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Research on Active Filters and Passive Filters

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Abstract:

Active filters have been a cornerstone of electronic engineering since their inception in the mid-20th century. As technology has advanced, these components have become increasingly sophisticated and integral to a wide range of applications, from audio equipment to telecommunications. This article introduces two types of active filters, active low-pass and active high-pass. Active filters play a vital role in modern electronic and communication systems. They can enhance signals, which is very important in signal transmission and processing. Active filters are very flexible in design and can achieve a variety of filtering functions. The circuit design can also be adjusted by adjusting the parameters of the filter. The composition and basic principles of the two active filters are briefly explained, as well as why we use active filters in circuits. Secondly, we explain the composition of high-order active filters and give a schematic diagram. Finally, this article explains the roll-off rate, design equations and transfer function of the Butterworth filter, describes the practical application of Butterworth and the shortcomings of the Butterworth filter.

Keywords: Active filters; Passive filters; Butterworth filter.

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1. Introduction

In the realm of electronic engineering, few components have had as profound an impact as active filters. Since their emergence in the mid-20th century, these versatile circuits have revolutionized signal processing and shaped the landscape of modern electronics [1]. As our world becomes increasingly interconnected and reliant on digital technologies, the importance of active filters in ensuring clear, precise signal transmission cannot be overstated.

From the smartphones in our pockets to the satellites orbiting Earth, active filters work tirelessly behind the scenes, separating desired signals from noise and interference [2]. Their ability to enhance and manipulate signals has made them indispensable in fields as diverse as telecommunications, audio engineering, medical imaging, and radar systems [3]. This article delves into the fascinating world of active filters, focusing on two fundamental types: active low-pass and active high-pass filters. We will explore their composition, operating principles, and the crucial roles they play in modern electronic and communication systems [4]. Additionally, we'll examine the design flexibility of active filters and how their parameters can be fine-tuned to achieve specific filtering functions. As we progress, we'll venture into more advanced territory, discussing high-order active filters and providing schematic diagrams for clarity. Special attention will be given to the Butterworth filter, a popular choice in many applications [5]. We'll analyze its roll-off rate, design equations, and transfer function, while also considering its practical applications and limitations [6].

2. Filters

Capacitive impedance refers to the opposition a capacitor presents to current flow. Unlike resistance, this impedance varies with frequency, exhibiting an inverse relationship. As frequency rises, capacitive impedance diminishes, and vice versa. This property allows capacitors to be integrated into Voltage Divider Networks, enabling the creation of low-pass and high-pass filtering effects.

By substituting one resistor in a voltage divider with an appropriate capacitor, one can construct passive low-pass and high-pass filters. In a low-pass configuration, high-frequency inputs encounter reduced capacitive impedance, resulting in decreased output voltage. Conversely, low-frequency inputs face higher impedance, leading to increased output voltage. The net result mimics the behavior of a low-frequency pass-through. For high-pass filters, the opposite occurs. High-frequency inputs experience lowered capacitive impedance, causing the divided voltage to decrease and consequently raising the output voltage. Low-frequency inputs, however, encounter increased impedance, elevating the divided voltage and thus reducing the output voltage. This arrangement effectively simulates a high-frequency pass-through.

Filters are categorized into two main types: active and passive. The key distinction lies in their signal amplification capabilities. Active filters incorporate amplification devices to enhance signal strength, whereas passive filters lack this feature. Consequently, passive filter designs, composed solely of non-amplifying components like resistors, capacitors, and inductors, invariably produce output signals with amplitudes lower than their corresponding inputs. This characteristic results in a gain less than unity for passive filters. The absence of amplification elements (such as transistors or operational amplifiers) in passive filters precludes any signal boost. As a result, the output level of a passive filter consistently remains below its input level, reflecting its inherent inability to amplify signals.

3. Passive Low-Pass RC Circuit

Low-pass filters are essential components in signal processing, designed to transmit frequencies from 0Hz up to a specified cutoff point while attenuating higher frequencies. The behavior of these filters stems from the unique properties of capacitors and resistors in alternating current circuits. Capacitive reactance exhibits an inverse relationship with frequency, whereas resistive impedance remains constant across the frequency spectrum. In low-frequency ranges, the capacitive reactance (XC) significantly exceeds the resistor's value (R), resulting in a larger voltage drop across the capacitor (VC) compared to that across the resistor (VR). Conversely, at higher frequencies, VC diminishes while VR increases due to the frequency-dependent nature of capacitive reactance. This RC configuration not only functions as a low-pass filter but can also be conceptualized as a frequency-dependent variable potential divider. High-frequency inputs yield attenuated outputs, while low-frequency inputs produce amplified results, effectively simulating a low-frequency voltage output. The filter's frequency response can be visualized graphically (Fig. 1).

