerable length of wire is required to achieve useful delays. For reasons of space efficiency, the wire is coiled. However, this configuration, although more space efficient, leads to performance problems. In the coiled form, the delay medium must be mechanically supported and these support points can contribute both attenuation and reflection.

The temperature coefficient of the transducer material is also important because it controls the mode of operation of the delay line. There are three typical modes of operation, and a delay line is usually designed for just one of the three. These modes of operation are: the return to zero (RZ or RTZ), the non-return to zero (NRZ), and the bipolar mode. In typical applications, the NRZ can store twice the information (number of bits) of the RZ mode. The advantage of the RZ mode is that it permits the simplest device specification. The advantage of bipolar operation is greater immunity to noise.

11.6.6 Environmental considerations. The environmental considerations associated with all sonic delay lines are:

a. Electromagnetic environment
b. Reduced barometric pressure
c. Humidity
d. Operational temperature range
e. Shock and vibration
f. Radiation hardness.

Virtually all of the environmental considerations associated with metal media delay lines are concerned with the transducer components rather than the delay medium used in an application. The exceptions to this are temperature and nuclear radiation.

Metal media delay line transducers can cause, in the electromagnetic environment, reduced barometric pressure, humidity, temperature excursions, shock-vibration, and nuclear radiation. However, transducer sensitivity to the environment is no greater than that of associated electrical and electronic components.

By their very nature metal media exhibit different physical and electrical characteristics as a function of temperature. For this reason, it is advisable this type of delay line be operated only in a moderate thermal environment.

Metal delay media are relatively insensitive to nuclear bombardment. The transducer used in the application and adjacent electronic components will most likely fail before significant delay medium deterioration will occur.

11.6 DELAY LINES, METAL SONIC

11.6.7 Reliability considerations. After a metal media delay line has been packaged, the number of reliability screening options is limited. Radiographic inspection is typically not an effective screen. Unless the internal construction of the delay line consists of a few macroscopic component parts with simple interconnections, the resultant radiographs will only exhibit indiscernable clutter.

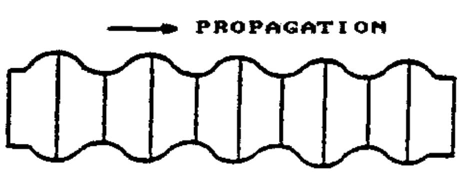
Burn-in and thermal shock under voltage are inexpensive and relatively fast reliability screens. Thermal shock is especially important as it provides a means of ensuring the integrity of the transducer. Both of these screen tests should be preceded and followed by functional electrical testing.

Vibration is also a recommended reliability screen. By their very nature, metal media devices are physically massive and labor intensive. Vibration reveals the mechanical integrity of the basic design and the physical integrity of the transducer.

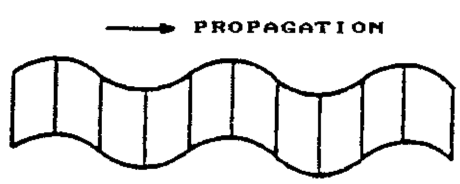
11.7 Surface acoustic wave.

11.7.1 Introduction. The delay of an electrical signal need not occur only in a dielectric medium. Electrical signal delay can also be achieved by translating an electrical wave into a sonic wave, passing the sonic wave through a bulk sonic medium, and then translating the delayed wave back into an electrical signal. This procedure is attractive because the velocity of sound in most bulk media is much less than that available in electrical circuitry. This sonic signal transmission through a bulk medium is by a compressed longitudinal wave (Figure 21A) or a shear transverse wave (Figure 21B).

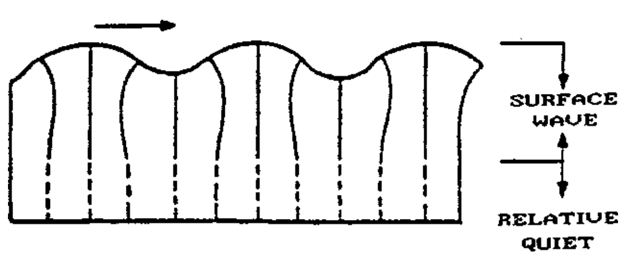
The surface acoustic wave (SAW) has both longitudinal and transverse components. However, the majority of the energy concentrated in SAW is within one acoustic wavelength along the surface of the bulk medium. The energy decreases exponentially normal to the surface of the medium (Figure 21C).



A. Compression wave



B. Shear wave



C. Surface acoustic wave

FIGURE 21. Sonic propagation modes in solids.

11.7 DELAY LINES, SURFACE ACOUSTIC WAVE

Many sonic bulk delay lines are made from amorphous materials such as quartz/glass (see subsection 11.4) and metal (see subsection 11.5). However, there exists the problem of exciting the sonic wave in such substances. The problem is greatly minimized if a piezoelectric crystal is used as the bulk material.

A pair of electrical conductors laid on the surface of a piezoelectric crystal will cause the crystal to distort mechanically when an electrical potential energizes the conductor pair. If several parallel pairs of conductors are placed on the surface and simultaneously energized, the combined distortion will create a surface acoustic wave at particular frequencies.

A similar pair (or pairs) of conductors placed on the surface in the path of this wave will be electrically excited when the wave passes under them. The efficiency of electrical coupling increases as a function of the contact between the conductors and the crystal because the crystals are essentially insulators, the conductors may be deposited directly onto the crystal surface. This is done in the same manner as deposition of conductive paths on integrated circuit substrates.

The velocity of an SAW is on the order of 10^{-5} that of an electrical wave in free space. As wavelength equals velocity-frequency, conductor arrays of the size of several wavelengths are practical at desirable frequencies. Proper design of such an array permits practically all of the electrical signal to excite the SAW mode and very little of the energy excites bulk modes.

11.7.2 Usual applications. Dispersive SAW devices are used in chirp radars. In this application, a narrow high intensity pulse may be stretched to a wide linear fm pulse suited to peak limited amplifiers. This results in an increase in effective radar power.

After reflection from the radar target and reception at the receiver, the wide pulse may be passed through a matching filter and be compressed into a narrow pulse. The resulting narrow pulse is used in the radar to discriminate between two or more targets at the same range.

Use has also been made of the fact that as the SAW travels along the delay medium that there is an accompanying electric field. With an amplifier on the surface to detect and amplify the field as it travels, it becomes possible for the signal to emerge as large or larger than it was at the input.

When the delay medium surface is coated with photosensitive resistive material, it will act as an electrical load. In response to an optical image focused on the surface of the resistive material, this load can be made variable. Choice of input waveform and electrode geometry will then allow the processing of the optical information. Direct optical information can be obtained from the traveling SAW by reflection, or when the crystal is transparent by variation in transmission caused by dimensional distortion accompanying the SAW.

11.7.3 Physical construction. The simplest form of the SAW line consists of two transducers and a piezoelectric delay medium. The practical way to achieve this is to deposit metallic fingers on the surface of the crystal to act as the electrical portion of the transducers.

The length, width, shape, and material of the transducer fingers all affect the production and pickup of the SAW and the creation of spurious reflections within the delay medium. Soft metals such as gold or aluminum are preferred for transducer materials.

