Channel Filter Design with DP8464B and DP8468B Pulse Detectors

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INTRODUCTION

Accurate reproduction of digital information from an analog read signal is one of the most important functions of the digital recording channel. The DP8464B and DP8468B pulse detector integrated circuits are designed specifically to perform this function. Although these circuits have greatly simplified the task of designing the read channel electronics and are quite easy to customize for different types of recording system applications, it remains the system designer's responsibility to implement a suitable channel filter for optimum system performance.

This filter is critical to the performance of the recording channel because it defines and controls important characteristics of the channel response. The channel filter performs many important front-end signal processing functions. For example pulse-shaping, signal-to-noise ratio, and channel induced peak-shift are just a few of the main components for which the filter have great control over. It is impossible to realize a practical filter which optimizes all these functions. The filter design can be a complex process as it usually involves careful compromise of the system response in order to meet the system requirements.

This note explains in detail the process of designing the channel filter with regards to the DP8464B and DP8468B pulse detectors for disk and tape drives applications. It is recommended that the user review the data sheets prior to reading this note. Furthermore, the user should also be intimately familiar with filter design fundamentals and their tradeoffs.

GENERAL CONSIDERATIONS

The purpose of the low pass channel filter is to remove the high frequency noise components present on the amplified signal. Since the noise sources involved are complex, the design of a suitable filter requires considerations of many factors including the gain-controlled-amplifier output stage characteristics, differentiator input stage characteristics, data rate, read head characteristics, desired frequency/noise characteristics, insertion loss, system transient response, etc. The channel filter may be implemented with an active filter or a passive realization depending on the system requirements. This note discusses the passive filter type since it is by far the most commonly used. Four basic filter types are employed in communication channel designs. They are Butterworth, Bessel, All-Pass, and Equiripple Linear-Phase filters. A brief description of their pertinent characteristics is listed below:

Butterworth

- Maximally Flat Magnitude Response
- Reasonable Group Delay except near the corner frequency

Bessel

- Maximally Flat Group Delay
- Poor Magnitude Response characteristics near the corner frequency

All-Pass

- Flat magnitude for all frequencies of interest
- Predictable phase charateristics. May be used to correct for group delay

Note: When correcting group delay, head circuit must be included.

Equiripple Linear-Phase

- Phase linearity may be approximated within a given amount of ripple in degrees
- Have better amplitude response in the stopband than does Bessel
- For the same *n* (order of filter), constant delay (linear phase) over a larger interval than the Bessel types. The region of constant delay is extended farther into the stopband.

In choosing a filter, the designer considers the performance of the filter in the frequency domain as well as in the time domain.[1] The impulse response and group delay may (at times) be more important than insertion loss and frequency response because they determine the filter induced peak-shift, which in turn affect the error-rate of the recording system. We encourage the user to experiment and choose the filter type that would result in the best performance for his particular requirements.

GROUP DELAY CONSIDERATIONS

What is group delay? In a general sense, the group delay describes the delay of a group of frequencies (such as the fundamental frequency and all its harmonics in a square wave), as opposed to the phase delay which describes the delay of a sinusoid. The group delay is defined as the derivative of phase ($d\phi$) versus derivative of the frequency ($d\omega$), which can be expressed as

$$T_{pd} = -d\phi/d\omega$$

Linear phase shift results in a constant group delay, since the derivative of the linear function is a constant.

If a filter's phase characteristic is linear with frequency and intersects zero phase shift at zero frequency (DC), both the fundamental and its harmonics (sidebands) will have the same delay in passing through the filter; so the output will be delayed replica of the input. If these conditions are not satisfied, the fundamental and its harmonics will be delayed by different amounts. This would result in an output that is distorted with respect to the input. This type of distortion at the output may in some circumstances be seen as time shifted peaks at the worst or asymmetrical shouldering in moderately distorted circumstances.