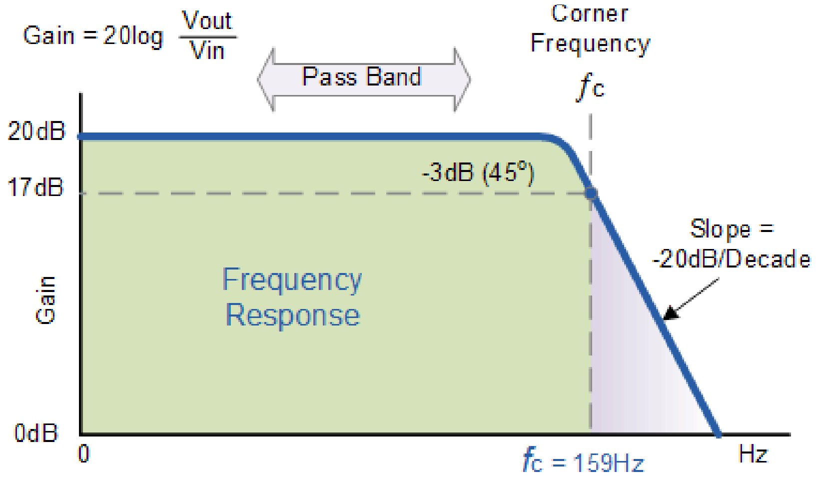

Fig. 1 Passive low-pass RC circuit frequency response graph (Photo/Picture credit: Original).

The frequency response curve illustrates a nearly flat response in the low-frequency range, where input signals pass to the output with minimal attenuation, maintaining a gain close to unity up to the cutoff frequency (fc). This occurs because the capacitor's high reactance at low frequencies impedes current flow. Beyond the cutoff point, high-frequency signals experience rapid attenuation as the capacitor's reactance approaches zero, effectively short-circuiting the output.

The passband, representing the filter's bandwidth, encompasses frequencies below the cutoff point that experience minimal attenuation. Frequencies above this threshold fall within the stopband and undergo significant reduction in amplitude. A basic first-order RC low-pass filter, comprising a series-connected resistor and capacitor, provides an attenuation slope of -20dB/decade above the cutoff frequency. For applications requiring steeper attenuation, multiple filters can be cascaded (Fig. 2).

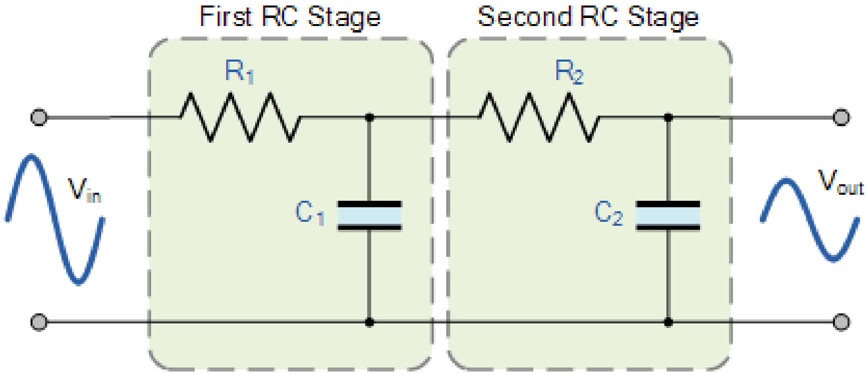

Fig. 2 First-Order RC Low-Pass Filter (Photo/Picture credit: Original).

Combining two first-order low-pass filters in series results in a second-order or two-pole filter network [7]. As additional RC stages are incorporated, the filter's order increases, leading to an "n-order" configuration with a roll-off slope of "n x -20dB/decade". For example, a second-order filter demonstrates a -40dB/decade slope (-12dB/octave), while a fourth-order filter achieves an impressive -80dB/decade (-24dB/octave). This progression allows higher-order filters to more closely approximate ideal stopband characteristics, featuring increasingly steep roll-off slopes.