Whereas the narrowband versions of the SAW delay line may have evenly spaced fingers, the wider band devices will vary both finger spacing and finger width (Figure 22). In addition, the structures may vary the finger overlap, weighting, or apodizing the response. The impulse response of the SAW line will approximate the appearance of an apodized line because the amplitude of a wave generated by a finger pair is controlled by the amount of overlap of the fingers.

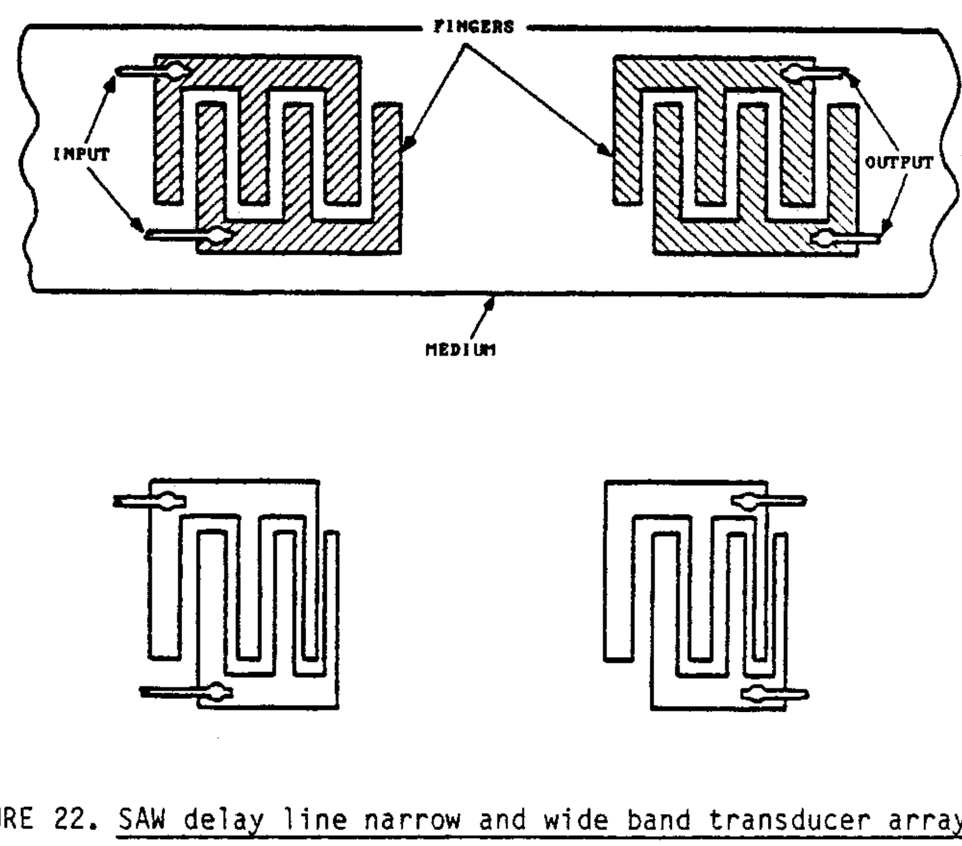


FIGURE 22. SAW delay line narrow and wide band transducer arrays.

11.7 DELAY LINES, SURFACE ACOUSTIC WAVE

Variation in the amount of overlap will cause a variation in the amount and distribution of acoustic reflection of a wave passing under the fingers. To minimize this variation, it is often useful to fill this space with dummy fingers of the same width as the missing section; these fingers are not connected to either electrical conductor.

The SAW generated by a finger array is bidirectional with approximately one-half of the energy moving in each direction. That portion of the energy moving in the undesired direction tends to reflect from the end of the medium and acts as an inverted signal. A common way to minimize this undesired reflection is to pad that end of the medium with an acoustic absorber.

Similarly, SAW energy not absorbed by the pickup transducer, will tend to reflect off the opposite end of the medium and reach the pick up transducer a second time if that end is not also padded. Note that it is possible to achieve a good match of the electrical signal into the medium by choice of physical configuration of the fingers and simple electrical circuitry such as a loading coil. The resulting goodness of the match is dependent on the bandwidth.

Choice of the delay medium depends on a number of factors. Bismuth germanium oxide has an attractively low acoustic velocity, lithium niobate has a high coupling constant, and ST quartz has a low temperature coefficient over temperature. Lithium niobate has low loss characteristics but stable operation requires its use in temperature controlled ovens. Lithium niobate also has some tendency to fracture from mechanical shock. Where higher insertion loss is permissible, ST quartz is a good choice for space and other critical environments.

Conductor pairs at intermediate positions along the delay line medium may be used to sample the SAW as it passes. This is effectively a tap and a large number of such taps may be used simultaneously. The amount of energy so withdrawn at a tap will lessen the signal's energy and may in extreme cases cause reflections back toward the origin of the signal. However, taps cause fewer problems on low coupling factor material (e.g., ST quartz) than high coupling factor material (e.g., lithium niobate).

11.7.4 Military designation. There are no applicable military specifications or standards for surface acoustic wave delay lines.

11.7.5 Electrical characteristics. SAW devices afford long delays with minimal distortion provided the signal is an alternating current wave whose frequencies are well within the passband. This includes a modulated pulse or pulse train if the sideband frequencies are also within the passband. However, compared with other types of sonic delay lines the SAW passband is narrow.

The requirements for this passband region are that the delay line phase response increases linearly with frequency and that the loss be constant as a function of frequency. The degree by which the line departs from these criteria determines the degree of distortion of the desired wave.

11.7 DELAY LINES, SURFACE ACOUSTIC WAVE

SAW devices have three undesirable electrical characteristics which are: direct feed through spurious, crosstalk, and other spurious. Direct feed through spurious occurs when electrical coupling takes place without a signal having traversed the delay medium. Crosstalk occurs when one or more delay medium is positioned in close proximity to another and their respective transducers pickup each other's signals. Other spurious pertains to any other types of undesirable characteristics such as reflections from the ends of the delay medium.

SAW devices usually have lower losses than other acoustic devices. However, insertion losses within the passband can be as great as 50 or 60 dB. As a result, the user needs to decide which frequency or frequencies for measurement are needed for the application. If a simple constant delay with no waveform change is needed, measurement of the center frequency insertion loss and group delay over the desired bandwidth is usually sufficient.

11.7.6 Environmental considerations. The environmental considerations associated with SAW delay lines as a whole are:

a. Electromagnetic environment
b. Reduced barometric pressure
c. Humidity
d. Operational temperature range
e. Shock and vibration
f. Radiation hardness.

Virtually all of the environmental considerations associated with SAW delay lines are concerned with the transducer components rather than the delay medium used in an application. The exceptions to this are temperature and nuclear radiation.

SAW delay line transducers can exhibit sensitivity to the electromagnetic environment, reduced barometric pressure, humidity, temperature excursions, shock-vibration and nuclear radiation. However, transducer sensitivity to the environment is no greater than that of associated electrical and electronic components.

SAW delay media are relatively insensitive to nuclear bombardment. The transducer utilized in the application and adjacent electronic components will most likely fail before significant delay medium deterioration will occur.

11.7.7 Reliability considerations. After a SAW delay line has been packaged, the number of reliability screening options is limited. Radiographic inspection is usually not an effective screen. Unless the internal construction of the delay line consists of a few macroscopic component parts with simple interconnections, the resultant radiographs will only exhibit indiscernable clutter.

