CES Engineering

# ELECTRONIC SYSTEM DESIGN

## PART 1: ANALOG FILTERS

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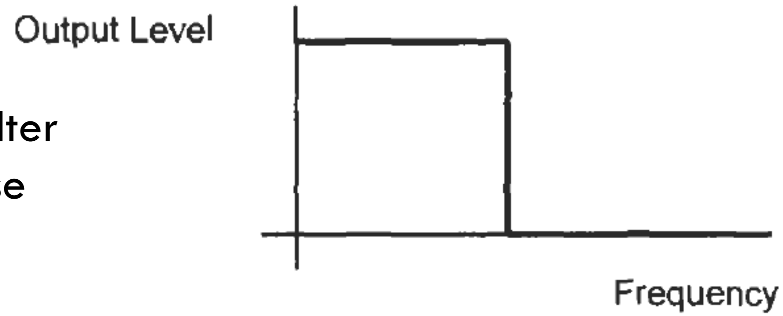
# Why Use Filters?



- Detection of a wanted signal may be impossible if unwanted signals and noise are not removed sufficiently by filtering
- Electronic filters allow some signals to pass, but stop others
  - To be more precise, filters allow some signal frequencies applied at their input terminals to pass through to their output terminals with little or no reduction in signal level

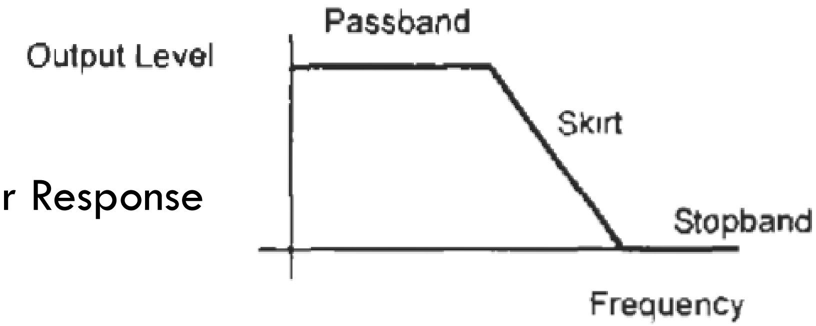
Ideal Filter Response



# Filter Terminology



- **Passband**: Range of signal frequencies that are allowed to pass through a filter, with little or no change to signal level
- **Passband cutoff frequency**: Passband edge where there is a 3 dB reduction in signal amplitude (half-power point)
- **Stopband**: Range of signal frequencies that are reduced in amplitude by an amount specified in the design, and effectively prevented from passing, is called the stopband
- **Transition Zone or Skirt Response**: Range of frequencies in between the passband and the stopband where the reduction in signal amplitude (also known as the attenuation) changes rapidly



