Tunable band-pass filter for continuous spectral analysis of cardiointervalogram

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Abstract. The developed device refers to analog low-pass filtering circuits and works as Butterworth-type broadband active RC filter. This filter can be used in devices for the human cardiovascular system diagnostic purposes, providing an opportunity to assess the state of the cardiovascular system. Such approach is based on the analysis of cardiointervalogram spectral power and can be implemented in biofeedback systems that use the current values of this power to generate feedback signals. The filter consists of second-order active bandpass filter blocks, connected together in series. Implemented schematic provides simultaneous tuning of the resonant frequency and the quality factor of the band-pass filter. This feature allowing to adjust the bandwidth while maintaining the center frequency and tuning the center frequency while maintaining the constancy of the band. The selection of bandpass filter tuning mode is made by selecting the appropriate adjustable components.

1. Introduction

In the diagnosis of human cardiovascular system, it is necessary to study the effects of the sympathetic and parasympathetic influences of the nervous system on the activity of heart. For this purpose, it is necessary to assess the state of various regulation levels of cardiovascular system. Such an assessment is based on the analysis and processing of the spectral power of cardiac rhythmogram (CRG) in different frequency ranges. The current values of the cardiointervalogram spectral power are also used in biocontrol systems, where a biological feedback signal is formed from them [1, 2].

In such systems, it is especially important to determine the spectral power of the individual components of frequency ranges in real time. The values of these frequency ranges used in the analysis of heart rate variability (HRV), and their physiological interpretation in the regulation of the cardiovascular system brought together in the table 1.

The use of continuous spectral analysis based on the frequency filtering of a cardiac rhythmogram allows quantifying the frequency components of heart rate fluctuations. This provides the ability for biofeedback control according to the amplitudes of frequency components of heart rhythm, associated with the activity of certain parts of regulatory mechanism of cardiovascular system and respiratory rate.
Table 1. Frequency ranges of HRV and their physiological interpretation.

| Name and designation of frequency ranges | Frequency range, Hz | Physiological interpretation of HRV frequency ranges |
|-----------------------------------------|---------------------|-----------------------------------------------------|
| HF (High Frequency)                     | 0.15 – 0.4          | Parasympathetic component of regulation              |
| LF (Low Frequency)                      | 0.04 – 0.15         | Sympathetic and partially parasympathetic components of regulation |
| VLF (Very Low Frequency)                | 0.003 – 0.04        | Thermoregulation and other long-term systems (renin-angiotensin and sympathetic nervous systems) |
| UVLF (Ultra Very Low Frequency)         | less than 0.003     | Daily periodicals                                    |
| Breath                                  | 0.08 – 0.125        | Cardiorespiratory synchronization                    |

In medical practice, when performing spectral studies in the field of low and very low frequencies, bandpass filters (BPF) in the range from hundredths to units of Hertz are required. In this case, it is necessary to ensure the possibility of tuning them both at the center frequency $f_0$ while maintaining the passband $f_B$ (figure 1), and the passband $f_B$ while maintaining a constant center frequency $f_0$ (figure 2). The passband is defined as the difference between the lower $f_L$ and upper $f_H$ boundaries of the BPF frequency range.

$$f_0 = \text{var}$$
$$f_B = f_H - f_L = \text{const}$$

Thus, our goal was to develop a band-pass filter that allows tuning passband at a constant center frequency, and tuning of the center frequency while maintaining a constant filter Q value.

The choice of truly analog solutions was made due to the need for fast synchronous processing of the cardiac rhythmogram to select the appropriate frequency ranges, minimize the time delay (the requirement of biofeedback technology) and low power consumption of the entire device.

2. Materials and methods

There are various circuitry solutions for building adjustable BPF. In particular, RC low-pass (LPF) and high-pass filters (HPF) of the second order with fixed cut-off frequency and Q factor, in which, to tune the cut-off frequency, it is necessary to simultaneously change two or more frequency-dependent resistors or capacitors. Since the tuning of the cutoff frequency by changing the nominal value of the capacitance in the region of low and infra-low frequencies seems impossible, the only way to ensure the tuning of low-pass filters frequency is implementation of frequency-dependent resistors.
The most rational is the construction of fourth-order broadband band pass filters by cascading a high-pass filter and a low-pass filter of the second order, or by cascading a second-order filters. Then it is possible to provide the required bandwidth of the synthesized band pass filter by tuning cutoff frequency of each filter.