Burn-in and thermal shock under voltage are inexpensive and relatively fast reliability screens. Thermal shock is especially important as it provides a means of ensuring the integrity of the transducer. Both of these screen tests should be preceded and followed by functional electrical testing.

11.7 DELAY LINES, SURFACE ACOUSTIC WAVE

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12. MOTORS

12.1 General.

12.1.1 Introduction. This section discusses motors used for NASA applications. These devices are not included in MIL-STD-975.

Selection of the proper motor for a given application is extremely important. A motor that is too small can result in overheating and premature failure whereas a motor that is too large can waste power and space. In addition, selection of the wrong type of motor can cause excessive power consumption or poor response.

This section is restricted to the selection and application of conventional ac and dc motors.

12.1.1.1 Applicable military specifications. Motors are covered by the following military specifications:

Mil Spec	Title
MIL-M-7969	Motors, Alternating Current, 400 cycle, 115/200 Volt System, Aircraft, General Specification
MIL-M-8609	Motors, Direct Current, 28 Volt System, Aircraft, General Specification
MS 33543	Criteria - Temperature and Altitude Range Self Cooled Electric Equipment

12.1.2 General definitions.

Accelerating torque. The torque exerted by a motor during the entire acceleration time. A speed-torque curve is required to find this torque.

Breakaway torque. The torque that a motor is required to develop to break away its load from rest to rotation.

Full-load current. The current which the motor draws when the rated voltage and frequency are applied and when the motor is operated at rated power output (full load torque and speed).

Full-load torque. The torque developed by a motor during rated power output when the rated voltage and frequency are applied.

12.1 MOTORS, GENERAL

Locked-rotor current. The current that the motor draws when rated voltage and frequency are applied and the rotor does not rotate. Fuses, circuit breakers, and wire must be selected to accommodate this initial surge.

Locked-rotor torque. The minimum torque that a motor develops for all angular positions of its rotor when the rated voltage and frequency are applied and the rotor does not rotate.

Pull-in-torque of a synchronous motor. The maximum constant torque under which the motor will pull its connected inertia load into synchronism at rated voltage and frequency.

Pull-out torque of a synchronous motor. The maximum sustained torque which the motor will develop at synchronous speed with rated voltage and frequency applied.

Pull-up torque of a synchronous motor. The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs with rated voltage applied at rated frequency.

Starting torque. The minimum torque developed at zero rotation with rated voltage and frequency applied. This is normally expressed as a percentage of full-load torque.

Synchronous torque of a synchronous motor. The torque developed after voltage is applied. This is the total steady-state torque available to drive the load.

12.1.3 General device characteristics. An electric motor has a stator (which has a laminated steel core and insulated copper wire coils), a rotor, or armature, and a frame to position the stator and rotor. The rotor is attached to the shaft, and the rotor and shaft assemblies rotate on bearings. In an ac motor the rotating element is the rotor, and in a dc motor the rotating element is the armature.

A further classification to ac and dc motors may be made according to their construction and method of operation.

A dc motor is classified by the type of motor field. This includes permanent magnet, series-wound, shunt-wound, and compound wound designs. This motor is characterized by large changes in speed and current with changing loads.

An ac motor is classified as either induction or synchronous. Induction motors operate at speeds below synchronous speed but are still relatively constant speed devices. The torque developed in induction motors is the result of relative motion between an induced rotating field in the rotor and a rotating electrical field in the stator. Synchronous motors differ in that they operate at a constant speed which is synchronized with the speed of the rotating field in the stator. Synchronous motors supply torque when their speed is locked into the synchronous speed of the windings.

12.1 MOTORS, GENERAL

A dc motor is used in applications which do not require speed regulation or the fine control that is typical of a servo system. Shunt-wound dc motors are reversible during rotation and have good starting torque. However, the dc motor creates radio frequency interference due to arcing at the commutator. The dust contributed by the brush in normal wearout can cause failure of the bearings and voltage leakage paths.

An ac motor generally operates at constant speed and has moderate to high starting torques, but the direction of rotation cannot be reversed without stopping. The ac motor is simpler and has a more reliable design than the dc motor because it has no rotating windings, brushes, or commutator.

12.1.3.1 Motor enclosures. The correct enclosure should be selected for the type of motor to be used. Most motors used in NASA environments are totally enclosed nonventilated or explosion-proof. Following are definitions of the major types of motor enclosures.

Open motors. An open motor is one which has ventilating openings to permit passage of external cooling air over and around the windings.

Drip proof motors. Drip-proof motors are open motors in which the ventilating openings are constructed so that successful operation is not affected if drops of liquid or solid particles strike or enter the enclosure at any angle up to 15 degrees from the vertical.

Splash-proof motors. Splash proof motors are open motors in which the ventilating openings are constructed so that successful operation is not affected if drops of liquid or solid particles strike or enter the enclosure at any angle up to 100 degrees from the vertical.

Totally enclosed motors. These motors are enclosed to prevent free exchange of air between the inside and outside of the case. However, the enclosure might not be airtight.

Totally enclosed nonventilated (TENV) motors. TENV motors are not equipped for cooling by means external to the enclosure.

Totally-enclosed fan-cooled (TEFC) motors. TEFC motors are cooled by a fan attached to the motor outside of the enclosure.

Explosion-proof motors. Explosion-proof motors are totally enclosed motors with enclosures designed to withstand an explosion of a gas within them and to prevent ignition of the external environment by sparks, flashes, or explosions within the motor housing.

12.1 MOTORS, GENERAL

12.1.4 General parameter information.

12.1.4.1 Speed. The synchronous speeds of a motor can be calculated using the following formula:

$$\text{Synchronous speed} = \frac{120 \times \text{line frequency}}{\text{number of poles}}$$

The most commonly used speeds are given in Table I.

TABLE I. Commonly used synchronous speeds

No. of Poles	400 Hz	60 Hz
2	24,000 rpm	3,600 rpm
4	12,000 rpm	1,800 rpm
6	8,000 rpm	1,200 rpm
8	6,000 rpm	900 rpm
10	4,800 rpm	720 rpm
12	4,000 rpm	600 rpm

Induction motors operate at less than a synchronous speed, depending on the torque they are delivering and the shape of their speed-torque curve. The difference between synchronous speed and actual speed is the "slip" of the motor. This is usually expressed as a percentage of synchronous speed and is calculated using the following formula:

$$\text{Percent slip} = \frac{(\text{synchronous speed} - \text{full load speed}) \times 100\%}{\text{synchronous speed}}$$

As an example, if a 2-pole, 400-Hz motor with a synchronous speed of 24,000 rpm ran at 20,000 rpm, the slip would be 4,000 rpm or 16.7 percent.

The amount of slippage varies with the horsepower rating, number of phases, starting torque, and other factors. The induction motor speeds most commonly used are given in Table II.

TABLE II. Commonly used induction speeds.