BANDWIDTH CONSIDERATIONS

In the disk drive environment, the highest encoded frequency signal is essentially a sine wave at the inner radii. The Third harmonic amplitude at that point should be 30 dB or more below the fundamental (first harmonic). Whereas at the outer radii, the lowest encoded frequency signal usually contains substantial odd harmonics; these harmonics are essential to the peak definition of the waveform. Thus, if one chooses to bandwidth limit the channel through the use of a narrow band low-pass filter, it would result in the attenuation

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of the harmonics at the outer radii and would therefore result in filter induced peak-shift. But if the designer chooses a filter bandwidth which is too broad-band, more noise would pass through and would degrade the signal-to-noise performance.

Therefore, the filter bandwidth is a compromise between maintaining the harmonic content or pulse peak requirements and the signal-to-noise ratio. Most designers have been limiting the bandwidth of the filter between 1.5 to 2 times the highest write frequency. The user is encouraged to experiment and choose the filter type and bandwidth that would result in the best performance for his particular system.

FILTER IMPEDANCE

For a single ended filter, the filter impedance is defined as the DC resistance of the filter "looking" in from the unloaded input through the unloaded output of the filter to ground. For a differential filter, one should convert to a single ended half circuit and analyze the filter in that way.

Matching is generally not a primary concern due to the fact the driving impedance of the amplifier is very low (in the order of 20Ω), thus becomes essentially an ideal voltage source and the impedance is set by the series resistor at the filter input. Additionally, the loading impedance is relatively high (~1.7 kΩ) compared to the impedance of the filter that is realized. Therefore, the loading impedance is dominated by the shunt resistor at the output of the filter.

When calculating the load termination resistance for the channel filter, for the DP8464B device, the input impedance of the Time and Gate Channel input terminals (if they are connected together: $R_{Time} = 2.5$ kΩ differential, $R_{Gate} = 5$ kΩ differential or $R_{Parallel} = 1.67$ kΩ) must be included as part of the parallel load impedance. Therefore, if we want a differential load resistance of 500Ω, we need to apply a resistor (R_{Filter}) across the differential outputs of the filter that would result in a paralleled resistance of 500Ω between R_{Filter}, R_{Time}, and R_{Gate}, or a resistor value of 714Ω.

For the DP8468B, since this device does not have the gate and time channels separated, only the input impedance of the "CHAN-IN" pins ($R_{CHAN\text{-}IN} = 2.5$ kΩ) needs to be included. Therefore R_{Filter} becomes only 625Ω for a 500Ω filter.

Many applications use equal termination filters, resulting in a six dB loss in the pass band of the filter. If one desires lower attenuation filters, higher load to source impedance ratios would be required. For the DP8464B and DP8468B pulse detectors, we recommend the filter impedance be no lower than 500Ω differential. If the filter impedance is lower than the recommended value, the output stage of the AGC amplifier may saturate due to excessive output current to properly drive the filter. If the impedance is too high, one may find that the filter be difficult to realize and too sensitive to parasitics. The user is encouraged to experiment and optimize according to his needs.

DESIGN EXAMPLES

I. Realize a filter for a 15 Mbit/sec, 2,7 RLL recording system (i.e., for a maximum analog frequency of 5 MHz).

1. Select Filter Type and Order of the Filter

a. Choose a Linear Phase with Equiripple Error (of 0.5 degree) type of filter since filters of this type have a constant delay over a larger interval than the Bessel. It also has better amplitude response far above the cutoff frequency. In the transition region and below cutoff both approximations have nearly identical responses.

b. Next determine the order of our filter. The "rule of thumb" for Floppy (<1Mb/s) applications is a 3-pole filter, and for hard disk applications, a 5 or 7 pole channel filter is chosen. There is of course no hard and fast rule as to the number of poles that is required for a particular design. For discussion purposes, we will choose a 5-pole filter. Once designed, we would then go to the lab and test our system for error rate performance and optimize accordingly.