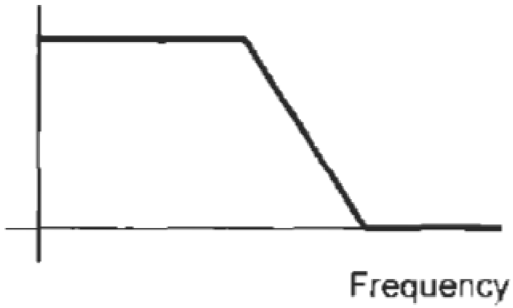

Practical Filter Response

# Common Types of Filters



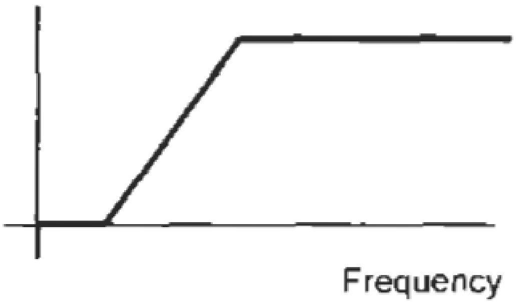
Output Level

Lowpass



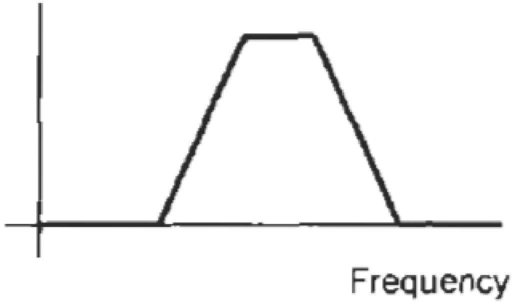

Output Level

Highpass



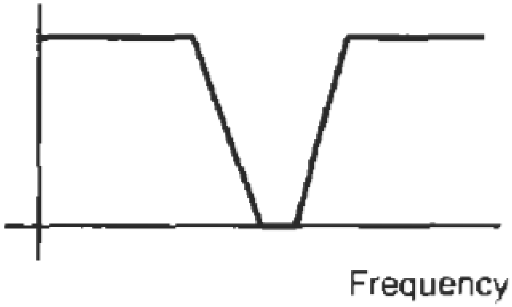

Output Level

Bandpass




Output Level

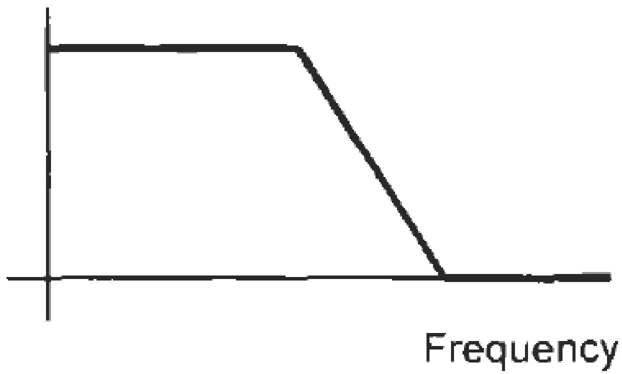
Bandstop



# Passband and Stopband Response



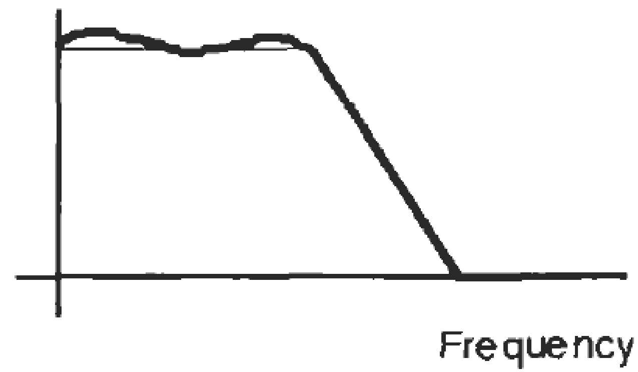
Output Level




Smooth
Passband

Butterworth or Bessel

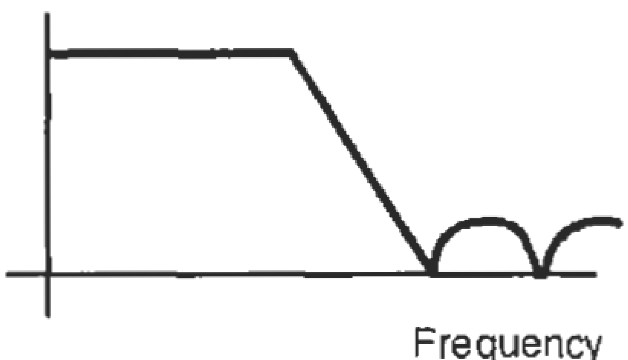
Output Level




Passband
Ribble

Chebyshev

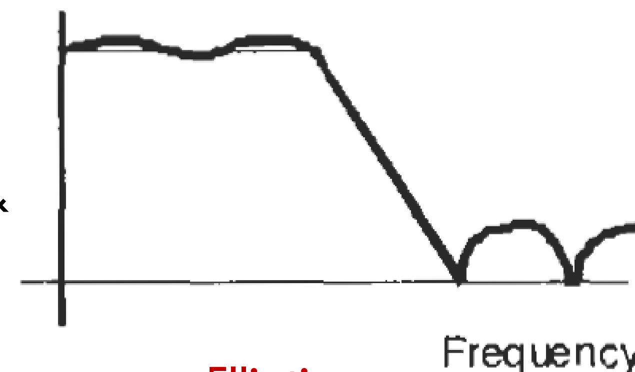
Output Level




Stopband
Ribble

Inverse Chebyshev

Output Level




Passband &
Stopband
Ribble

Elliptic

# Analog Filter Normalization



- A normalized filter is one in which the passband cutoff point is at $\omega$= 1 rad/s
  - Better than 1 Hz to remove $2\pi$ factor in calculations
- Passive filters are normalized for a 1 $\Omega$ load impedance
- The reason for normalization is to make the calculation of values simple
- Passive analog filters can be designed using the tables of normalized component values
  - One set of normalized component values can be used to design passive lowpass, highpass, bandpass, and bandstop filters with any load impedance

# Design with Normalized Analog Filters

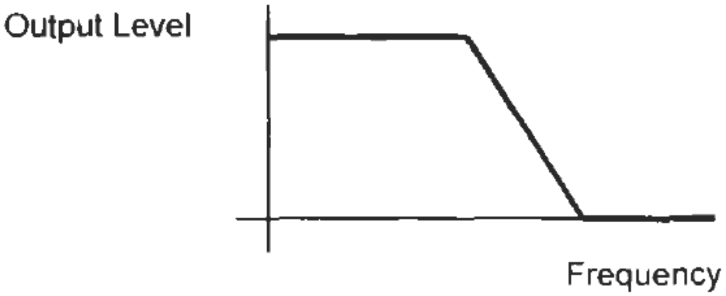


- Select the type of response required
- Determine the filter order using the frequency response graphs
- Use normalized analog filter tables to obtain a set of normalized component values
- Scale the obtained normalized component values for the frequency, impedance, and frequency response (lowpass, highpass. etc.) as required

# Bessel Response



- Bessel response is smooth in the passband, and attenuation rises smoothly in the stopband
  - Stopband attenuation increases very slowly until the signal frequency is several times higher than cutoff point
  - Far away from the cutoff point the attenuation rises at 6n dB/octave, where n is the filter order and an octave is the doubling of frequency.
  - For example, a third-order filter will give an 18 dB/octave rise in attenuation



# Bessel Response

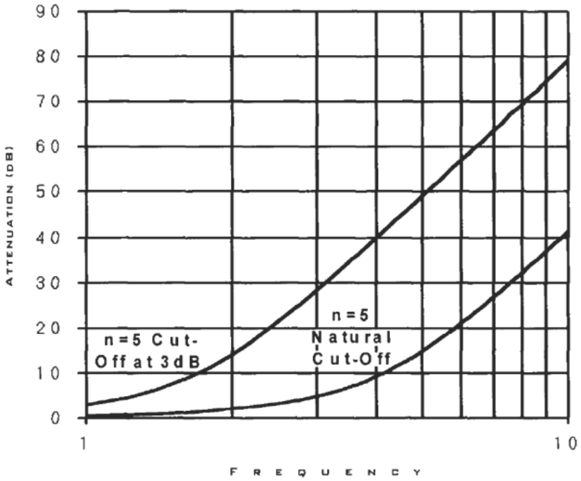


- Natural cutoff frequency for the Bessel response is that which gives a 1 s delay
  - This is not a constant value, but depends on filter order
- To simplify design, Bessel response can be scaled to give a 3 dB at ω=1 for all filter orders
  - Scale frequency components of the transfer function

Normalization Factors

$$\sqrt{(2n-1)\cdot\ln 2}$$

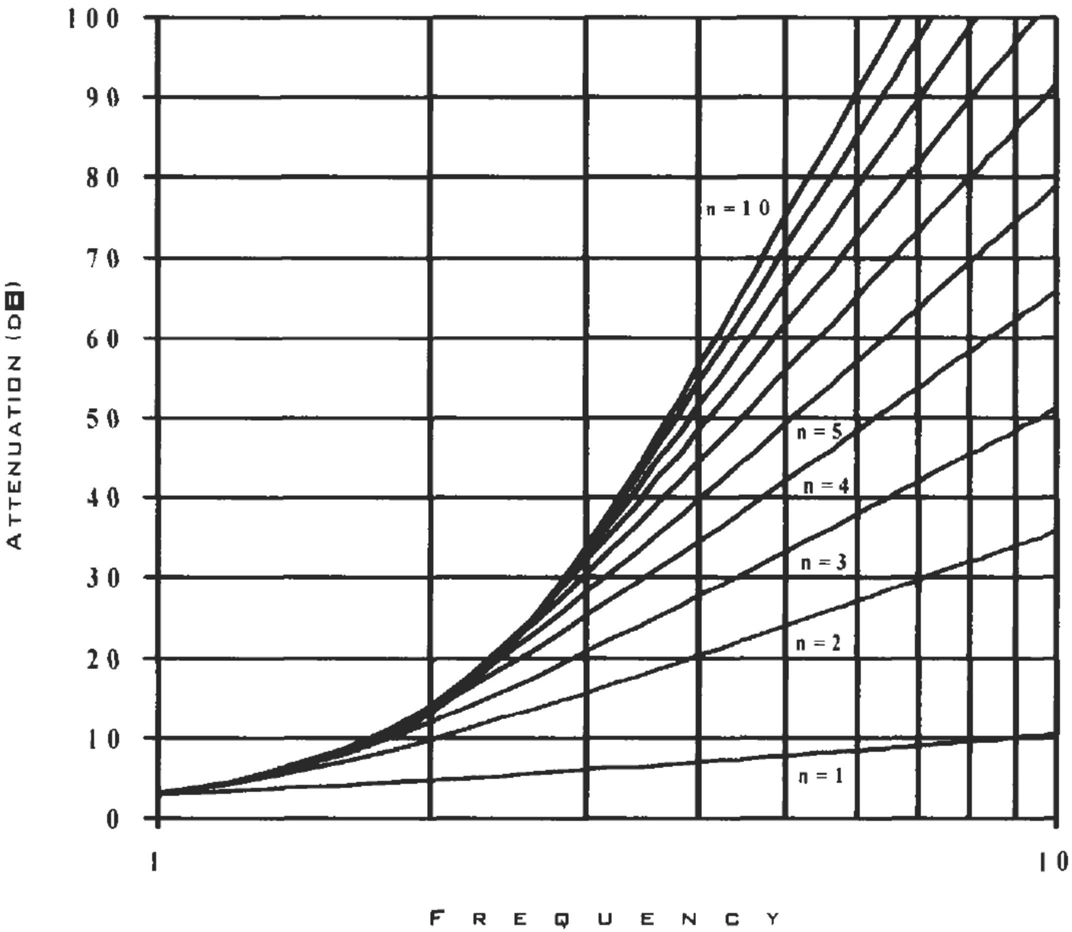
| Order, n | Normalizing Factor |
|---|---|
| 1 | 1 |
| 2 | 1.36 |
| 3 | 1.75 |
| 4 | 2.13 |
| 5 | 2.42 |
| 6 | 2.7 |
| 7 | 2.95 |
| 8 | 3.17 |
| 9 | 3.39 |
| 10 | 3.58 |



