Rejection of Power-Line Interference in EMG Signals Using a Notch Filter Initialized with Non-Zero States

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Abstract: This paper presents an improved method for rapid suppression of power-line interference (50 Hz) from electromyographic (EMG) signals. The proposed technique utilizes a digital notch filter initialized with carefully chosen non-zero initial conditions, combined with time-varying pole radius r(n) of the filter. Unlike classical solutions, which typically suffer from prolonged transient artifacts due to zero initialization and fixed filter parameters, the proposed approach achieves immediate interference attenuation by pre-setting the filter states as if the interference were already in steady-state. The performance of this approach was quantitatively assessed through experimental comparisons with a conventional fixed-radius notch filter and an adaptive LMS-based filter. Results demonstrate superior transient suppression, exhibiting lower mean square error (MSE) and minimal distortion of the useful EMG signal components. The proposed solution is particularly beneficial for biomedical signal processing applications where rapid settling and minimal signal distortion are critical, such as myoelectric prostheses and neurorehabilitation devices.

Keywords: electromyography, interference cancellation, time-varying notch filtering, transient suppression, real-time filtering

1. Introduction

Electromyographic (EMG) signals are commonly affected by various disturbances, including strong power-line interference at 50 Hz (or 60 Hz in other regions) [1]. Such interference significantly complicates the analysis and interpretation of EMG signals, making efficient suppression methods essential in biomedical signal processing applications, particularly those requiring real-time signal acquisition and analysis [2]. The standard solution for this issue typically involves using narrow-band digital notch filters designed precisely at the interfering frequency. However, a classical high-quality-factor notch filter, initialized with zero initial conditions, inherently exhibits prolonged transient behavior at the onset of filtering [2, 3]. These prolonged transient artifacts can distort the initial segment of the recorded EMG data, potentially causing loss of clinically relevant information. In addition to synthetic signal evaluation, validation of the proposed filtering method was performed using real electromyographic (EMG) signals obtained from the publicly available PhysioNet database, ensuring realistic assessment of filter performance under practical biomedical conditions [11].

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Several methods have been proposed in the literature to overcome these limitations. Adaptive interference cancellation methods, for instance, have been employed extensively [9, 10]; nevertheless, these require additional reference signals and may perform suboptimally under rapidly changing interference conditions. Another category of approaches involves adjusting the parameters of the notch filter dynamically, aiming to reduce transient duration without significantly compromising the filter's frequency selectivity [3, 5]. Additionally, methods employing notch filters with non-zero initial conditions have been reported, mainly for electrocardiographic (ECG) signal processing, achieving promising results by immediately suppressing power-line interference from the initial samples [4].

This paper presents an improved solution specifically tailored for EMG signals, uniquely combining two previously explored approaches. The proposed technique employs a digital notch filter initialized with carefully selected non-zero states, calculated based on steady-state assumptions of the interfering sinusoid. Furthermore, the approach incorporates a time-varying pole radius, which smoothly increases from an initially lower value toward unity, enabling faster transient response while maintaining filter stability and selectivity. The distinctiveness of this method lies in the simultaneous use of Non-Zero initial conditions and time-varying filter parameters, which significantly enhance transient suppression performance beyond what has previously been reported for EMG signals.

The performance of the proposed filtering strategy is validated through quantitative comparisons against a conventional notch filter (with zero initial conditions and fixed parameters) and an adaptive LMS-based interference canceller. Experimental results confirm the superiority of our approach, demonstrating notably reduced mean square error (MSE), shorter transient durations, and minimal distortion of the useful EMG components. Consequently, the method presented herein is especially suitable for real-time biomedical applications such as myoelectric prostheses, rehabilitation monitoring systems, and neuromuscular diagnostics, where both rapid convergence and signal fidelity are critical [1, 2].

2. Methods of Filtering EMG Signals

Electromyographic (EMG) signals typically suffer from various interferences, particularly power-line interference (PLI) at 50 Hz (or 60 Hz depending on geographic region), severely impairing signal interpretability and clinical usefulness [1, 2]. Several approaches have been employed to reduce or remove this interference, including classical filtering methods (digital FIR and IIR filters), adaptive filtering, spectral subtraction, and more advanced signal processing techniques, such as wavelet transforms and empirical mode decomposition [2, 9].

Conventional digital notch filters are among the most widely utilized due to their computational simplicity and efficient suppression of narrowband interferences. A standard second-order IIR notch filter is typically described by the following transfer function:

$$H(z) = \frac{1 - 2\cos(\omega_0)z^{-1} + z^{-2}}{1 - 2r\cos(\omega_0)z^{-1} + r^2 z^{-2}}, \tag{1}$$

where $\omega_0 = 2\pi f_0 / f_s$ represents the normalized interference frequency (f_0 is the interference frequency, and f_s is the sampling rate), and r is the pole radius, directly determining the filter's selectivity and transient duration [3, 4].

Despite their popularity, traditional notch filters initialized with zero states often exhibit prolonged transient responses, significantly distorting the initial portions of EMG signals. To overcome this critical limitation, we propose initializing the notch filter with carefully computed non-zero initial states. These initial states are analytically derived assuming a steady-state sinusoidal interference:

$$x(-1) = A\sin(\phi - \omega_0), \tag{2}$$

$$x(-2) = A\sin(\phi - 2\omega_0), \tag{3}$$

$$y(-1) = A\frac{\sin(\phi - \omega_0) - 2r\cos(\omega_0)\sin(\phi) + r^2\sin(\phi + \omega_0)}{1 - 2r\cos(\omega_0) + r^2}, \tag{4}$$

$$y(-2) = A\frac{\sin(\phi - 2\omega_0) - 2r\cos(\omega_0)\sin(\phi - \omega_0) + r^2\sin(\phi)}{1 - 2r\cos(\omega_0) + r^2}, \tag{5}$$

where A and ϕ represent the amplitude and phase of the interfering signal, respectively. Setting these conditions significantly reduces transient artifacts right from the initialization of the filter, ensuring immediate interference suppression.