2. Select filter impedance and consider biasing of the AGC amplifier

a. In selecting the filter impedance, the designer must be aware that the DP8464B and DP8468B both require a pull-down resistor to bias the output stage of the Gain-Controlled-Amplifier. This bias resistor, when working with the DP8464B, should be in the range of 4.3 kΩ to (not lower than) 2 kΩ at the high data rates. For the DP8468B, this resistor range is from 2 kΩ to 1 kΩ. The equation for calculating this resistor is stated in the data sheet of each of the devices. But what is not stated is that when these devices are used in high frequency applications (above 5 MHz analog data frequency), there is a possibility that the output signal from the Gain-Controlled-Amplifier may distort due to the parasitic PCB capacitance. This circumstance requires a larger amount of current to drive the filter properly. This distortion is at the negative peak of the signal. It results from current starving of the amplifier output emitter followers when driving the negative peak. Bottom Side Clipping is most likely to occur at higher data rates and lower filter impedances. Prevention of bottom side clipping requires that sufficient current be pulled from the output emitter followers of the amplifier.

b. The filter impedance is proportional to the value of the inductor, but inversely proportional to the value of the capacitors. Thus the higher the impedance, the larger the inductor and smaller the capacitors must become. Therefore, as the impedance increases, the filter becomes more sensitive to parasitics of the system. Additionally, for the DP8464B and DP8468B devices, it is recommended that the filter be designed with an impedance no smaller than 500Ω. Lower filter impedances can cause saturation of the output stage of the Gain-Controlled-Amplifier.

The channel filter may be implemented with different ratios of output to input terminations. A large ratio of output to input impedance reduces the insertion loss, whereas low ratios tend to increase the insertion loss of the filter. The most commonly used is the equal termination filter (i.e., $R_S = R_L$). We will use equal terminations and a differential impedance of 1 kΩ, see *Figure 1*. An equally terminated filter is less sensitive to component variations. However, an equally terminated filter also results in a 6 dB loss. This is not a problem as the GCA has sufficient gain and output signal swing to make up for this loss.

Since the AGC holds the amplitude at the Gate Channel Input constant, this 6 dB loss through the Gate Channel filter will cause the Gain-Controlled-Amplifier's output to be increased by 6 dB larger than the Gate Channel input. To prevent the GCA from saturating, the V_{Ref} level must be set so the maximum amplifier output voltage is 4 V_{PP} (refer to the application information, Automatic Gain Control section, on the DP8464B and DP8468 data sheet for a more detailed discussion).

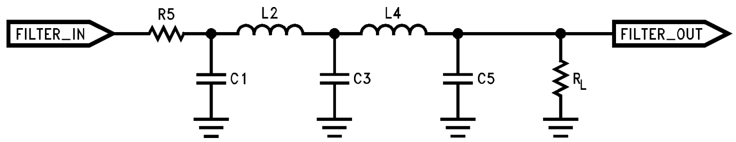

FIGURE 1. Single Ended Filter with Equal Termination

When calculating the load termination resistor (R_L) one must also include the input impedances of the loading stage (i.e., the input impedance of the "Gate-Channel" and "Time-Channel" ports). For the DP8464B, if the Time and Gate Channel Inputs are tied together, we must treat each of the input impedances in parallel with the filter termination. The parallel impedance of the Time and Gate channel inputs are approximately 1.7 kΩ (2.5 kΩ||5 kΩ). Thus if we want a differential 1 kΩ filter, a 700Ω load resistor should be used between the differential outputs of the filter.

The input termination is in series with the filter. Thus for a 1 kΩ differential filter, a series termination (R_S) of 250Ω is required in each leg.

3. Select filter bandwidth

In practice, designers have limited the channel filter bandwidth between 1.5 to 2 times the highest analog data frequency. This is to minimize the high frequency noise that is allowed to pass through the differentiator while also maintaining sufficient third order harmonic amplitude (required to preserve pulse shape at lower frequencies). We will use a factor of 1.75 times the highest analog frequency for the −3 dB corner frequency. If we were to actually implement this into a product, we would experiment with several frequencies in the range and determine which one would give us the best noise margin. For 15 Mbit/sec 2,7 RLL code, the highest analog frequency is 5 MHz. Thus a (5 MHz) (1.75) = 8.75 MHz bandwidth filter will be designed.

4. Filter realization

a. This is really the easy part of the design because once we have determined the required parameters, we need simply look up the filter tables, and calculate the filter components. The filter books such as [1] through [3] provide all the required tables. The inductor values are denormalized by

$$C = C'/(\omega_C * Z)$$

$$L = (L' * Z)/(\omega_C)$$

C′ = Normalized capacitor value, given in filter tables.