No. of Poles	400 Hz	60 Hz
2	22,500 - 20,000 rpm	3,250 - 3,000 rpm
4	11,200 - 10,000 rpm	1,675 - 1,550 rpm
6	7,500 - 7,000 rpm	1,100 - 1,050 rpm
8	5,500 - 5,300 rpm	825 - 800 rpm
10	4,400 - 4,200 rpm	680 - 650 rpm
12	3,700 - 3,500 rpm	530 - 500 rpm

12.1.4.2 Full-load torque. To properly select a motor, it is necessary to know the continuous operating torque required and the speed at which the load must be driven. If a gear head is applied to a motor, it is necessary to know the gear ratio desired in the gear head and the efficiency of the gear head, so that the speed and torque output for the motor can be calculated.

12.1.4.3 Locked-rotor torque. Locked-rotor torque is the minimum torque a motor develops at zero rotation when the rated voltage and frequency are applied. This torque is generally expressed in percent of full-load torque. Thus, a motor rated at 1/10 hp, 10,500 rpm, and 340 percent locked-rotor torque develops a 9.6 ounce-inch torque minimum at 10,500 rpm and 32.6 ounce-inch torque at zero rpm.

The locked-rotor torque must be known to select the correct motor. A high locked-rotor torque motor generally has a lower full-load speed than a motor of the same rating with a lower locked-rotor torque. Therefore, a low-slip motor (high full-load speed) is obtained by having relatively low locked-rotor torque.

Very high locked-rotor torque requirements require a larger motor than is ordinarily used.

A typical motor performance curve is shown in Figure 1.

12.1.4.4 Developed power. The developed power may be calculated from either of the two formulas given below:

$$\text{Horsepower (hp)} = \frac{\text{torque (inch-ounce)} \times \text{rpm}}{1{,}008{,}000}$$

$$= \text{torque (inch-ounce)} \times \text{rpm} \times 10^{-6}$$

$$\text{Watts out} = \frac{746 \times \text{torque (inch-ounce)} \times \text{rpm}}{1{,}008{,}000}$$

$$= 746 \times \text{torque (inch-ounce)} \times \text{rpm} \times 10^{-6}$$

12.1 MOTORS, GENERAL

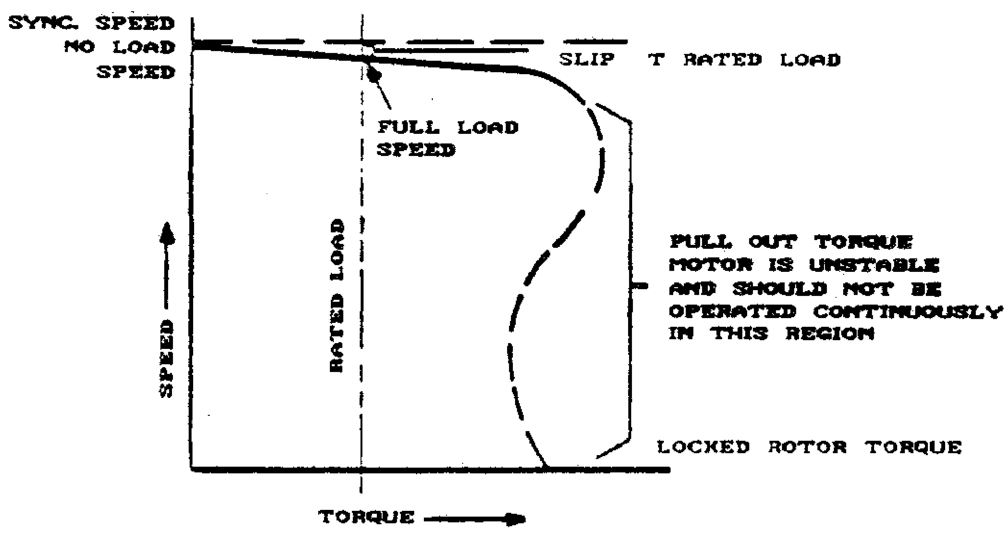


FIGURE 1. Typical motor performance curve.

12.1.4.5 Torque. The torque (T) may be calculated from the formula below.

$$T = \frac{hp \times 1{,}008{,}000}{rpm}$$

$$= \frac{hp}{rpm} \times 10^6$$

12.1.4.6 Volt ampere input. The volt-ampere input may be found as follows:

for a dc motor = E x I

for a single-phase ac motor = E x I

for a three-phase ac motor = $\sqrt{3} \times E \times I$

where E and I are the line voltage and current, respectively

12.1.4.7 Power input. The power input may be found as follows:

for a dc motor = E x I

for a single-phase ac motor = E x I x power factor

for a three-phase ac motor = $\sqrt{3} \times E \times I \times$ power factor

12.1.4.8 Efficiency. The efficiency (Eff) may be calculated from the following formula:

$$\text{Eff} = \frac{\text{Developed power}}{\text{Power in}} \times 100\%$$

12.1.4.9 Required input current. The required input current may be found as follows:

for dc motors: $$I = \frac{\text{hp} \times 746}{E \times \text{Eff}}$$

for single-phase ac motors: $$I = \frac{\text{hp} \times 746}{E \times \text{Eff} \times \text{power factor}}$$

for three-phase ac motors: $$I = \frac{\text{hp} \times 746}{\sqrt{3} \times E \times \text{Eff} \times \text{power factor}}$$

where E is the line voltage.

12.1.4.10 Power factor. For ac motors, the power factor (PF) is:

$$PF = \frac{\text{watts in}}{\text{volt amperes in}}$$

12.1.4.11 Rise time. Another factor in some applications is the time required to accelerate a given load to a given speed. The time (T), in seconds, for a motor with an inertia (I_M) and supplying a torque (L) to accelerate an inertial load (I_L) to a speed (N) can be found from the expression:

$$T = 0.0162\ (I_M + I_L)\ (N/L)$$

where

I_M is in inch-ounce^2 and may be obtained from published data or calculated from the formula:

$I_M = 0.5\ mr^2$ where m is the rotor's weight in ounces, r is the radius in inches

I_L is the inertia of the load in inch-ounce^2

N is the speed in revolutions per second, and L is the torque supplied by the motor in inch-ounces

When a hysteresis synchronous motor is used, the starting torque may be substituted for L. For other motors, the value of the average torque must be used for L.

12.1 MOTORS, GENERAL

12.1.4.12 Duty cycle. Motors are designed to operate in various duty cycles, depending upon their application. These duty cycles include:

Continuous duty. Operating at approximately a constant load for an indefinite period. If load is on for more than 15 minutes, this is considered continuous.

Intermittent duty. Intermittent duty includes the following:

a. Load and power-off periods

b. Load and no-load periods

c. Load, no-load, and power-off periods.

To select the correct motor for a given application, it is necessary to have a correct definition of this duty cycle including the time and ambient temperature for each phase of the duty cycle.

12.1.5 General guides and charts. An important consideration in selecting a motor is the configuration of its speed torque curve. The following are the typical speed torque curves of the different types of motors discussed later.