Second-order filters play a pivotal role in filter design, serving as building blocks that can be combined with first-order filters to create filters of any higher order. As an illustration, a third-order low-pass filter is constructed by connecting first and second-order low-pass filters in series.

Despite these advantages, cascading multiple stages can present challenges. As filter order increases, there is a tendency for decreased gain and reduced accuracy. In configurations where identical RC stages are cascaded, the output gain at the cutoff frequency (fc) experiences greater attenuation proportional to the number of stages employed. Furthermore, the practical implementation of high-order passive filters is complicated by inter-stage impedance interactions. To address loading effects, a common strategy involves designing subsequent stages with impedances ten times higher than the preceding stage (R2 = 10 x R1 and C2 = 1/10C1). This approach helps maintain signal integrity throughout the filter chain.

Second-order and higher filter networks find frequent application in operational amplifier feedback circuits, where they form active filters, or as phase shift networks in RC oscillator circuits [8]. These configurations offer enhanced performance and versatility in complex signal processing scenarios, enabling designers to meet stringent requirements in various applications. The utilization of higher-order filters allows for more precise control over frequency response, enabling sharper cutoffs and improved noise rejection. This capability is particularly valuable in fields such as audio processing, telecommunications, and instrumentation, where accurate signal filtering is crucial for optimal system performance.

By understanding and leveraging the properties of cascaded filter stages, engineers can design sophisticated filtering solutions that balance performance, complexity, and practical implementation considerations. This approach enables the development of highly effective signal processing systems tailored to specific application requirements.

4. Passive high-pass RC circuit

High-pass filters are essential components in signal processing, designed to transmit frequencies above a specified cutoff point while attenuating lower frequencies. These filters exhibit unique behavior due to the frequency-dependent properties of capacitors and resistors in alternating current circuits. When subjected to high-frequency inputs, the output voltage of a high-pass filter closely approximates the input voltage. Conversely, low-frequency inputs result in significantly diminished output voltages. This characteristic effectively allows the circuit to isolate high-frequency components from the input signal. The frequency response of a high-pass filter can be visualized graphically, revealing substantial attenuation in the low-frequency region up to the cutoff frequency point. This phenomenon occurs due to the capacitor's high reactance at low frequencies, which causes it to behave like an open circuit, impeding the passage of input signals. Frequencies above the cutoff point experience minimal attenuation, with the majority of the input signal passing directly to the output. This results in a gain approaching unity for high-frequency components. The capacitor's reactance decreases significantly at elevated frequencies, causing it to function more like a short circuit and allowing unimpeded signal transmission. The filter's response in the low-frequency domain is characterized by an enhanced positive slope of +20dB/decade for frequencies below the cutoff point. This behavior contrasts with that of low-pass filters, which exhibit a negative slope in their stopband.

5. Active Low-Pass Filters

Active filters, particularly those designed for low-pass applications, represent a significant leap forward in signal processing technology. These advanced circuits integrate operational amplifiers (op amps) as their primary amplification component, complemented by resistors and capacitors to achieve exceptional filtering performance at lower frequencies. While passive filters can be constructed using basic components, they are inherently limited in their capabilities.

The main drawback of passive filters is their inability to amplify signals, resulting in output amplitudes that are invariably lower than input amplitudes. This limitation, combined with the fact that load impedance significantly influences filter characteristics, can lead to substantial signal attenuation, especially in multi-stage configurations. This signal loss, often termed "roll-off," necessitates the implementation of active filtering techniques.

Active filters differentiate themselves by incorporating dynamic components such as op amps, transistors, or FETs into their design. These elements utilize external power sources to enhance and amplify output signals. The use of op amps in active filters capitalizes on their high input impedance, low output impedance, and precisely controllable voltage gain, which is determined by the resistor network within the feedback loop.

Despite their numerous advantages, active filters have a maximum frequency response constrained by the gain-bandwidth product (or open-loop gain) of the employed op amp. This contrasts with passive high-pass filters, which theoretically offer an infinite high-frequency response. Nevertheless, active filters generally prove more straightforward to design and, when implemented effectively, exhibit superior performance characteristics, including precise roll-off and minimal noise.