L′ = Normalized inductor value, given in filter tables.

Z = Filter impedance (250Ω, for single ended)

ω_C = Corner frequency (−3 dB Frequency) of the filter = 54.98×10^6 radians/sec

Note: Filter tables provide single ended filter component values only. The designer must convert this single ended filter design to a differential filter before it can be used in the DP8464B and DP8468B pulse detectors.

From the filter tables in references [1], [2], and [3] the normalized values for each of the filter components (for the single ended filter are:

C1′ = 0.3658	L2′ = 0.6768
C3′ = 0.9513	L4′ = 1.0113
C5′ = 2.4446	

After de-normalized, the following filter component values are obtained, see *Figure 2a* for filter schematic:

C1 = 27 pF	L2 = 3.3 μH
C3 = 68 pF	L4 = 4.7μH
C5 = 180 pF	

To convert to a differential filter, one must halve the capacitor values and connect the capacitors across the two channels of the differential line, see *Figure 2b* and *2c*. *Figure 2c* shows a typical connection for a differential filter. However, some designers have replaced C5 with two ground connected capacitors (each having twice the value of C5), in order to improve common mode rejection of the filter.

II. Filter component values for other types of codes are similarly realized. Begin with the highest analog frequency, (e.g., multiply that by 1.75) to get the filter bandwidth. Start with a five pole linear phase filter. Choose a filter impedance (1 kΩ is a good start), then look up the normalized filter values, and finally de-normalize the component values.

For a 33 Mbit/sec 1,7 system (12 MHz highest analog data frequency), the component values for a 5-pole channel filter is as follows:

F_{bw} = 21 MHz, $R_L = R_S$ = 250Ω, n = 5

C1 = 12 pF	L2 = 1.5 μH
C3 = 27 pF	L4 = 1.8 μH
C5 = 75 pF	

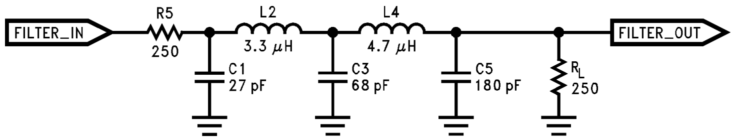

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FIGURE 2a. Single Ended Filter

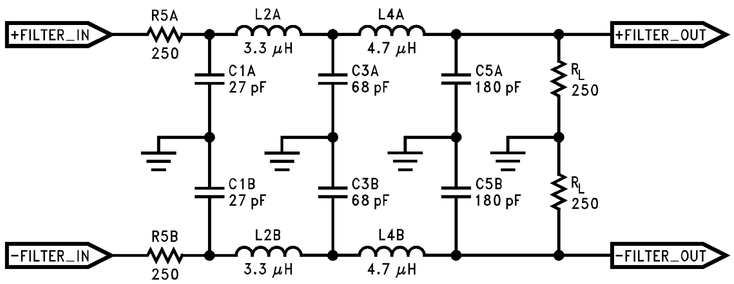

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FIGURE 2b. Combined Filter

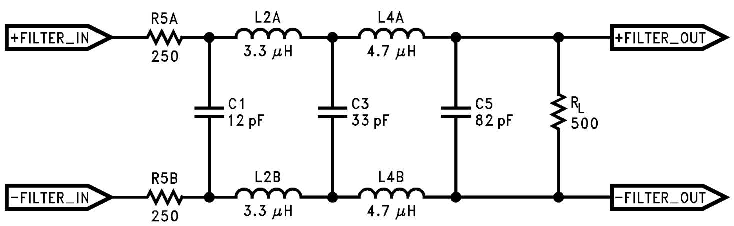

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FIGURE 2c. Differential Filter

SUMMARY

The design of the channel filter is an essential part of designing a read channel. The actual realization of this filter is generally a compromise between the system signal-to-noise performance and the filter induced peak-shift. When the filter bandwidth is made excessively high to preserve harmonic content, high frequency noise is allowed to pass through the filter therefore degrading the channel signal-to-noise ratio. If the filter bandwidth is too narrow, then harmonic distortion will occur and will adversely affect the time position of the peaks, which cause filter induced peak-shift. Therefore, there is no "right" filter for all read channel designs. Each implementation must be carefully considered with the particular system which it is designed for.