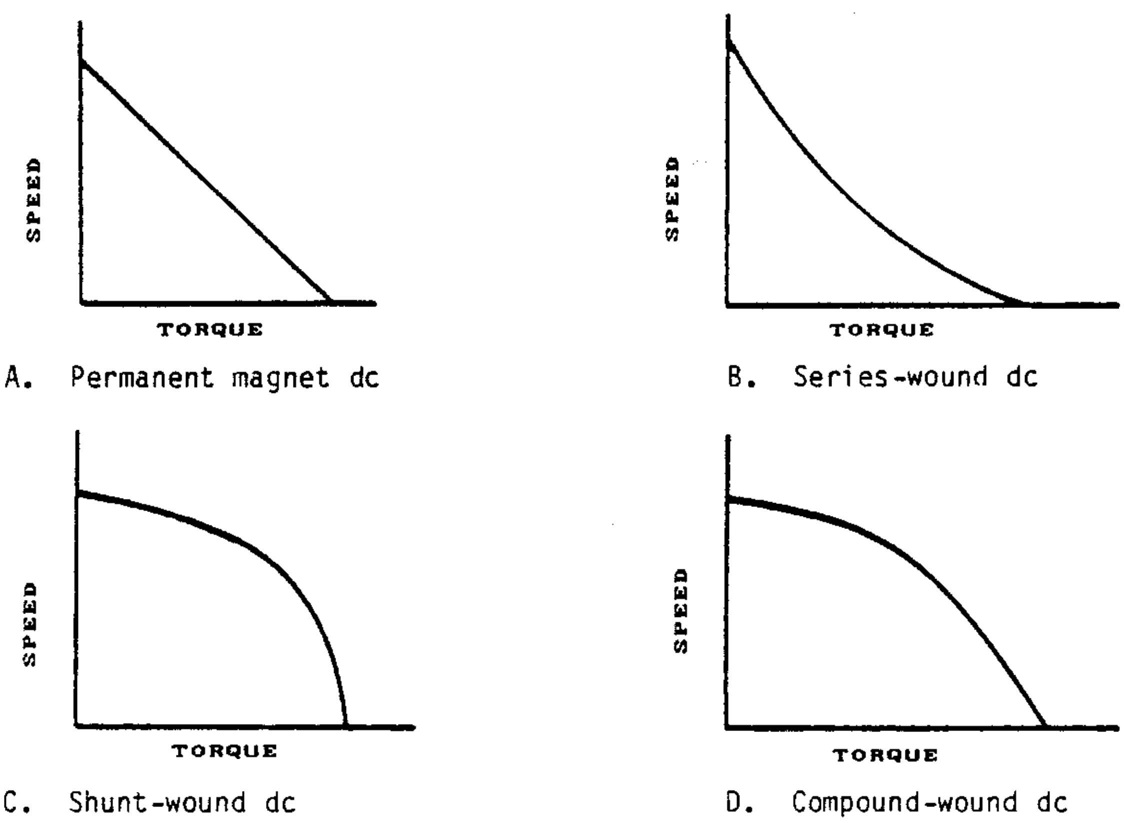
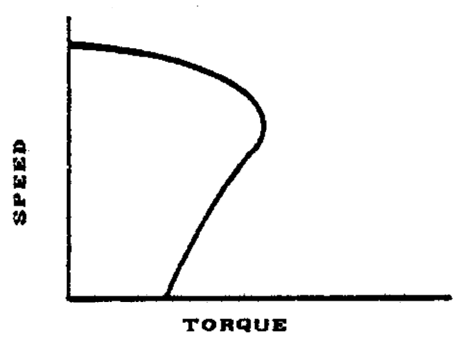
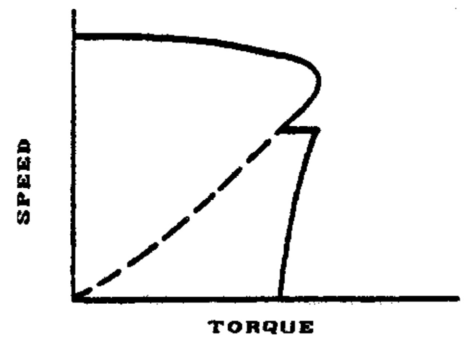


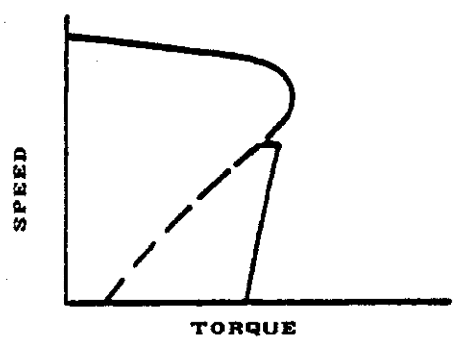
FIGURE 2. Typical speed torque curves.



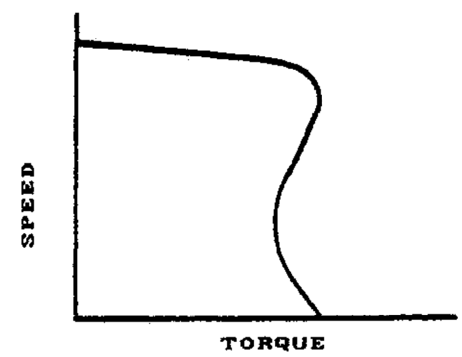
E. Permanent split capacitor, ac



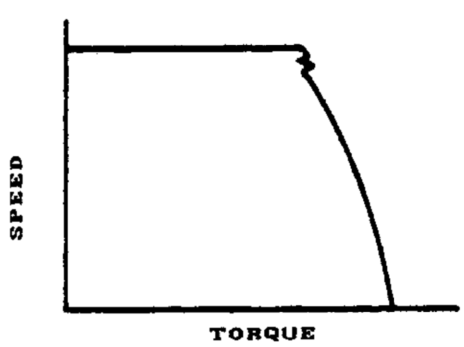
F. Capacitor-start, ac



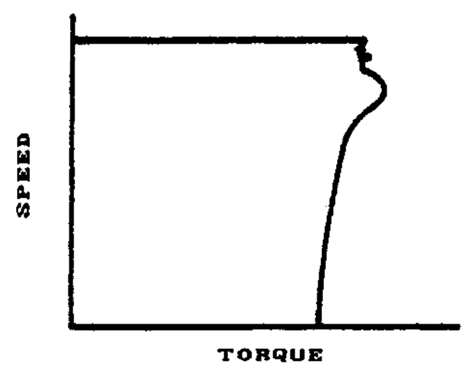
G. Capacitor start-capacitor run, ac



H. Three-phase induction, ac



I. Reluctance ac



J. Hysteresis permanent magnet induction ac

FIGURE 2. Typical speed torque curves (Continued).

12.1 MOTORS, GENERAL

12.1.6 General reliability considerations. The motor should be able to deliver the torque required for the application in the given environment. A motor that provides satisfactory performance at room temperature or at sea level may be inadequate at higher temperatures or altitudes. The overheating that results from selecting a unit that is not satisfactory for its duty cycle or environment leads to either catastrophic failure or shortened bearing and insulation life due to excessive winding temperatures.

When selecting motors to operate over wide temperature ranges, care should be taken to ensure that the bearing design is adequate for the application. This is particularly true if a unit capable of operating continuously at high temperatures must also operate at extreme cold temperatures.

In designing a motor in a system, care should be taken to ensure that the unit is mounted to a sufficiently large heat sink. Improper heat sinking can cause the same types of failure as overloading. The availability of cooling air will help minimize problems caused by overheating.

As with all electromechanical components, motors should be protected from extremely high voltage.