The active low-pass filter is one of the most common and easily understood active filter configurations. Its operational principles and frequency response mirror those of its passive counterpart, with the key distinction being the incorporation of an op amp for amplification and gain control. In its simplest form, it combines an inverting or non-inverting amplifier with a fundamental RC low-pass filter circuit. A first-order low-pass active filter typically comprises a passive RC stage feeding into a non-inverting op amp configured as a voltage follower (buffer). This arrangement provides unity gain (Av = +1) at DC, in contrast to the sub-unity gain of passive RC filters. The op amp's high input impedance prevents excessive loading of the filter output, while its low output impedance ensures that load impedance variations do not affect the filter's cutoff frequency.

While this configuration offers excellent stability, its primary limitation is the inability to provide voltage gain above unity. However, the power gain remains substantial due to the significant disparity between input and output impedances. To achieve higher-order filtering, a first-order low-pass active filter can be expanded to a second-order configuration by incorporating an additional RC network in the input path. The resulting second-order filter exhibits a frequency response similar to its first-order counterpart but with doubled stop-band roll-off, reaching 40dB/decade (12dB/octave). This enhanced roll-off characteristic makes higher-order active filters particularly valuable in applications requiring sharp frequency selectivity and efficient signal conditioning. By leveraging the advantages of active components, these filters overcome the limitations of passive designs, offering improved performance and flexibility across a wide range of signal processing scenarios.

6. Active High-Pass Filters

Active high-pass filters (HPFs) represent an evolution of their passive counterparts, incorporating operational amplifiers (op amps) to provide amplification and gain control. While the fundamental operation remains similar to RC passive high-pass filters, the inclusion of active components introduces significant enhancements and limitations. It is worth noting that, strictly speaking, there is no "pure" active high-pass filter. Unlike passive high-pass filters with theoretically infinite frequency responses, active HPFs exhibit a maximum passband frequency response constrained by the open-loop characteristics or bandwidth of the utilized op amp. The high-frequency cutoff is determined by the specific op amp and gain configuration.

Op amps are inherently bandwidth-limited, with their maximum frequency response dictated by the gain-bandwidth product or open-loop voltage gain (A V). This limitation manifests where the closed-loop response intersects the open-loop response. For instance, common op amps like the uA741 typically feature a maximum "open-loop" DC voltage gain of approximately 100dB, with a roll-off rate of -20dB/decade (-6dB/octave) as input frequency increases. The gain diminishes until reaching unity gain (0dB) at the "transition frequency" (ft), usually around 1MHz for such devices. This behavior results in a frequency response curve resembling a first-order low-pass filter (Fig. 3).

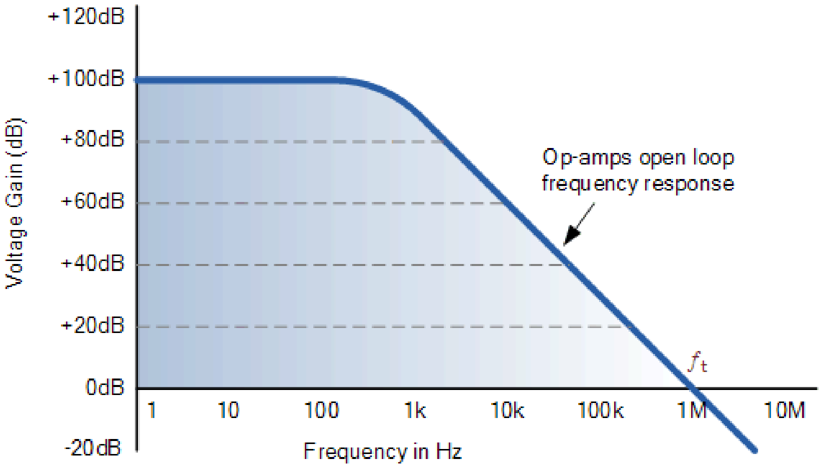

Fig. 3 Active high-pass filter frequency response curve (Photo/Picture credit: Original).

The high-frequency performance of active HPFs is thus bounded by the unity-gain crossover frequency, which defines the overall bandwidth of the open-loop amplifier. Gain-bandwidth products vary from around 100kHz for small-signal amplifiers to approximately 1GHz for high-speed digital video amplifiers. Despite these limitations, op-amp-based active filters can achieve exceptional accuracy and performance when implemented with low-tolerance resistors and capacitors.