# Bessel Response



- Attenuation vs. frequency for different order



# Bessel Normalized Lowpass Filter Component Values



- Bessel LC Values $R_s = \infty$ or $R_s = 0$

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.0000 | | | | | | | | | |
| 2 | 1.36 | 0.4539 | | | | | | | | |
| 3 | 1.4631 | 0.8427 | 0.2926 | | | | | | | |
| 4 | 1.5012 | 0.9781 | 0.6127 | 0.2114 | | | | | | |
| 5 | 1.5125 | 1.0232 | 0.7531 | 0.4729 | 0.1618 | | | | | |
| 6 | 1.5124 | 1.0329 | 0.8125 | 0.6072 | 0.3785 | 0.1287 | | | | |
| 7 | 1.5087 | 1.0293 | 0.8345 | 0.6752 | 0.5031 | 0.3113 | 0.1054 | | | |
| 8 | 1.5044 | 1.0214 | 0.8392 | 0.7081 | 0.5743 | 0.4253 | 0.2616 | 0.0883 | | |
| 9 | 1.5006 | 1.0127 | 0.8361 | 0.722 | 0.6142 | 0.4963 | 0.3654 | 0.2238 | 0.0754 | |
| 10 | 1.4973 | 1.0045 | 0.8297 | 0.7258 | 0.6355 | 0.5401 | 0.4342 | 0.3182 | 0.1942 | 0.0653 |
| Rs = 0 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

# Bessel Normalized Lowpass Filter Component Values



- Bessel LC Values $R_s = 1$

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.000 | | | | | | | | | |
| 2 | 0.576 | 2.148 | | | | | | | | |
| 3 | 0.3374 | 0.9705 | 2.2034 | | | | | | | |
| 4 | 0.2334 | 0.6725 | 1.0815 | 2.2404 | | | | | | |
| 5 | 0.1743 | 0.5072 | 0.804 | 1.111 | 2.2582 | | | | | |
| 6 | 0.1365 | 0.4002 | 0.6392 | 0.8538 | 1.1126 | 2.2645 | | | | |
| 7 | 0.1106 | 0.3259 | 0.5249 | 0.702 | 0.869 | 1.1052 | 2.2659 | | | |
| 8 | 0.0919 | 0.2719 | 0.4409 | 0.5936 | 0.7303 | 0.8695 | 1.0956 | 2.2656 | | |
| 9 | 0.078 | 0.2313 | 0.377 | 0.5108 | 0.6306 | 0.7407 | 0.8639 | 1.0863 | 2.2649 | |
| 10 | 0.0672 | 0.1998 | 0.327 | 0.4454 | 0.5528 | 0.6493 | 0.742 | 0.8561 | 1.0781 | 2.2641 |
| Rs = 1 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

# Bessel Normalized Lowpass Filter Component Values



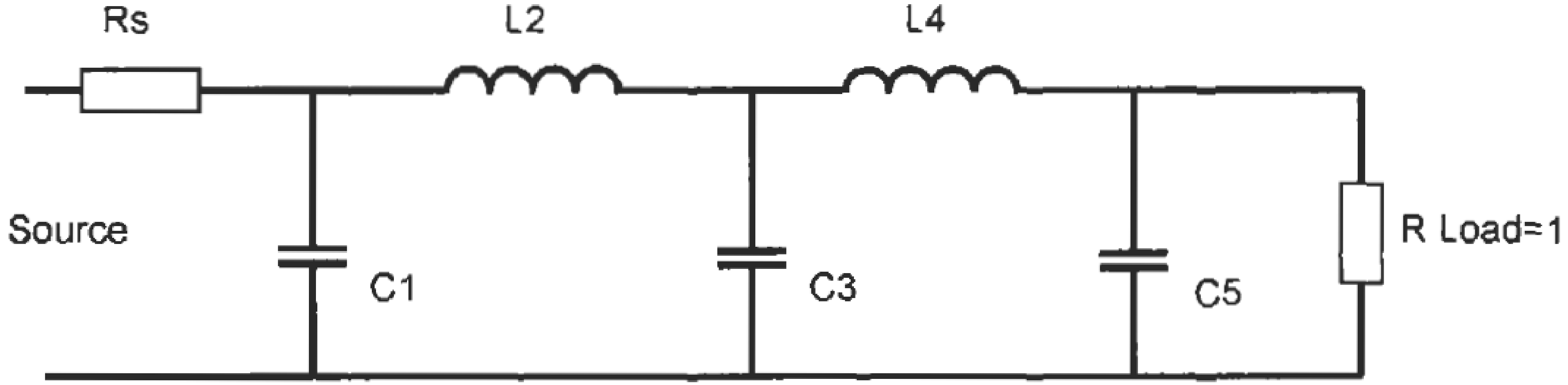
- Bessel LC Values $R_s = 2$

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.5000 | | | | | | | | | |
| 2 | 0.2601 | 3.5649 | | | | | | | | |
| 3 | 1.8572 | 0.9174 | 0.3176 | | | | | | | |
| 4 | 0.112 | 1.2952 | 0.5202 | 3.7824 | | | | | | |
| 5 | 1.90385 | 1.0764 | 0.7836 | 0.493 | 0.169 | | | | | |
| 6 | 0.0666 | 0.7824 | 0.3131 | 1.6752 | 0.5405 | 3.8122 | | | | |
| 7 | 1.9045 | 1.0748 | 0.8555 | 0.6914 | 0.51605 | 0.3198 | 0.1084 | | | |
| 8 | 0.0452 | 0.5354 | 0.2173 | 1.1718 | 0.3608 | 1.7153 | 0.5329 | 3.8041 | | |
| 9 | 1.8996 | 1.0566 | 0.8530 | 0.7334 | 0.62415 | 0.505 | 0.37225 | 0.2282 | 0.0769 | |
| 10 | 0.0332 | 0.3951 | 0.1617 | 0.8818 | 0.2739 | 1.2879 | 0.3678 | 1.6913 | 0.5242 | 3.7953 |
| Rs = ½ | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