In operation, small decreases in voltage are actually more harmful than small increases. Decreased voltage reduces the torques available, reduces full-load speed, increases full-load currents, and causes increased winding temperatures. An increase in voltage will increase the magnetic noise from the motor.

In an ac motor, fluctuations in line frequency affect performance and reliability. The speed of an ac motor is proportional to the frequency. Starting torque and overload capacity are reduced by increased frequency, whereas winding temperatures are increased by reduced frequency.

For a three-phase motor, care should be taken to protect the motor from operating in single phase if one phase should be lost. Single-phase operation will cause the unit to operate at a continuous stall condition and overheat or, if the unit is rotating at the time, will cause it to be overloaded and develop excessive winding temperatures.

Since bearings or rotating parts are damaged by shock loads, care should be taken in handling units before they are installed in equipment. Bearings become brinelled by excessive shock loads resulting in noisy operation and premature bearing failures.

For a three-phase motor, the rated performance assumes a balanced power supply. The voltage and power factor, as determined for each lead or pair of leads, should be equal when the motor is delivering full load. The effects of unbalanced voltage are measurable in the motor current, speed, torque, and temperature rise. An unbalance of as little as 3.5 percent between highest phase voltage and the average of all three voltages in a three-phase motor will result in a temperature rise of about 25 percent above normal. Also, the current per phase resulting from a severe power unbalance makes it quite difficult to protect and control the motor.

Another factor in selecting a reliable motor is the trade-off between bearing life and motor size. Slower rotating motors have a longer bearing life and require less gear reduction. Higher speed motors develop more horsepower than a slower speed motor of the same size.

12.2 MOTORS, AC

12.2 AC motors.

12.2.1 Introduction. The two major categories of ac motors are induction and synchronous. There are several types in each category.

12.2.1.1 Induction motors. The induction motor, which is the most widely used, is often referred to a "squirrel cage" motor because of the squirrel cage configuration of the electrical conductors when the steel core is removed from the rotor. There are no brushes or slip rings which need adjustment as a result of wear. The rotor consists of either a series of bars connected together by end rings or a single unit of cast aluminum. The only friction or wearing of parts occurs in the shaft support bearings. The induction motor runs at less than synchronous speed.

The induction motor is so named because current is induced in the rotor with no outside connection. This induced current reacts with the stator's field, causing rotor rotation. These motors are preferable to dc motors for constant speed work because the initial cost is less and the absence of slip rings or permanent magnets eliminates problems inherent in dc designs.

Single-phase and three-phase motors are the types most commonly used. Single-phase motors require some means of starting rotation. If single-phase power were supplied to a motor without an auxiliary starting winding, the motor would not run unless some external force were applied to start shaft rotation. Single-phase motors are generally referred to by designations which describe the starting method used. They exhibit more noise in operation and less efficiency than polyphase motors.

Induction motors may be subdivided into three types, they are discussed in the following paragraphs.

Permanent split-capacitor. Permanent split-capacitor units have a capacitor placed between one phase winding and the power supply. The other phase is connected directly across the power line as shown in Figure 3.

Motors of this type have a characteristically low locked-rotor torque, generally 30 percent of full-load torque (FLT). Permanent-split capacitor motor windings usually differ in capacitor phase and main phase to obtain the best possible performance and capacitor size. This is the most common type of single-phase motor.

Capacitor start--capacitor run. To correct the starting torque limitation of the permanent-split capacitor motor, an external relay is used to put a second capacitor in parallel with the running capacitor during starting as shown in Figure 4. This second capacitor is then eliminated from the circuit as the motor attains a predetermined speed or current value. By this means, locked-rotor torques of 500 percent are obtainable. The major limitations of this system are the externally mounted relay and two capacitors, which also increase cost.

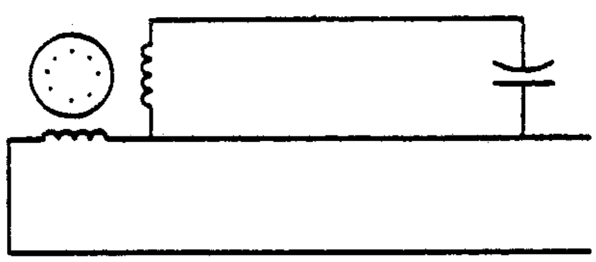


FIGURE 3. Permanent split-capacitor induction motor.

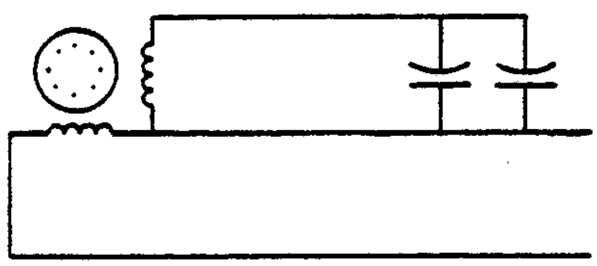


FIGURE 4. Capacitor start-capacitor run induction motor.

Three-phase motors. Three-phase motors provide the most horsepower per weight and are highly stable units. Exceptionally high locked-rotor torques are obtained, with typical locked-rotor torques ranging from 250 to 300 percent. Higher locked rotor torques are readily obtained and extremely high locked-rotor torques are provided through proportionate increases in size and weight. Efficiency is higher than that for single-phase motors, but the power factor is less than that of a permanent-split capacitor type. The schematic for a typical three-phase motor is shown in Figure 5.

This section does not include a discussion of such types as wound rotor induction motors, repulsion-induction motors, repulsion-start induction motors, split-phase induction motors, or universal ac and dc motors, since these units are not often used in NASA applications.

12.2 MOTORS, AC

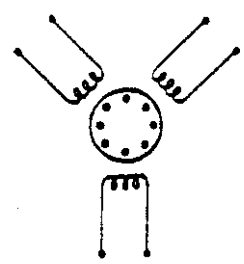


FIGURE 5. Three-phase induction motor.

12.2.1.2 Synchronous motors. In contrast to induction motors, synchronous motors rotate in exact step with line frequency. In large motors, this is accomplished by connecting the rotor to a dc supply. This provides a strong field in the rotor that locks in step with the rotating field of the stator.

Reluctance. Except for having flats on the periphery, reluctance synchronous (salient pole) motors have the same type of squirrel cage rotors as induction motors. The flats affect the reluctance (resistance to establishing a magnetic field) which causes synchronism. The poles tend to align with the flux field. Current alternating off and on continually pulls the poles around in exact step. Motors of this type approach synchronous speed as induction motors and, after effecting synchronism, run synchronously as reluctance motors.

In cases where the motor load has relatively high inertia, the reluctance type motor is limited. It may be incapable of attaining synchronism, since it runs as an induction motor until near-synchronous speeds. The torque exerted by the rotor pole must be sufficient to accelerate the rotor and the load into synchronism rapidly. This must happen in time for the rotor to rotate one-half pole pitch. Therefore, a reluctance motor may start a load that it cannot pull into synchronism and the motor will continue to run as an induction motor.

Considerable cogging effects in starting, together with greater than normal induction motor noise and vibration, are present because of salient pole construction.

