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# Optimised Design of the Front-End Analogue High-Pass Filter for a Diagnostic Quality ECG Monitoring System

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*Abstract*—**Even though an analogue high-pass single pole filter with 0.05Hz cut-off has been used for decades to define the low frequency response of electrocardiographs, in recent years the requirements for diagnostic quality ECG recordings have been expressed in terms of the system magnitude characteristic and its response to a rectangular pulse. The objective of this work is to design an analogue high-pass filter for the front-end of an ECG monitoring system directly from these new specifications. A constrained numerical optimisation procedure is implemented to determine the parameters of second and third order filters having the best rejection properties allowed by the requirements for distortion-free ECG recording. The outcome of the process, aimed at maximising the filter 3dB point, is a system having better attenuation characteristics than the reference 0.05Hz first order filter. The cut-off frequency of the optimised second order filter is indeed equal to 0.068Hz, whereas for the third order system the 3dB point can be as high as 0.123Hz.**

## I. Introduction

To avoid misinterpretation of diagnostically significant features of the electrocardiogram (ECG), a monitoring system should faithfully reproduce the morphology of the electrocardiographic signal. The filters incorporated in the system are critically important because they can distort the ECG if their frequency response is inadequate [1, 2, 3]. In the following, special attention is directed at the high-pass filter needed to reject baseline wander and d.c. offsets generated at the skin-electrode interface. In particular, a front-end analogue filter is under design for a dry electrode ambulatory system aiming at recording diagnostic quality ECGs. Since it must comply with international standards that guarantee the fidelity of the electrocardiographic recordings [4], the high-pass filter, although intended for a low-power application, could indeed be employed in any ECG monitoring system.

## II. Background

After a study performed by Berson & Pipberger in 1965 on the distortions introduced in ST segments and T waves of the electrocardiogram by different high-pass filters [1], a 0.05Hz single pole analogue filter has often been used to define the low frequency response of electrocardiographs. The employment of such a filter has become so customary that, up to these days, it is considered the reference by which the performance of other analogue high-pass filters for electrocardiographic applications is assessed [3].

However, in recent years, the specifications for the low frequency characteristic of the ECG filter have been expressed in terms of magnitude and pulse response, due to the widespread use of digital recording systems. The requirements that an electrocardiograph must satisfy to achieve the minimum accuracy for diagnostic recordings are defined in both the 2003 European Standard 60601-2-51 [4] and the 1990 American Heart Association (AHA) Recommendations [5]. If the most stringent specification is chosen, the magnitude of the high-pass filter should be confined within ±0.5dB for frequencies higher than 0.67Hz. This frequency is taken as the low frequency bound of the ECG spectrum and corresponds to a heart rate of 40 beats per minute. The criteria for the pulse response detailed in the European Standard are shown in Fig. 1. According to this standard, a rectangular pulse of 3mV amplitude and 100ms duration should not produce at the system output:

(i) an offset from the isoelectric line greater than 100μV;
(ii) a slope greater than 250μV/s in a 200ms region following the impulse;
(iii) a slope greater than 100μV/s anywhere outside the region of the pulse.

The reference 0.05Hz single pole high-pass filter satisfies all the above requirements, but it does not provide sufficient suppression of low-frequency movement and respiratory artefacts. Therefore, the possibility of designing the analogue high-pass filter directly from the magnitude and pulse response specifications is analysed. The design goal is a system of limited complexity that filters out as much low frequency interference as is actually feasible, given the

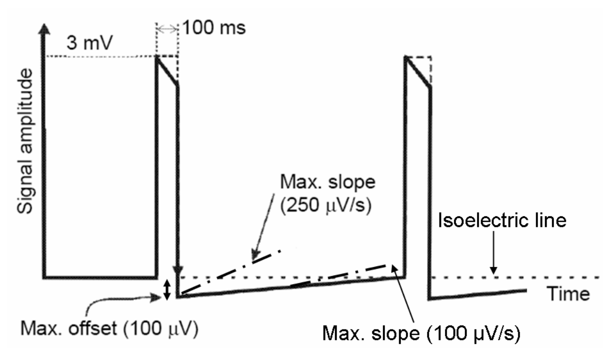


Fig. 1. Requirements for the pulse response of the ECG filter (modified from [4]).