Typically, the maximum passband required for closed-loop active high-pass or bandpass filters falls well below the maximum open-loop transition frequency. However, careful selection of the appropriate op amp is crucial to prevent signal distortion due to high-frequency signal loss. A first-order (single-pole) active high-pass filter attenuates low frequencies while passing high-frequency signals. It comprises a passive filter section followed by a non-inverting op amp. The circuit's frequency response mirrors that of a passive filter, but with signal amplitude amplified by the op amp's gain. For a non-inverting amplifier configuration, the passband voltage gain is given by 1 + R2/R1, analogous to low-pass filter circuits. To achieve higher-order filtering, a first-order active high-pass filter can be extended to a second-order configuration by incorporating an additional RC network in the input path. The resulting second-order high-pass filter exhibits a frequency response similar to its first-order counterpart, but with doubled stop-band roll-off, reaching 40dB/decade (12dB/octave) [9][10].

This enhanced roll-off characteristic makes higher-order active high-pass filters particularly valuable in applications requiring sharp frequency selectivity and efficient signal conditioning. By leveraging the advantages of active components, these filters overcome the limitations of passive designs, offering improved performance and flexibility across a wide range of signal processing scenarios.

7. Butterworth Filter Design

When discussing frequency scales in signal processing, it's crucial to understand the concepts of decades and octaves. These logarithmic units provide a convenient way to describe frequency ranges and filter characteristics. A decade represents a tenfold change in frequency, either an increase (multiplication by 10) or a decrease (division by 10). For instance, the range from 2 Hz to 20 Hz constitutes one decade, while the span from 50 Hz to 5000 Hz encompasses two decades (50 to 500 Hz, followed by 500 to 5000 Hz). In contrast, an octave denotes a doubling or halving of frequency. The interval from 10 Hz to 20 Hz exemplifies a single octave, whereas the range from 2 Hz to 16 Hz spans three octaves (2 to 4 Hz, 4 to 8 Hz, and 8 to 16 Hz), with each step doubling the previous frequency. Logarithmic scales are extensively employed in frequency domain analysis, particularly when working with amplifiers and filters. Their widespread use underscores the importance of grasping these concepts for effective signal processing design and analysis. The Butterworth filter approximation function is renowned for its “maximally flat” frequency response. This characteristic implies a pass band that maintains a mathematically optimal flatness from 0 Hz (DC) up to the -3 dB cut-off frequency, devoid of ripples. Beyond this point, higher frequencies in the stop band experience a roll-off, diminishing to zero at a rate of 20 dB/decade or 6 dB/octave. This behavior stems from the filter’s “quality factor” (Q) of 0.707.

While the Butterworth filter excels in pass band flatness, it does have some limitations. The trade-off for this flat response is a relatively wide transition band as the filter transitions from the pass band to the stop band. Additionally, the Butterworth filter exhibits suboptimal phase characteristics. These properties make the Butterworth filter an excellent choice for applications prioritizing magnitude response flatness in the pass band. However, designers must carefully consider the wider transition band and phase response limitations when selecting this filter topology for specific signal processing tasks. Understanding these nuances in filter behavior and frequency scaling is essential for engineers and researchers working in fields such as audio processing, telecommunications, and control systems. By leveraging this knowledge, practitioners can make informed decisions when designing and implementing filters to meet precise specifications in various applications [11].

8. Conclusion

This article briefly introduces the passive low-pass RC circuit and the passive RC high-pass circuit, and simply explains that the reason why the passive filter can have this filtering selectivity is because of the characteristics of the capacitor. Next, it mainly talks about the active low-pass filter, the active high-pass filter and the Butterworth filter. The active filter is based on the passive filter with an amplification element, the operational amplifier (op-amp). Because the gain of the passive filter is always less than 1, when the order of the passive filter increases, the amplitude loss of its attenuated signal will be very serious. The operational amplifier can control this effect by actively increasing the gain. The Butterworth filter is an analog filter design that produces the best output response, with no ripples in the passband or stopband, thereby achieving the maximum flat filter response, but at the cost of a relatively wide transition band. Active filters are used in many fields, such as signal processing, communications, and medical equipment. With the development of technology, the current signal processing requirements are becoming more and more complex, so active filter circuits also need lower power consumption, wider tuning range, and stronger digital control capabilities.

9. Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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