The major advantage of the reluctance synchronous motor is that it will phase (synchronize at a fixed angular position). Therefore, a two-pole unit phases in two positions, 0 and 180 degrees apart, and a four-pole unit phases in four positions, 0, 90, 180, and 270 degrees apart. The output of a reluctance motor is only about 40 percent of the same size induction motor.

Hysteresis. If the discrete poles of a reluctance motor are eliminated, the rotor still becomes magnetized but the flux is not channeled as in the reluctance motor and, thus, it is not as efficient. The rotor's tendency to maintain a magnetized condition in one position is called hysteresis. The hysteresis rotor uses this principle to run as the induced rotor poles are pulled around by the alternating field.

The rotor of a hysteresis synchronous motor is constructed of a ring of magnetic materials such as 37 percent cobalt and alnico.

Because of its smooth rotor, the hysteresis motor is free of magnetic pulsation resulting from pole saliency or slots, and is much quieter and generates less vibration than other types of synchronous motors.

A constant synchronous speed is obtained, but a load angle is assumed that changes with variations of load or applied voltage. There are no phasing or locking points for this type motor.

The hysteresis synchronous motor, unlike the reluctance type, is capable of synchronizing high-inertia loads. Because there is no cogging, smooth and uniform starting conditions prevail.

Permanent magnet induction (synchronous). Permanent magnet induction motors are often referred to as polarized hysteresis motors and are used in applications where lock-in position is important. The rotors of these units may be either smooth or salient pole.

This type of motor provides the advantage of overcoming the limitations of the hysteresis type and improving the reluctance-type phasing properties. Permanent magnet synchronous motors lock-in at one-half the number of positions required by a reluctance motor. Lock-in of a two-pole unit occurs in one place, and a four-pole in two places. A disadvantage lies in the reduced horsepower output per frame size, as compared to hysteresis types.

12.2.2 Usual applications. Wherever constant speed motion is required, ac motors are used. Although this is normally angular motion, it can be linear by use of a special gearing.

These motors are used to drive rotating devices such as antennas, tape systems, fans, pumps, timers, and counters, and to operate sliding devices such as valves and doors.

12.2.3 Physical construction.

12.2.3.1 Typical size and ratings. The mechanical dimensions of a motor are dependent upon the ratings. A typical outline configuration is shown in Figure 6. The ratings for a given motor frame size depend upon rotational speed, ambient temperature, heat dissipation through the frame, and duty cycle and thus cannot be demonstrated here.

12.2 MOTORS, AC

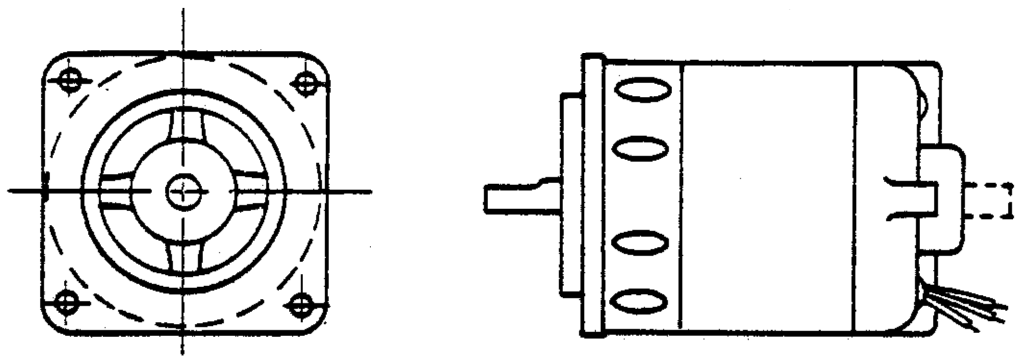


FIGURE 6. Typical outline of an ac motor.

12.2.4 Military designation. The ac motors used in aerospace electronics have not been standardized to the point where a military part designation is available.

However, motors are available that conform to the requirements of MIL-M-7969 for 400-Hz airborne applications.

12.2.5 Electrical characteristics. Most AC motors are designed to operate with 400-Hz, 115- or 200-V single- or three-phase power supply. However, because 400-Hz, 28-V power is also available in many applications, the same motors are available with stators wound for that voltage.

Electrical Current requirements generally vary according to the power requirements of the motor.

12.2.6 Environmental considerations. Motors conforming to MIL-M-7969 will withstand the environments of many aerospace applications. This specification describes two types of motors which differ only in temperature and altitude requirements. Class A motors are operable under the temperature-altitude conditions of Curve II of MS33543, while Class B motors are operable under the conditions of Curve I of MS33543, as shown in Figure 7.

These motors will not operate in high altitude or vacuum environments.

12.2.7 Reliability considerations. Because of their construction, ac motors have fewer failure modes than dc motors. As discussed in paragraph 15.1.7, these modes include:

a. Brinelling or damaging of bearings from shock loads during handling

b. Overloading of the motor by the application of too large a load, causing overheating

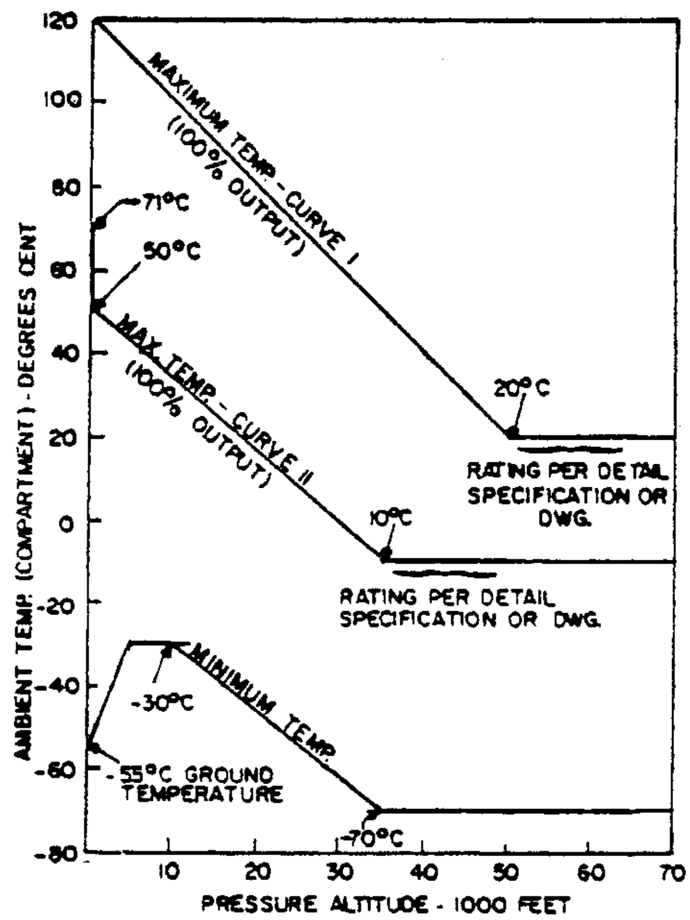
c. Failure of one phase of a three-phase motor, causing it to overheat

d. Operation at too low a voltage, causing overheating of the windings

e. Defective wire and/or insulation in the manufacturing process, causing shorts or open circuits during system application

f. Bearing failures from misapplication of a bearing design.

Most motors are screened 100 percent to ensure that they operate at rated current and speed with rated input. In addition, all motors are given a high voltage potential test to determine the integrity of the insulation system.