There are, of course, a few general guidelines that the designer should follow. One of the most important is that the filter must have a constant group delay in the passband of interest. Additionally, the filter bandwidth should be chosen so as to provide optimum error rate performance. Designers have in the past used filter bandwidth which ranges between 1.5 to 2 times the highest analog data frequency with a Linear Phase (with equiripple error of 0.5 or 0.05 degree) type filter to maintain the harmonic content in addition to having a constant group delay.

When designing with the DP8464B and DP8468B devices, the designer must ensure not to saturate the output stage of the Gain-controlled-amplifier. This means to bias the device properly for his application, using filter impedances that are not lower than the recommended value of 500Ω differential, and accounting for the effect of filter loss on the amplifier output signal swing.

APPENDIX A

Input Coupling Capacitor Considerations

From time to time customers have asked about how to select the value of input capacitors. As mentioned in the data sheet, the pole formed by the coupling capacitor and the 1 kΩ internal bias resistor at the amp input should be a factor of 100 lower than the lowest signal frequency. This is to maintain good group delay. This consideration is also true with regard to the channel input coupling capacitors.

Another area which affects the capacitor selection is DC offsets. Both during a write operation and head switching, large DC offsets can appear at the output of the read/write amplifier. These DC offsets accumulate across the gain-controlled amplifier input coupling capacitors. This DC offset must be removed in order to quickly recover from a write or head switching mode. Consequently, it is necessary to quickly discharge the input coupling capacitors. The amount of time required to discharge the input capacitors is proportional to their value.

Unfortunately, the input capacitors can not be made arbitrarily small. They must be sufficiently large so as not to cause significant group delay errors at the lowest disk frequency. Typically the $1/(2*\pi*R*C)$ should be a factor of 100 less than the lowest frequency of interest from the analog input waveform (R is the input impedance and C is the input coupling capacitor).

Example:

For 10 Mbit/sec 1,7 code the lowest analog frequency is:

NRZ:F_{analog} = 1:3/32
0.0937 (data rate)
0.0937 (10 Mbits/sec)
(3/32)* 10 = 937 kHz

The input zero should be located at 937 kHz/100 or 9.37 kHz.

Thus $1/(2*\pi*R*C) = 9.37$ kHz;

$Z_c = 1/(2*\pi*R*F_C)$

$1/RC = 2*\pi*9.37$ kHz

or $C = 1/(2*\pi*R*9.37$ kHz)

For a 1 kΩ input impedance:

$C = 1/(2*\pi*1$ kΩ$*9.37$ kHz)

$C = 0.017\ \mu F$

APPENDIX B

Passive Filter Components

There are basically three types of components that make up a filter, inductors, capacitors and resistors. The following is a discussion of each of the three components that a filter is comprised of.

Resistors

Fixed Resistors: The function of the resistor is to set the input and output impedance of the filter. Therefore proper resistor selection is critical to a successful filter design. There are several types of resistors that are available to the user. They are carbon composition, carbon film, Cermet film, metal film and wire wound (see Table I for typical properties).

TABLE I. Typical Properties of Fixed Resistors

Type	Range (Ω)	Standard Tolerances (%)	Wattage Rating	Temperature Coefficient (ppm/°C)
Carbon Composition	1–100M	5, 10, 20	1/8, 1/4, 1/2, 1, 2	±1000
Carbon Film	1–10M	2, 5	1/8, 1/4, 1/2	±200
Cermet Film	10–22M	0.5, 1	1/4, 1/2	±100
Metal Film	0.1–1M	0.1, 0.25, 0.5, 1	1/8, 1/4, 1/2, 1, 2	±25
Wirewound	1–100k	5, 10, 20	3, 5, 10, 20	±50

Of the five types mentioned in Table I, only three are commonly used. They are:

1. **Carbon Composition** resistors are one of the most commonly used resistor types. They are available over a wide range of values and power ratings. Resistor values are maintained to ±10% by the manufacturing process and are sorted for ±5% tolerances. Their major drawback is their high temperature coefficient (1000 ppm/°C). In addition permanent resistance changes of a few percent will occur due to poor retrace and aging characteristics. These resistors exhibit only a few parasitic effects above 10 MHz. These are also the most economical of the various resistor types. They are often used in general-purpose active filters, where stability is not a critical requirement.
2. **Carbon Film** resistors are manufactured by depositing a thin layer of resistance element on a nonconductive substrate. The resistive element is usually spiral in form to increase the net resistance. Carbon film resistors are especially suited for general-purpose applications requiring better performance than can be obtained using the carbon composition type at competitive pricing.
3. **Metal Film** resistors are by far the most widely used type for precision requirements. They are manufactured by depositing alloys on a rod substrate. Exceptional characteristics are obtained from this process. Normal tolerances are ±1%, but lower tolerances (to ±0.02%) are available. Temperature coefficients are typically 25 ppm/°C (although coefficients to ±2 ppm/°C are also available). Retrace and aging result in changes usually not exceeding 0.25%.

   These film resistors have many highly desirable characteristics; including low temperature coefficients, good long-term stability, lowest (Johnson) noise attainable in resistors except in the best wire wound resistors. Parasitic effects are minimal and have no significant effect below 10 MHz. Of all the resistor types mentioned, the metal film resistor will give the best performance over a given temperature range (25 ppm/°C) and long term stability. It is available over a large range of values from 0.1Ω to 1 GΩ, is available in standard of 0.1% to 5% percent tolerances, and has few parasitics. Because of these characteristics, this type of resistor is highly desirable in filter applications.

Inductors

Inductors consist of a winding, usually supported by a bobin or coil former, a core or slug to concentrate the magnetic field, and some assembly hardware. For frequencies up to approximately 10 MHz, the best core material available are ferrites. Those of the highest quality have temperature coefficients which are positive. For more detailed list of ferrites, the user should consult vendor catalogs.

The reduction of Q (figure of merit or quality factor of a reactive component; $Q = \omega^* L/R_L$) in coils containing magnetic materials, is caused by two contributing factors which become effective in different portions of the frequency range. At the lower frequencies, the losses are mainly due to the resistance of the windings. This is a frequency-dependent quantity because of the skin effects. To reduce these effects, litz wire is often preferred for the winding. As the frequency increases, the eddy currents in the magnetic material dominate. These currents have essentially the same effect as if they were induced in a secondary winding and an external load resistor. Therefore, their effect will be the same as if a resistor were connected in parallel to the winding. The combined effect of both resistors results in a frequency-dependant Q. For a given inductance and coil construction, the Q-curves are bell-shaped.

The Q of an inductor is further reduced by the dielectric losses of the parasitic winding capacitances. These losses can be significant if the winding capacitance contributes to a large percentage of the total tuning range of the resonant circuit.

Capacitors

To compensate for the positive temperature coefficients of the inductors and to hold resonant frequencies constant, one should employ capacitors which have negative temperature coefficients. There are two types of capacitors which would meet this requirement, the mica and polystyrene or polypropylene capacitors. Several of the more commonly used capacitors that are employed in filter designs are listed below:

1. **Mica** capacitors are constructed from stacked foil, glass-fixed, or silver-plated mica plates and are encapsulated either in plastic material or dipped in a plastic compound. Their quality factors ($Q = \omega^* R_C^* C$) are guaranteed to be over 1000, and are available in standard 1% or 5% values. This type of capacitor is most practical in values below 1000 pF. Mica capacitors are best known for their temperature stabilities. The temperature coefficients of these capacitors lie in the range between 0 and $+70 \times 10^{-6}$/°C.
2. **NPO/COG**, this Ultra-Stable capacitor offers maximum capacitance stability over a wide temperature range, environmental conditions, applied voltages and frequencies. These capacitors are ideally suited for RC network circuit applications where extreme stability is of paramount importance. They are generally available in 5% or 10% tolerances. In addition they have smaller footprints than all other capacitor types discussed here (except surface mount types), thus require less real estate than other types of capacitors. The Q's of these capacitors are generally not as high as those of micas. Additionally, these capacitors are available as chip capacitors. This may be of great importance when board space is of great concern.
3. **Polystyrene and Polypropylene:** Other capacitor types that are used in filters are the polystyrene and polypropylene. These are used extensively in communication equipment. These capacitors have Q's in excess of 10,000 and have closely controlled temperature coefficients (generally $\pm 50 \times 10^{-6}$). Their major drawback is their sensitivity to extreme temperatures. Permanent damage may occur at temperatures above 80°C or at low temperatures.