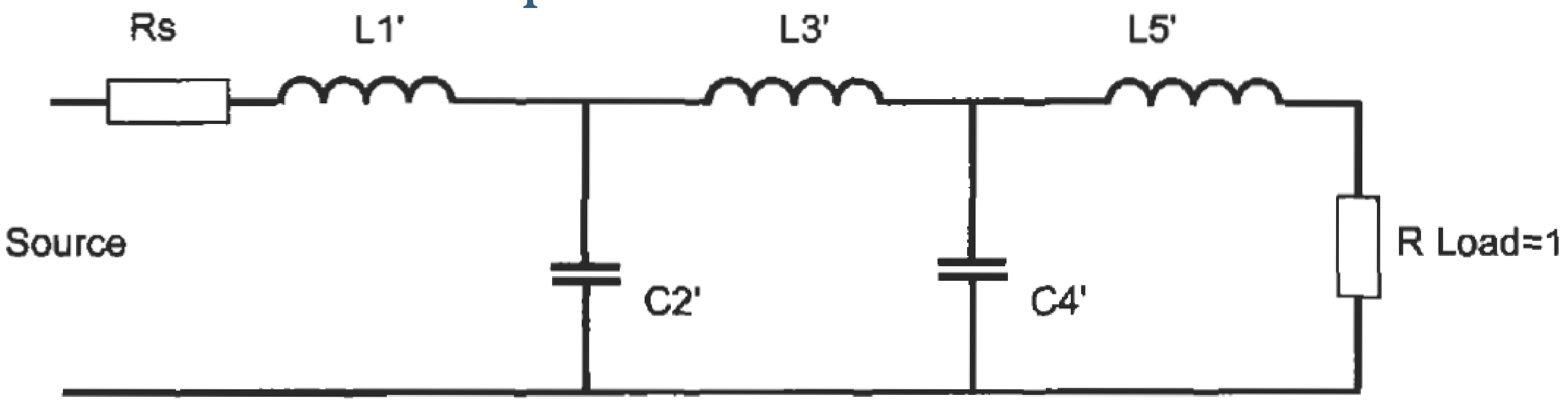
# Bessel Response Filter Examples



- Fifth-Order Lowpass Rs ≥1



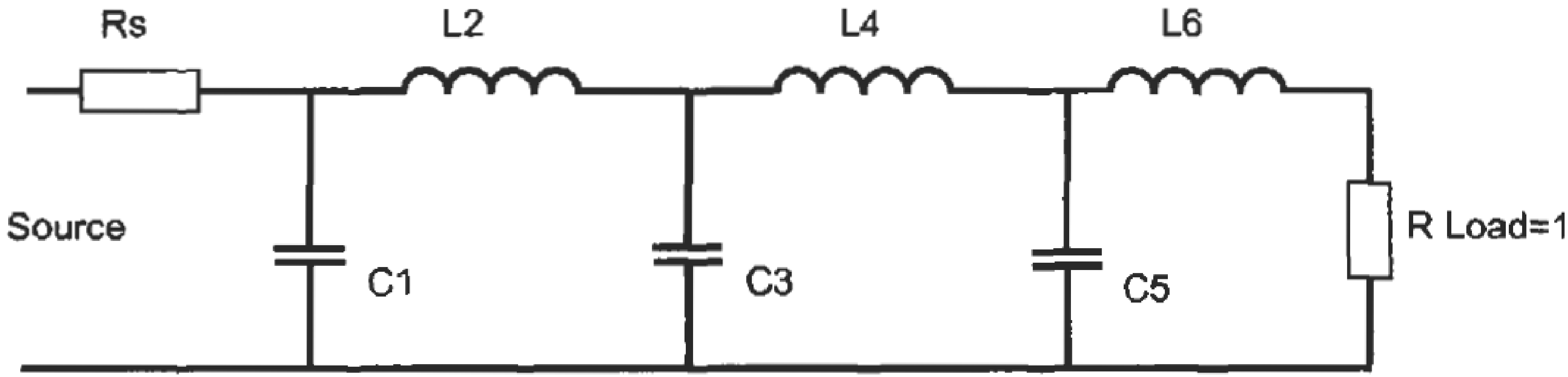

- Fifth-Order Lowpass Rs ≤1



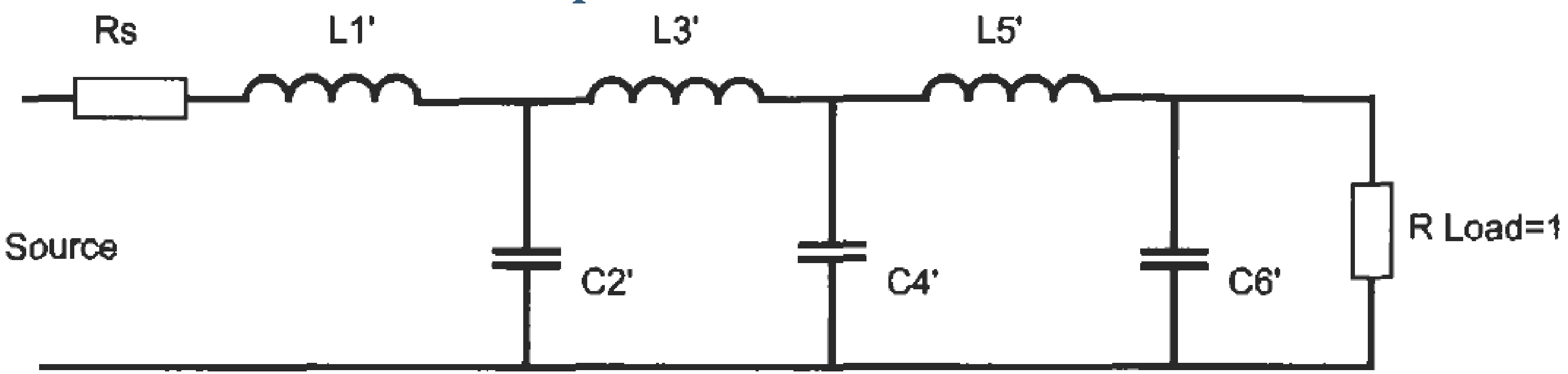
# Bessel Response Filter Examples



- Sixth-Order Lowpass Rs ≥1




- Sixth-Order Lowpass Rs ≤1

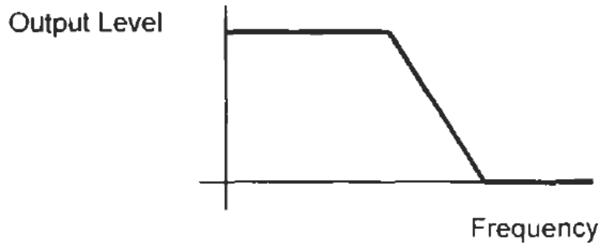


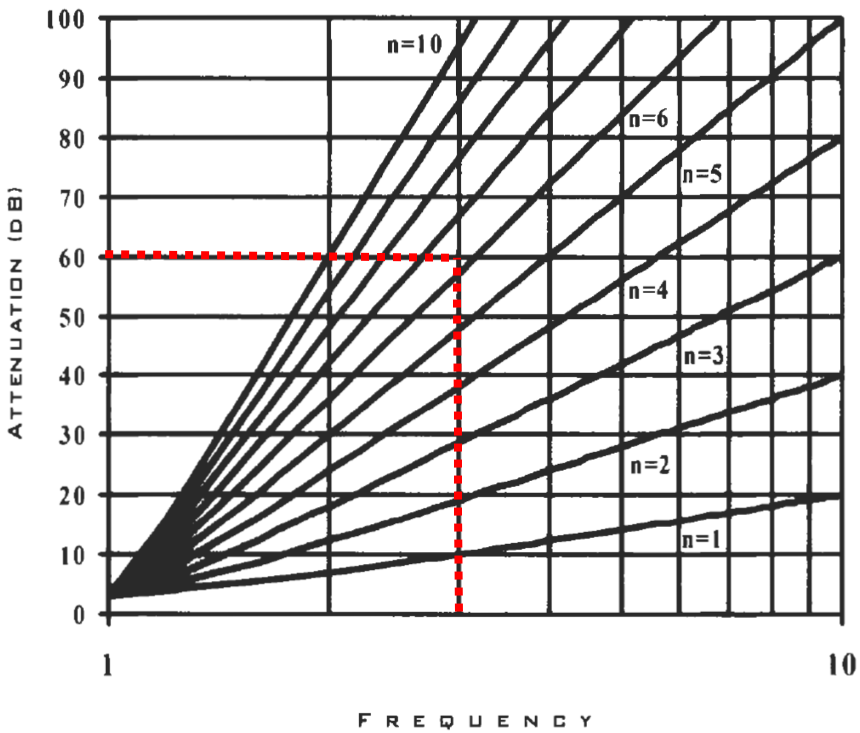
# Butterworth Response



- Butterworth response has a smooth passband and a smooth increase in stopband attenuation.
  - It differs from Bessel response in that the attenuation in the stopband rises by 6n dB/octave almost immediately outside the passband

Example: For 60dB attenuation at 3x cutoff Frequency, the $\omega=3$ axis and 60dB attenuation axis cross at a point midway between the curves of n = 6 and n = 7. Choose order=7.



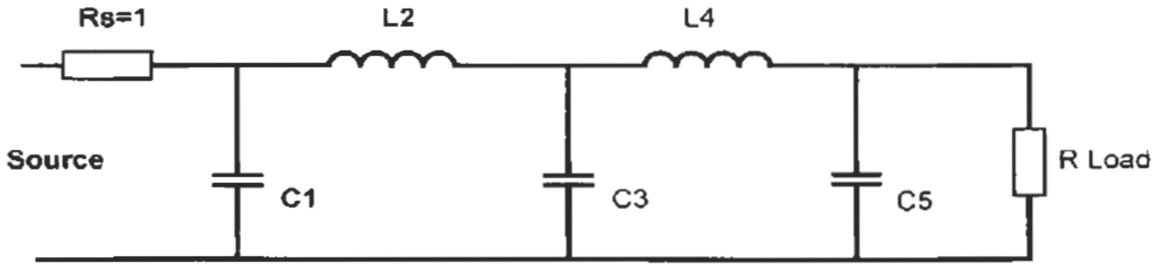



# Butterworth Response

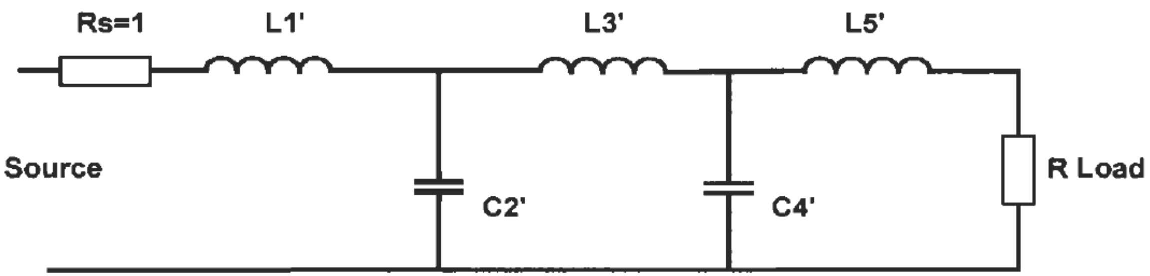


- Butterworth passive lowpass filters have a ladder network of series inductors with shunt capacitors at their connection nodes