To ensure a sharp graph of frequency response, it is necessary to use a high-pass filter and a low-pass filter of at least second order, therefore, the created broadband BPF must be at least fourth order. Moreover, it should have flattest frequency response as possible. For ensure this approach, it is formed by cascading the filters of the low-pass and high-pass filters of the second order such as Butterworth. In this case, the cutoff frequencies of the broadband BPF are formed by the cutoff frequencies of the high-pass filter on the left and the low-pass filter on the right.

In this paper, we consider the construction of fourth-order broadband regulated BPF by cascading a second-order BPF. As a second-order BPF with adjustable parameters, Kelvin-Hülsmann-Newcomb (KHN) filter, also known as a biquad filter, was selected [3].

This filter simultaneously includes BPF, low-pass filter and high-pass filter, and when supplemented with one differential amplifier and notch filter, KHN has the ability to easily control the cutoff frequency (fL for the low-pass filter, fH for the high-pass filter, f0 for the BPF) and Q-factor by using two corresponding resistors. All this makes it possible to use the same circuitry, and therefore design solutions for various types of filters with controlled parameters.

3. Results

The block diagram of the adjustable BPF is shown in Figure 3. It shows the initial scheme of KHN (circled by a dotted line) where S1 is the adder, A1 and A2 are amplifiers with amplification factors k1 and k2, Int1 and Int2 are integrators with cutoff frequency f0 (ω0 = 2πf0), nodes A, B and C are the possible inputs/outputs of the filter. Adders S3, S4 and amplifiers A3, A4 and A5 with amplification factors k3, k4 and k5, respectively, has been added to the original KHN circuit.

The transfer function of the developed filter, for k2 = 1, looks like this:

\[ K_{BP}(s) = \frac{1}{k_4} \frac{s \omega_0}{s^2 + (1 + \frac{k_5}{k_4})s \omega_0 + k_4 \omega_0^2}, \]

where s is the Laplace operator; ω0 is the cyclic cutoff frequency of Int1 and Int2. In accordance with it, the quality factor of the developed BPF is:

\[ Q = \frac{k_4}{k_4 + k_5}. \]

With the condition k3 + k5 = 1, the quality factor Q = k4. At the same time, due to the presence of a common factor 1/k4 in the transfer function, the effect of changing the Q value on the filter transmission coefficient is compensated. Thus, in the scheme of the developed BPF, it is possible to control independently the quality factor by changing the value of the coefficient k4 while maintaining the possibility of independent adjustment of the resonant frequency by changing the value of the coefficient k4, i.e. the condition for adjusting the filter parameters, illustrated in figures 1 and 2 is fulfilled.

All additional elements of the developed BPF (figure 3) are implemented on the basis of additional special circuit based on operational amplifier and potentiometer [4], due to which the condition k4 + k5 = 1 is also fulfilled. The required suppression is achieved by cascading sequential connection of the required number of developed BPF.
The block diagram of adjustable BPF: S adders, A amplifiers with gain k, Int integrators.

The figure 4 shows the frequency response graphs of three BPF’s obtained in the Microcap 12 electrical circuit simulation program. The BPF’s are made according to the proposed schematic and configured in accordance with the three standard frequency ranges of heart rate variability (HRV) HF (curve 1), LF (curve 2) and VLF (curve 3).

Figure 3. The block diagram of adjustable BPF: S adders, A amplifiers with gain k, Int integrators.

Figure 4. Frequency response of three BPFs, made according to the proposed schematic and configured in accordance with the three standard frequency ranges of HRV VLF (curve 1), LF (curve 2) and HF (curve 3) (Microcap 12).

4. Discussion
To select the frequency components corresponding to the three standard frequency ranges of HRV, three previously configured filters. To check the operation of filters with real signals, CRG of a healthy subject was fed to their inputs. The figure 5 shows: the original cardiac rhythmogram (curve 1); transient analysis graphs of three BPFs performed according to the proposed scheme CRG filtering results in three ranges - HF (curve 2), LF (curve 3) and VLF (curve 4); and the total output
voltage of the three bandpass filters (curve 5), corresponding to the original CRG (curve 1). These graphs illustrate the process of continuous spectral analysis of CRG.

![Graphs illustrating the process of continuous spectral analysis of CRG.](image)

**Figure 5.** The initial CRG (curve 1); transient analysis graphs of three BPF’s in three ranges: HF (curve 2), LF (curve 3) and VLF (curve 4); and the total output voltage of three bandpass filters (curve 5), corresponding to the original CRG (curve 1).

Thus, the technical result was achieved. The developed BPF provides operation in two modes changing the filter passband while maintaining a constant central frequency, as well as changing the central frequency while maintaining a constant Q factor only by adjusting two coefficients.

**References**

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