In the selection of channel filter components, one must consider the temperature performance, quality factor of those components at the desired frequency range. Both silver mica and TC ceramic capacitors feature low loss, high Q, and excellent insulation resistance. Mica has better temperature stability, while ceramic has better controlled temperature coefficients. Both capacitor types are suitable for use as channel filter components. In many cases, space considerations and/or cost will determine the final choice. For inductors, coils with high Q's at the desired corner frequency constructed with litz wire wound around ferrite cores should be used.

The most critical problem caused by a finite Q in designs intended for lossless reactance is the effect on the response shape near the cutoff. At the passband edge, the response becomes more rounded, ripples are diminished and may completely vanish. The insertion loss of the filter is increased within the passband, see *Figure 3*. The attenuation in the stopband is maintained (except in the vicinity of the transmission zeros); so the relative attenuation between the passband and the stopband is reduced. Estimating the extent of this effect is somewhat difficult without extensive empirical data.

The effect of low Q on the response near the cutoff frequency can be compensated by choosing a higher order network or a steeper rolloff filter using a larger design bandwidth. However, this design approach does not always result in satisfactory results, since the Q requirements may also increase. *Figure 4* in the following page shows the minimum Q requirements for some of the filter types.

The insertion loss of a low-pass filter can be calculated by replacing the reactive elements with resistances corresponding to their Q's, because at DC the inductors become short circuits and capacitors become open circuits, which leaves the resistance elements ($R_L = L/Q$, $R_C = Q/C$).

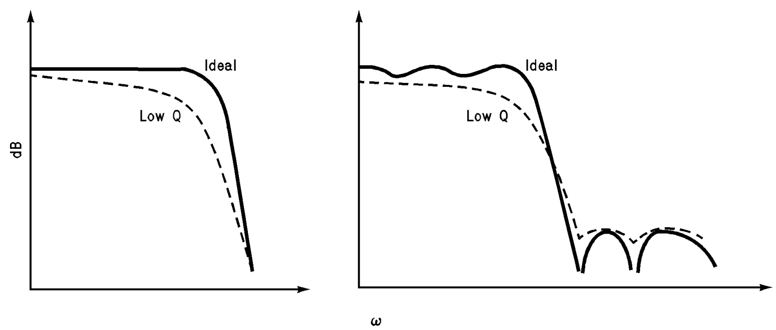

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FIGURE 3. Effects of Finite Q

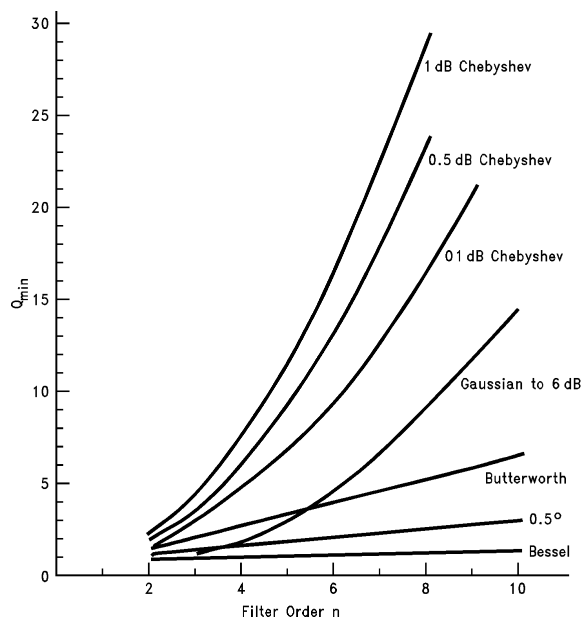

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FIGURE 4. Minimum Q Requirements

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