  - First component in this ladder can be either a series inductor or a shunt capacitor

First Component is Shunt C




First Component is Series L



# Butterworth Normalized Lowpass Component Values



- Butterworth LC Values $R_s = \infty$ or $R_s = 0$

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00000 | | | | | | | | | |
| 2 | 1.41422 | 0.70711 | | | | | | | | |
| 3 | 1.50000 | 1.33333 | 0.50000 | | | | | | | |
| 4 | 1.53074 | 1.57716 | 1.08239 | 0.38268 | | | | | | |
| 5 | 1.54509 | 1.69443 | 1.38196 | 0.89443 | 0.30902 | | | | | |
| 6 | 1.55292 | 1.75931 | 1.55291 | 1.20163 | 0.75787 | 0.25882 | | | | |
| 7 | 1.55765 | 1.79883 | 1.65883 | 1.39717 | 1.05496 | 0.65597 | 0.22521 | | | |
| 8 | 1.56073 | 1.82464 | 1.72874 | 1.52832 | 1.25882 | 0.93705 | 0.57755 | 0.19509 | | |
| 9 | 1.56284 | 1.84241 | 1.77719 | 1.62019 | 1.40373 | 1.14076 | 0.84136 | 0.51555 | 0.17365 | |
| 10 | 1.56435 | 1.85516 | 1.81211 | 1.68689 | 1.51000 | 1.29209 | 1.04062 | 0.76263 | 0.46538 | 0.15643 |
| Rs = 0 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