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specific requirements that are to be met. An optimisation procedure is presented, aimed at maximising either the stop-band limit or the 3dB point of general second and third order filters.

## III. Methodology

The transfer functions for the second and third order filters used in the optimisation process are, respectively,

$$H_2(s) = \frac{s(s+a_1)}{s^2+b_1 s+b_0} \text{ and}$$
$$H_3(s) = \left(\frac{s^2+a_1 s+a_0}{s^2+b_1 s+b_0}\right)\left(\frac{s}{s+p_0}\right), \quad (1)$$

where all the parameters are real and the coefficients of the denominator must be positive for the system to be stable. A transmission zero is fixed at 0Hz because d.c. offset voltages generated at the skin-electrode interface may saturate the input amplifier of the recoding system, if not properly rejected. The parameters of the filters are determined through a constrained numerical optimisation implemented in MATLAB using the function *fmincon*. This function employs a gradient-based method to minimise an objective function, while attempting to keep all the constraints satisfied. The stop-band limit or the cut-off frequency are, in turn, defined as the opposite of the objective function and thus maximised.

Figure 2 shows the bounds imposed on the filter amplitude response when the optimisation of the stop-band limit is performed. The ripple in the stop-band, if any, needs to remain below the minimum required attenuation, $A_s$. Moreover, the 0.5dB upper limit is applied throughout the filter transition region in order to avoid the amplification of noise and interference that have components at frequencies lower than the ECG spectrum. As regarding the response to the rectangular pulse, the conditions on the undershoot and the slope are enforced in terms of absolute values.

When maximising the filter 3dB point, some modifications are needed in the definition of the allowable region for the magnitude response, which is represented in Fig. 3. Since the optimised filter is required to perform better in terms of rejection than the high-pass 0.05Hz single pole filter, the amplitude curve of the system under design is constrained to be lower than that of the reference filter from the stop-band limit up to their eventual crossing at frequencies higher than the cut-off. Furthermore, the filter magnitude is also forced to be either monotonically increasing or concave over the same interval. These two extra conditions are necessary to prevent the amplitude of the third order filter from levelling out at the 3dB point attenuation level.

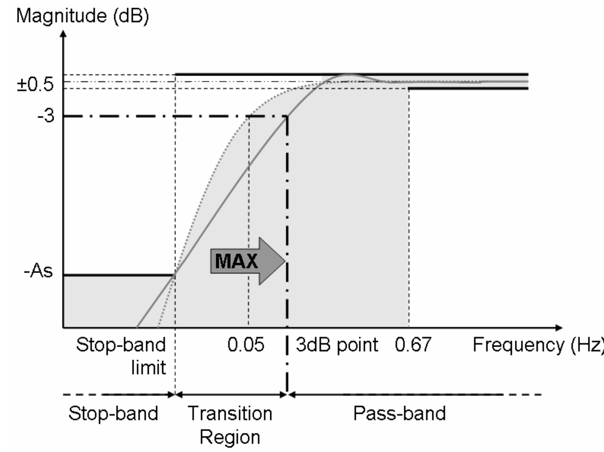


Fig. 3. Mask showing the limits imposed on the filter amplitude for the optimisation of the 3dB point. The frequency ranges of stop-band, pass-band and transition region are also clearly identified.

The starting point for the optimisation is taken as the set of parameters describing a standard third order high-pass filter. Butterworth, Chebyshev and Elliptic filters are used to check the robustness of the optimisation algorithm. For the optimisation of the stop-band limit, the parameters of these standard filters are determined by fixing the 3dB point to be 0.01Hz. The chosen cut-off allows the starting point to satisfy all the constraints and the set of initial parameters to be included in the solution space. As for the 3dB point optimisation, because of the added constraints, the starting point would not simultaneously satisfy all the magnitude and pulse response requirements. Hence, in order to assess the convergence of the algorithm, different initial conditions are determined by setting the 3dB point at various frequencies between 0.05Hz and 0.15Hz.