Curve I indicates the maximum temperatures to which equipment must be designed to operate satisfactorily in unconditioned compartments of high performance aircraft powered by air consuming engines.

Curve II indicates the maximum temperature for which the equipment must be designed to operate satisfactorily in conditioned compartments of high performance or low performance aircraft.

FIGURE 7. Altitude vs ambient temperature operation.

12.3 MOTORS, DC

12.3 DC motors.

12.3.1 Introduction. DC motors may be classified into four categories.

12.3.1.1 Permanent magnet. Permanent magnet motors are used in applications requiring less than 0.1 hp or in power motors of less than 1 1/4-inch case diameter. Permanent magnet motors run cooler than wound field types because no power is expended to maintain a magnetic field. Placing the motor in an excessive external magnetic field can demagnetize the permanent magnet material. Furthermore, demagnetization can occur if the applied voltage is significantly higher than the design voltage of the armature. Excessive current flow created by instantaneous reversal of applied voltage will also cause demagnetization. A remedy is to use an armature winding with sufficient resistance to safely limit this current during reversal or to provide a current limiting component, usually a low-value resistor, in the circuit.

The performance of a permanent magnet motor is varied by changing the armature voltage or winding. Figure 8 shows the schematic for this type of motor.

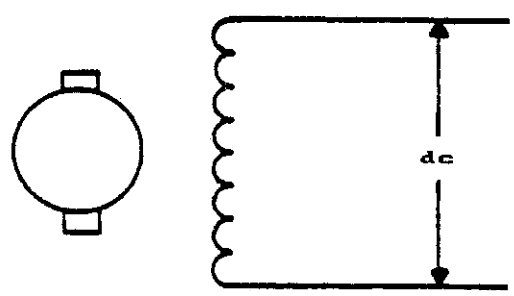


FIGURE 8. Permanent magnet dc motor.

12.3.1.2 Series-wound. The armature (rotor) and stator windings are connected in series with current passing through both.

Field strength in a series motor is a function of the armature current flowing through the field. Heavy motor loads cause more armature current to flow through the field and, thus, increase the field strength. Series motors are characterized by high stall torques and high no-load speeds. For this reason, a series motor should not be used in a system that will permit it to run without load.

Speed varies with load. These units are not usually used where power requirements are below 0.02 hp because permanent magnet motors perform the job more efficiently.

Small-size units can be operated on either dc or ac power and are called universal motors. Operation on ac is possible only with laminated field poles (Figure 9).

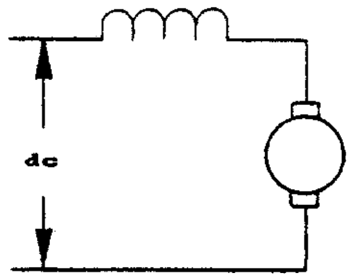


FIGURE 9. Series-wound dc motor.

12.3.1.3 Shunt-wound. The armature and stator are connected in parallel. Voltage across the armature and the stator is equal. This type gives a lower starting torque, and a constant speed with varying load. Under constant voltage, the motor operates like a permanent magnet motor because its magnetic field strength is held constant. As is the case with the series wound dc motor, this design is less efficient than a permanent magnet motor where power requirements are below 0.1 hp. This type is recommended for applications requiring constant speed (Figure 10).

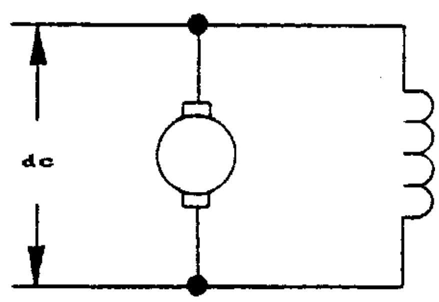


FIGURE 10. Shunt-wound dc motor.

12.3.1.4 Compound-wound. A compound-wound motor is a combination of series-wound and shunt-wound. Speed variation is much less than the series-wound motor but greater than the shunt-wound. This type is used for heavy starting loads or where loads change suddenly (Figure 11).

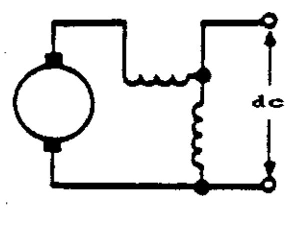


FIGURE 11. Compound-wound dc motor.

12.3 MOTORS, DC

12.3.2 Usual applications. As with ac motors, dc motors are used wherever angular motion or linear motion is desired. The dc motors are used where speed control is desired (by voltage adjustment) or where speed change with changing loads is desired.

12.3.3 Physical construction. As with ac motors (paragraph 12.2.3.1), there are many factors that determine the output of a given size dc motor. For comparison purposes, a typical outline is shown in Figure 12.

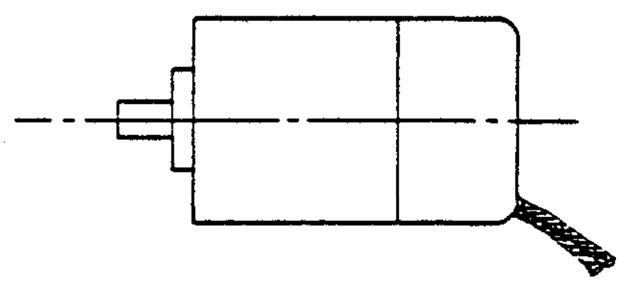


Figure 12. Typical outline of dc motors.

12.3.4 Military designation. Dc motors have not been standardized for NASA applications.

However, motors are available which conform to the requirements of MIL-M-8609 for 28 V dc airborne applications.

12.3.5 Electrical characteristics. Most dc motors are designed to operate at 28 V dc; however, where other dc voltages are required, units can be wound for these voltages.

The dc motors designed to meet the requirements of CC-M-645 are designed for either 115 V ac or 230 V dc. As with aerospace motors, these may also be designed for different voltages.

12.3.6 Environmental considerations. Motors conforming to MIL-M-8609 will withstand many aerospace applications. This specification describes two types of motors which differ only in temperature and altitude requirements. Class A motors are operable under the temperature-altitude conditions of Curve II of MS 35543 while Class B motors are operable under Curve I of the same specification. This military standard is included in the environmental section shown earlier for ac motors (refer to Figure 7). The dc motors have disadvantages associated with brush wear; brushes wear out faster at higher altitudes.

12.3.7 Reliability considerations.

12.3.7.1 Failure modes. Because brushes are required, dc motors, have more failure modes and are more prone to failure than ac motors. Failure modes for these designs include:

a. Fracture of brushes

b. Rapid brush wear at high altitude

c. Contamination of bearings resulting from wear of brushes

d. Brinelling or damaging of bearings from heavy shock loads

e. Insufficient voltage to drive the required load, causing overheated windings

f. Bearing failure from misapplication of bearing designs

g. Defective wire or insulation resulting in shorted windings or open circuits

h. Demagnetizing of permanent magnets in permanent magnet motors caused by exposure to electromagnetic fields or rapid reversal of voltage polarity.

DC motors should be inspected for speed and current at a specified voltage. They are also subjected to high voltage potential inspection to determine the integrity of insulation systems.

12.3 MOTORS, DC

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