# Butterworth Normalized Lowpass Component Values



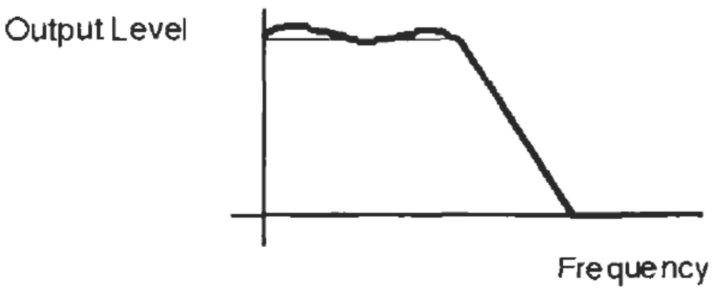
- Butterworth LC Values $R_s = 1$

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.0000 | | | | | | | | | |
| 2 | 1.41421 | 1.41421 | | | | | | | | |
| 3 | 1.00000 | 2.00000 | 1.00000 | | | | | | | |
| 4 | 0.76537 | 1.84776 | 1.84776 | 0.76537 | | | | | | |
| 5 | 0.61803 | 1.61803 | 2.00000 | 1.61803 | 0.61803 | | | | | |
| 6 | 0.51764 | 1.41421 | 1.93185 | 1.93185 | 1.41421 | 0.51764 | | | | |
| 7 | 0.44504 | 1.24698 | 1.80194 | 2.00000 | 1.80194 | 1.24698 | 0.44504 | | | |
| 8 | 0.39018 | 1.11114 | 1.66294 | 1.96157 | 1.96157 | 1.66294 | 1.11114 | 0.39018 | | |
| 9 | 0.34730 | 1.00000 | 1.53209 | 1.87938 | 2.00000 | 1.87938 | 1.53209 | 1.00000 | 0.34730 | |
| 10 | 0.31287 | 0.90798 | 1.41421 | 1.78201 | 1.97538 | 1.97538 | 1.78201 | 1.41421 | 0.90798 | 0.31287 |
| | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

# Chebyshev Response



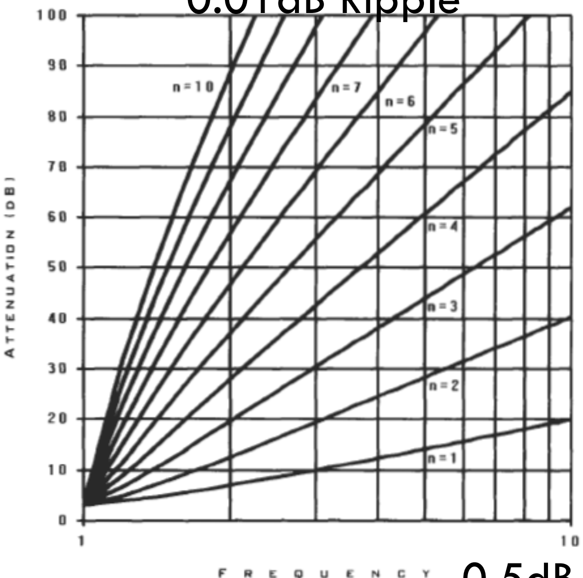
- Chebyshev response has ripples in the passband but a smooth increase in stopband attenuation.
  - By allowing the passband response to have ripples, the stopband attenuation rises sharply just beyond the cutoff frequency.
- Further beyond the cutoff frequency, the attenuation rises by 6n dB/octave, which is the same as the Butterworth.
  - However, for a filter of equal order measured at the same frequency, a Chebyshev response will produce more stopband attenuation because of the sudden rise in attenuation immediately beyond the cutoff point.
- Graphs are for different passband ripples



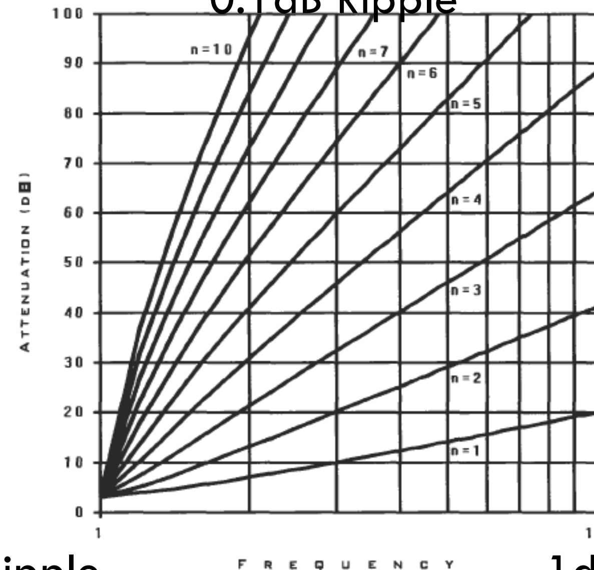
# Chebyshev Response



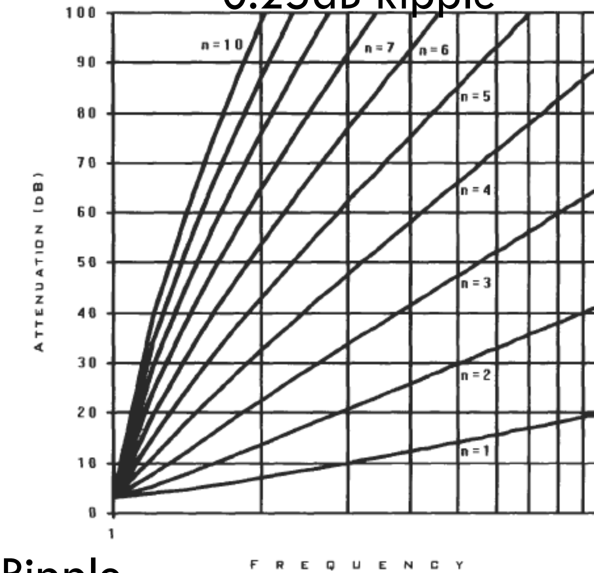
0.01dB Ripple



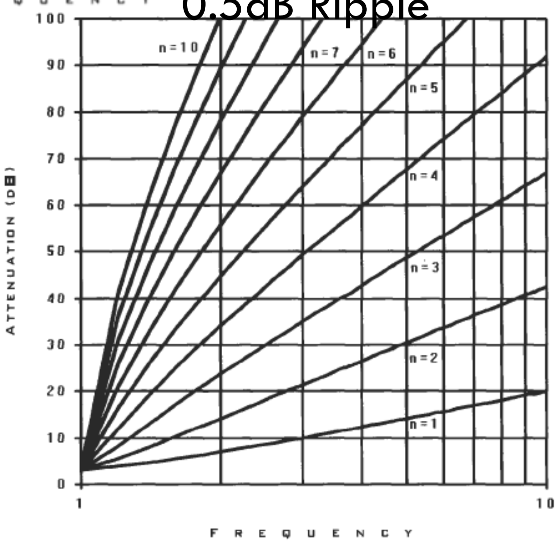

0.1dB Ripple



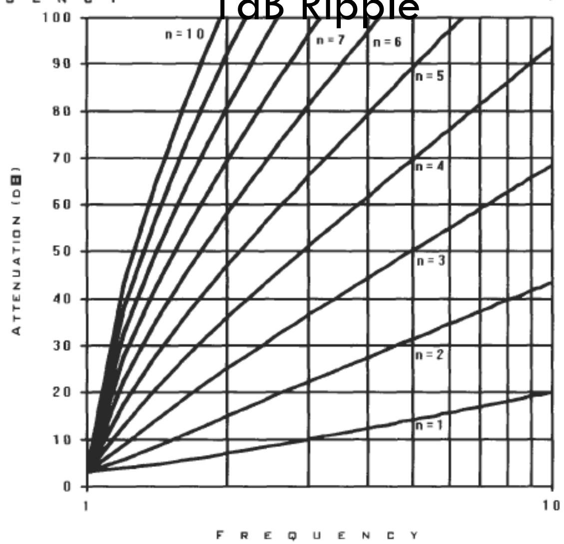

0.25dB Ripple




0.5dB Ripple




1dB Ripple



# Chebyshev Tables: Equal Source and Load Impedances



| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1.18111 | 1.82142 | 1.18111 | | | | | | |
| 5 | 0.97660 | 1.68494 | 2.03666 | 1.68494 | 0.97660 | | | | |
| 7 | 0.91273 | 1.59470 | 2.00209 | 1.87037 | 2.00209 | 1.59470 | 0.91273 | | |
| 9 | 0.88538 | 1.55131 | 1.96146 | 1.86164 | 2.07173 | 1.86164 | 1.96146 | 1.55131 | 0.88538 |
| | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ |

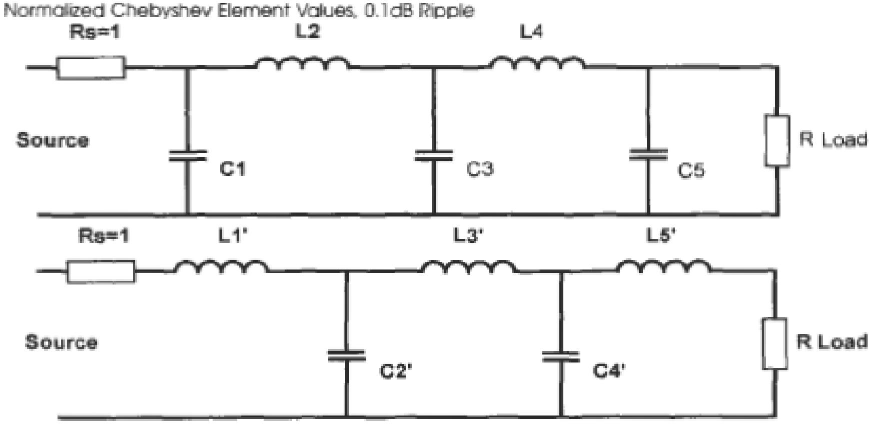
**Table 2.10**

Normalized Chebyshev Element Values, 0.01dB Ripple

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1.43286 | 1.59373 | 1.43286 | | | | | | |
| 5 | 1.30134 | 1.55594 | 2.24110 | 1.55594 | 1.30134 | | | | |
| 7 | 1.26152 | 1.51955 | 2.23927 | 1.68038 | 2.23927 | 1.51955 | 1.26152 | | |
| 9 | 1.24466 | 1.50168 | 2.22199 | 1.68293 | 2.29571 | 1.68293 | 2.22199 | 1.50168 | 1.24466 |
| | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ |

**Table 2.11**

Normalized Chebyshev Element Values, 0.1dB Ripple




| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1.63306 | 1.43616 | 1.63306 | | | | | | |
| 5 | 1.53996 | 1.43493 | 2.44027 | 1.43493 | 1.53996 | | | | |
| 7 | 1.51189 | 1.41692 | 2.45311 | 1.53492 | 2.45311 | 1.41692 | 1.51189 | | |
| 9 | 1.50000 | 1.40755 | 2.44460 | 1.54062 | 2.50767 | 1.54062 | 2.44460 | 1.40755 | 1.50000 |
| | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ |

**Table 2.12**

Normalized Chebyshev Element Values, 0.25 dB Ripple

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 1.86369 | 1.28036 | 1.86369 | | | | | | |
| 5 | 1.80691 | 1.30248 | 2.69145 | 1.30248 | 1.80691 | | | | |
| 7 | 1.78962 | 1.29608 | 2.71773 | 1.38476 | 2.71773 | 1.29608 | 1.78962 | | |
| 9 | 1.78229 | 1.29208 | 2.71630 | 1.39214 | 2.77344 | 1.39214 | 2.71630 | 1.29208 | 1.78229 |
| | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ |

**Table 2.13**

Normalized Chebyshev Element Values, 0.5 dB Ripple

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 2.21565 | 1.08839 | 2.21565 | | | | | | |
| 5 | 2.20715 | 1.12798 | 3.10248 | 1.12798 | 2.20715 | | | | |
| 7 | 2.20391 | 1.13061 | 3.14695 | 1.19368 | 3.14695 | 1.13061 | 2.20391 | | |
| 9 | 2.20246 | 1.13079 | 3.15397 | 1.20201 | 3.20772 | 1.20201 | 3.15397 | 1.13079 | 2.20246 |
| | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ |

**Table 2.14**

Normalized Chebyshev Element Values, 1 dB Ripple

# Chebyshev Tables: Zero or Infinite Source Impedances



| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00000 | | | | | | | | | |
| 2 | 1.41336 | 0.74228 | | | | | | | | |
| 3 | 1.50124 | 1.43296 | 0.59054 | | | | | | | |
| 4 | 1.52930 | 1.69459 | 1.31270 | 0.52307 | | | | | | |
| 5 | 1.54664 | 1.79501 | 1.64491 | 1.23650 | 0.48829 | | | | | |
| 6 | 1.55130 | 1.84753 | 1.79009 | 1.59789 | 1.19066 | 0.46868 | | | | |
| 7 | 1.55932 | 1.86709 | 1.86566 | 1.76514 | 1.56334 | 1.16096 | 0.45636 | | | |
| 8 | 1.55903 | 1.88502 | 1.89902 | 1.85578 | 1.74349 | 1.53932 | 1.14133 | 0.44834 | | |
| 9 | 1.56456 | 1.88838 | 1.92421 | 1.89768 | 1.84251 | 1.72607 | 1.52167 | 1.12734 | 0.44269 | |
| 10 | 1.56262 | 1.89792 | 1.93251 | 1.92894 | 1.89081 | 1.83103 | 1.71295 | 1.50890 | 1.11738 | 0.43868 |
| Rs = 0 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

**Table 2.16**

Normalized 0.01dB Chebyshev Element Values, Rs = ∞ or 0

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00000 | | | | | | | | | |
| 2 | 1.40488 | 0.82725 | | | | | | | | |
| 3 | 1.51328 | 1.50900 | 0.71642 | | | | | | | |
| 4 | 1.51567 | 1.77396 | 1.45978 | 0.67474 | | | | | | |
| 5 | 1.56126 | 1.80689 | 1.76588 | 1.41728 | 0.65065 | | | | | |
| 6 | 1.53633 | 1.88669 | 1.83342 | 1.75125 | 1.39590 | 0.63933 | | | | |
| 7 | 1.57477 | 1.85775 | 1.92103 | 1.82699 | 1.73396 | 1.37856 | 0.63075 | | | |
| 8 | 1.54355 | 1.91231 | 1.90251 | 1.92697 | 1.82167 | 1.72463 | 1.36955 | 0.62633 | | |
| 9 | 1.58037 | 1.87275 | 1.95841 | 1.90942 | 1.92294 | 1.81361 | 1.71504 | 1.36113 | 0.62232 | |
| 10 | 1.54689 | 1.92121 | 1.92274 | 1.97115 | 1.91128 | 1.92054 | 1.80936 | 1.71000 | 1.35669 | 0.62020 |
| Rs = 0 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