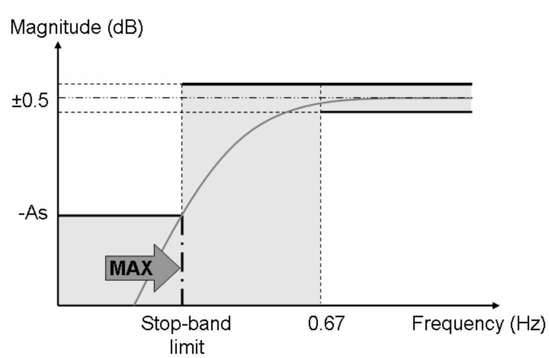


Fig. 2. Bounds fixed for the filter magnitude response in the optimisation of the stop-band limit. The regions of the plane where the amplitude response is allowed to be located are shaded.

## IV. Results

### A. Stop-Band Limit Optimisation

The optimisation of the stop-band limit is performed for the third order filter described by the transfer function in (1) for different values of desired attenuation. The locations of poles and zeros of the optimised filters are reported in Table I. The frequencies at which given levels of attenuation are reached by the filter amplitude are also shown. It can be seen that a given attenuation occurs at lower frequencies as $A_s$ is increased. In particular, the 3dB point drops by approximately one third if the stop-band attenuation is changed from 20dB to 60dB.

TABLE I

STOP-BAND OPTIMISATION RESULTS FOR A THIRD ORDER FILTER

| $A_s$ (dB) | 20 | 40 | 60 |
|---|---|---|---|
| $f_{3dB}$ (Hz) | 0.038 | 0.027 | 0.025 |
| $f_{20dB}$ (Hz) | 0.026 | 0.016 | 0.014 |
| $f_{40dB}$ (Hz) | $9.3 \cdot 10^{-4}$ | 0.010 | 0.007 |
| $f_{60dB}$ (Hz) | $9.3 \cdot 10^{-5}$ | $3.6 \cdot 10^{-4}$ | 0.005 |
| p (rad/s) | -0.202<br>-0.082±0.236i | -0.212<br>-0.065±0.175i | -0.213<br>-0.063±0.164i |
| z (rad/s) | 0<br>-0.015±0.147i | 0<br>-0.003±0.057i | 0<br>-0.001±0.026i |

The stop-band limit, which has been maximised in the optimisation process, is highlighted.

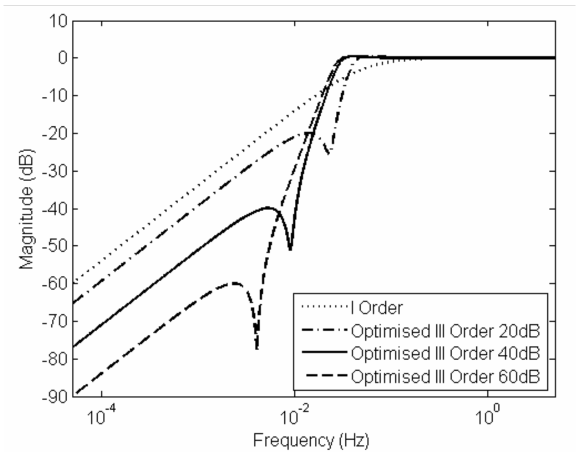


Fig. 4. Amplitude responses of the third order filters obtained by optimising the stop-band limit for different values of minimum required attenuation.

The magnitude responses of the optimised filters are illustrated in Fig. 4, in comparison with a 0.05Hz single pole filter. Even though the third order filters have far superior performances in the stop-band than the reference filter, it can be seen from Table I that their 3dB points are lower than 0.05Hz. This means that the input signals are passed unaltered over a wider frequency range than in the case of the 0.05Hz single pole system. Therefore, while the stop-band limit has been maximised, the transition region has also been narrowed by the optimisation procedure at the expense of a reduced cut-off frequency.