**Table 2.17**

Normalized 0.1dB Chebyshev Element Values, Rs = ∞ or 0

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00000 | | | | | | | | | |
| 2 | 1.38934 | 0.90986 | | | | | | | | |
| 3 | 1.53459 | 1.52828 | 0.81651 | | | | | | | |
| 4 | 1.49240 | 1.83405 | 1.51681 | 0.79093 | | | | | | |
| 5 | 1.58646 | 1.78565 | 1.83856 | 1.48558 | 0.76996 | | | | | |
| 6 | 1.51127 | 1.92783 | 1.82548 | 1.83907 | 1.47670 | 0.76375 | | | | |
| 7 | 1.60115 | 1.82834 | 1.96618 | 1.82342 | 1.82607 | 1.46285 | 0.75593 | | | |
| 8 | 1.51783 | 1.94883 | 1.87811 | 1.97925 | 1.82513 | 1.82364 | 1.45940 | 0.75382 | | |
| 9 | 1.60726 | 1.84134 | 1.99659 | 1.88630 | 1.97701 | 1.81910 | 1.81573 | 1.45231 | 0.75000 | |
| 10 | 1.52086 | 1.95624 | 1.89342 | 2.01317 | 1.89184 | 1.97865 | 1.81878 | 1.81444 | 1.45086 | 0.74915 |
| Rs = 0 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

**Table 2.18**

Normalized 0.25 dB Chebyshev Element Values, Rs = ∞ or 0

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00000 | | | | | | | | | |
| 2 | 1.36144 | 1.01565 | | | | | | | | |
| 3 | 1.57200 | 1.51790 | 0.93182 | | | | | | | |
| 4 | 1.45345 | 1.91162 | 1.53954 | 0.92395 | | | | | | |
| 5 | 1.62994 | 1.73996 | 1.92168 | 1.51377 | 0.90343 | | | | | |
| 6 | 1.46994 | 1.99084 | 1.79019 | 1.93593 | 1.51606 | 0.90305 | | | | |
| 7 | 1.64643 | 1.77716 | 2.03065 | 1.78918 | 1.92388 | 1.50337 | 0.89478 | | | |
| 8 | 1.47565 | 2.00848 | 1.83056 | 2.05041 | 1.79671 | 1.92786 | 1.50504 | 0.89433 | | |
| 9 | 1.65329 | 1.78899 | 2.05701 | 1.83833 | 2.04815 | 1.79101 | 1.91988 | 1.49810 | 0.89112 | |
| 10 | 1.47828 | 2.01478 | 1.84229 | 2.07746 | 1.84692 | 2.05357 | 1.79404 | 1.92217 | 1.49949 | 0.89185 |
| Rs = 0 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

**Table 2.19**

Normalized 0.5 dB Chebyshev Element Values, Rs = ∞ or 0

| Order | C1 | L2 | C3 | L4 | C5 | L6 | C7 | L8 | C9 | L10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00000 | | | | | | | | | |
| 2 | 1.30223 | 1.19145 | | | | | | | | |
| 3 | 1.65199 | 1.45972 | 1.10778 | | | | | | | |
| 4 | 1.37686 | 2.05105 | 1.51740 | 1.12742 | | | | | | |
| 5 | 1.72155 | 1.64455 | 2.06119 | 1.49297 | 1.10354 | | | | | |
| 6 | 1.38984 | 2.11627 | 1.70474 | 2.09336 | 1.50789 | 1.11259 | | | | |
| 7 | 1.74142 | 1.67712 | 2.15585 | 1.70229 | 2.07901 | 1.49453 | 1.10192 | | | |
| 8 | 1.39431 | 2.13071 | 1.73338 | 2.18479 | 1.71600 | 2.09151 | 1.50218 | 1.10717 | | |
| 9 | 1.74970 | 1.68810 | 2.17984 | 1.73916 | 2.18069 | 1.70937 | 2.08153 | 1.49435 | 1.10119 | |
| 10 | 1.39636 | 2.13592 | 1.74170 | 2.20597 | 1.75099 | 2.19124 | 1.71609 | 2.08873 | 1.49916 | 1.10462 |
| Rs = 0 | L1′ | C2′ | L3′ | C4′ | L5′ | C6′ | L7′ | C8′ | L9′ | C10′ |

**Table 2.20**

Normalized 1dB Chebyshev Element Values, Rs = ∞ or 0

# Formulae for Passive Lowpass Filter Denormalization



- In practice, the design would be scaled for impedance and frequency in one step, by substitution of values into the given formulae:

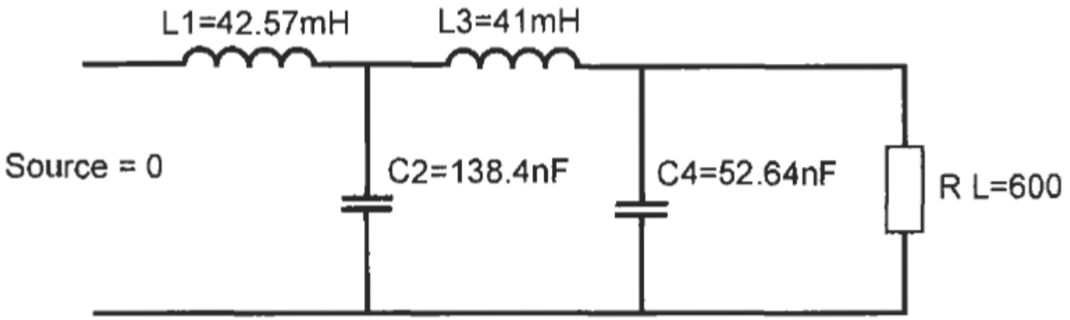
$$L = \frac{RL^*}{2\pi F_c} \qquad C = \frac{C^*}{2\pi F_c R}$$

  - L* and C* are the normalized lowpass component values, while L and C are the final values after scaling

# Analog Filter Design Example



- Design a fourth-order lowpass filter with 600Ω load impedance and a cutoff frequency of 3.4kHz for telephone band speech. The filter is to be driven from a 0Ω source (an ideal op-amp) and a 0.1 dB ripple Chebyshev response
  - From tables, normalized component values are L1'= 1.51567; C2' = 1.77396; L3' = 1.45978; C4' = 0.67474.
  - The apostrophe indicates that ladder network begins with a series inductor
  - Scaled component values for this filter are: L1 = 42.57mH; C2 = 138.4nF; L3 = 41.0mH; C4 = 52.64nF.



# Assignments



- Design a 5th order Butterworth low pass filter with 1kΩ load impedance and a cutoff frequency of 10 kHz for telephone band speech. The filter is to be driven from a 0Ω source (an ideal op-amp).
- Repeat the above problem for a Bessel filter.