### *B. 3dB Point Optimisation*

The optimisation aimed at maximising the cut-off frequency of second and third order filters yields results that are independent of the stop-band attenuation $A_s$. Table II summarises the outcomes of the procedure for three different types of filters and it can be noticed that the 3dB points of the optimised filters are all higher than 0.05Hz. The amplitude responses of these filters and that of the 0.05Hz first order system are shown in Fig. 5. The optimised second order filter is characterised by an attenuation that is up to 4.5dB higher than that of the 0.05Hz single pole filter, over the stop-band and most of the transition region. On the other hand, the magnitude curves of the third order filters converge to the response of the reference filter for attenuations of higher than 10dB.

From Table II it can be calculated that the 3dB point of the system with a monotonically changing magnitude is 37% higher than that of the concave filter. However, Fig. 6 shows that the attenuation curve for the first filter tends to level out at frequencies immediately lower than the 3dB point. Therefore, the concave filter may be preferred if a better rejection is required at the higher end of the transition region, because of the larger steepness of its magnitude response in the cut-off region.

TABLE II

CUT-OFF OPTIMISATION RESULTS

| Filter Type | 2nd Order | 3rd Order Concave | 3rd Order Monotonically Increasing |
|---|---|---|---|
| $f_{3dB}$ (Hz) | 0.068 | 0.090 | 0.123 |
| $f_{20dB}$ (Hz) | 0.009 | 0.005 | 0.005 |
| $f_{40dB}$ (Hz) | $8.5 \cdot 10^{-4}$ | $5.0 \cdot 10^{-4}$ | $5.0 \cdot 10^{-4}$ |
| $f_{60dB}$ (Hz) | $8.5 \cdot 10^{-5}$ | $5.0 \cdot 10^{-5}$ | $5.0 \cdot 10^{-5}$ |
| p (rad/s) | -0.655±0.344i | -0.188<br>-0.602±0.732i | -0.256<br>-0.271±0.927i |
| z (rad/s) | 0<br>-1.025 | 0<br>-0.557±0.478i | 0<br>-0.237±0.838i |

The 3dB point, which has been maximised, is highlighted.

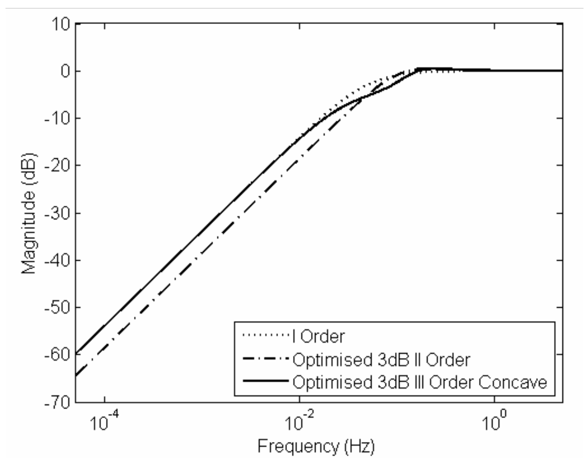


Fig. 5. Magnitude responses of the second and third order filters determined through the optimisation of the 3dB point.

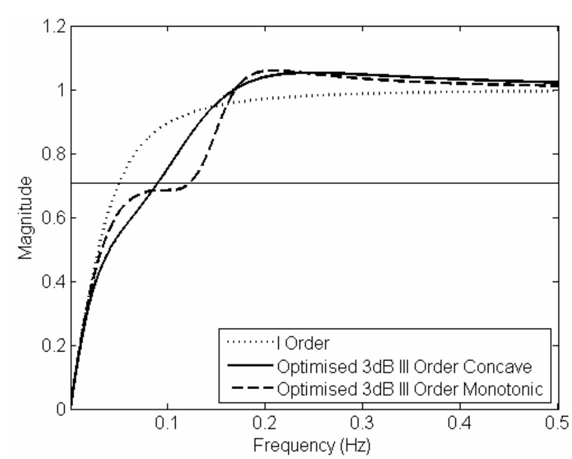


Fig. 6. Amplitude responses of the filters with optimised cut-off point shown on a linear scale graph limited to frequencies lower than the ECG spectrum. The thin continuous line represents the 3dB attenuation level.

## V. Discussion

The optimisation of the filter stop-band limit leads to a system with a cut-off frequency lower than 0.05Hz. The employment of such a filter can be justified by the presence of high intensity interference at frequencies lower than 0.03Hz. However, since limited information is available on the noise and interference in ECG measurements [6], especially for frequencies lower than 0.05Hz, the results achieved through the optimisation of the filter 3dB point seem more relevant. In fact, both second and third order filters have better rejection properties than the reference single pole filter and no detrimental change can be seen in the magnitude responses of the optimised filters. If a stop-band attenuation higher than that of the 0.05Hz first order system is desired, a second order filter with cut-off frequency lower than 0.068Hz or a third order filter with 3dB point between this frequency and 0.090Hz can be implemented. Alternatively, if the cut-off frequency is considered the most valuable characteristic of the system, a third order filter with 3dB point as high as 0.123Hz can be constructed.

It should be pointed out that not all the constraints imposed on the filter characteristics are equally critical for the optimisation outcome. In particular, the condition on the displacement from the isoelectric line of the response to the rectangular pulse is tightly matched by all the optimised systems, meaning that this requirement is primarily determining the filter properties.

A Monte Carlo simulation for a 5% tolerance in the transfer function coefficients for the concave third order filter obtained from the 3dB point optimisation has been performed. The peak in the magnitude response can be as high as 1.1dB and exceeds the 0.5dB limit in approximately 40% of cases. The bound on the pulse response undershoot is violated approximately 60% of cases, with the maximum offset from the isoelectric line being 120μV. On the other hand, the cases in which the constraints are greatly exceeded are limited. Only 6% of the amplitude peaks are higher than 0.8dB and less than 9% of the curves show offsets larger than 110μV. In order for the hardware implementation to have sufficient accuracy, the optimisation procedure should be re-run with stricter conditions for the limit on the magnitude response and the bound on the pulse response undershoot. Parameters $b_1$ and $a_1$ in (1) appear to be very critical and the tolerance of the circuit components generating these values should be kept to a minimum.

## VI. Conclusion

It has been shown that it is possible to design an analogue high-pass filter for ECG monitoring applications directly from the magnitude and pulse response requirements detailed in international standards. A process has been described for determining an optimised transfer function for second and third order filters. When the 3dB point is maximised, the result of the procedure is a system having better rejection characteristics than the traditional 0.05Hz first order filter.

Tests will be carried out on simulated ECG waves and on actual electrocardiographic recordings to evaluate if morphological modifications are introduced by the proposed systems into the signal and, in particular, into ST segments and T waves. The fidelity criterion for visual reading described in the 1990 AHA Recommendations [5] will be considered as the benchmark to assess the performance of the filters.

Attention will then be directed at the implementation of the filters obtained from the 3dB point optimisation. For both the second and third order systems it will be necessary to realise a general biquadratic function. Circuit structures allowing the coefficients of the transfer function to be individually controlled are available in the literature [7]. These networks generally contain three operational amplifiers, thus limiting the filter power consumption. Moreover, the possibility of implementing the biquadratic network using a Friend circuit topology [8], which employs a single operational amplifier, will be explored. A sensitivity analysis will be carried out in order to evaluate the robustness of the different designs and choose the circuit configuration for the hardware construction.

Furthermore, the possibility of designing higher order filters is being considered. It is expected that a fifth order system, when properly optimised, will perform better than a third order one. However, if the maximisation of the cut-off frequency is to be attempted, it will be beneficial to analytically derive the space of solutions satisfying all the constraints. An alternative is to define the fifth order filter as a combination of a second and a third order system, each of them independently optimised.

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