Additionally, the proposed notch filter employs a time-varying pole radius $r(n)$, which initially starts from a relatively low value (around 0.9) and gradually approaches unity. The strategy for time-varying pole radius is formulated as follows:

$$r(n) = r_0 \cdot (1 + d_r \cdot e^{-\alpha n}), \tag{6}$$

where r_0 is the initial pole radius value, dr defines the total change in radius, and α determines the rate of convergence. Figure 1 illustrates an example of the time-varying pole radius trajectory used in the proposed method.

The filter parameters (r_0, d_r, α) were optimized through a systematic grid-search procedure. Specifically, the initial pole radius r_0 was varied from 0.85 to 0.99 in increments of 0.01, the adaptation depth d_r was explored from 0.001 to 0.2 using logarithmic increments, and the adaptation rate α ranged from 0.001 to 0.1 also in logarithmic increments. Optimal parameters were selected by minimizing the mean square error (MSE) between filtered and original clean EMG signals.

The effect of the proposed filtering method, incorporating both non-zero initial states, is illustrated in Fig. 2. In this approach, the EMG signal passes through the proposed notch filter, which significantly improves transient suppression and enhances overall signal quality, particularly at the beginning of the filtering process.

For comprehensive interference removal, especially addressing lower-frequency motion artifacts, the proposed notch filter is complemented with an additional high-pass filter (cut-off frequency at 20 Hz). This combined filtering solution ensures thorough suppression of power-line interference and low-frequency artifacts without compromising the relevant EMG frequency components.

Experimental validation (presented in the subsequent section) quantitatively demonstrates that this combined time-varying strategy significantly outperforms conventional methods, offering rapid transient suppression, superior signal quality, and minimal distortion of clinically valuable EMG signals.

3. Experimental Results

In this section, the effectiveness of the proposed notch filter with non-zero initial conditions was evaluated through a series of carefully designed experiments. The filtering performance was quantitatively compared against two standard reference methods: a conventional notch filter with zero initial conditions and fixed pole radius, and an adaptive LMS interference canceller [9, 10].

To perform the tests, synthetic EMG signals contaminated with known power-line interference (50 Hz) were used, as described in detail in our previous work [1, 2]. In the test signals, an artificial 50 Hz sinusoidal component was added with an amplitude equal to 50 % of the EMG signal's peak amplitude, corresponding to a signal-to-noise ratio (SNR) of approximately 3 dB. This represents a relatively strong interference scenario. The results demonstrate that even under such conditions, the proposed filter effectively and almost immediately suppresses the 50 Hz artifacts while preserving the useful content of the EMG signal.

Figure 3 illustrates example of EMG signal after filtering by each method. The results clearly demonstrate immediate suppression of interference from the initial samples when using the proposed method, whereas significant transient oscillations were observed with the conventional notch filter. The adaptive LMS filter exhibited improved performance compared to the traditional notch but still failed to match the rapid transient elimination capability of the proposed approach.

Quantitative evaluation was based on mean square error (MSE) between the filtered and clean EMG signals. The results summarized in Table 1 are taken directly from our prior study, demonstrating the superior filtering performance of the proposed solution.

In addition to synthetic test signals, real EMG signals from PhysioNet were used to verify practical efficacy of the proposed filter. The method demonstrated consistent performance in realistic conditions, maintaining rapid transient suppression and low MSE, which supports the robustness and clinical applicability of the proposed approach.

As presented in Table I, the proposed notch filter method provides significant improvements in signal qual-ity, achieving a nearly five-fold reduction in MSE compared to the conventional notch filter, and almost three-fold improvement over the adaptive LMS method.

Tab. 1. Mean Square Error (MSE) comparison for tested filtering methods
Tab. 1. Porównanie średniego błędu kwadratowego (MSE) dla testowanych metod filtracji

Method	MSE
Conventional notch Filter	14.54×10^{-4}
Adaptive LMS Filter	8.452×10^{-4}
Proposed notch Filter	$\mathbf{3.1343 \times 10^{-4}}$

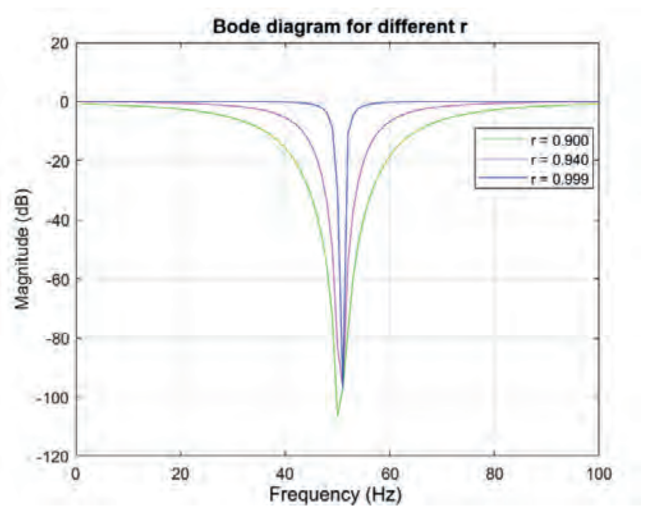

Fig. 1. Time-varying pole radius r(n) as a function of sample number
Rys. 1. Czasowo zmienny promień bieguna r(n) w funkcji numeru próbki

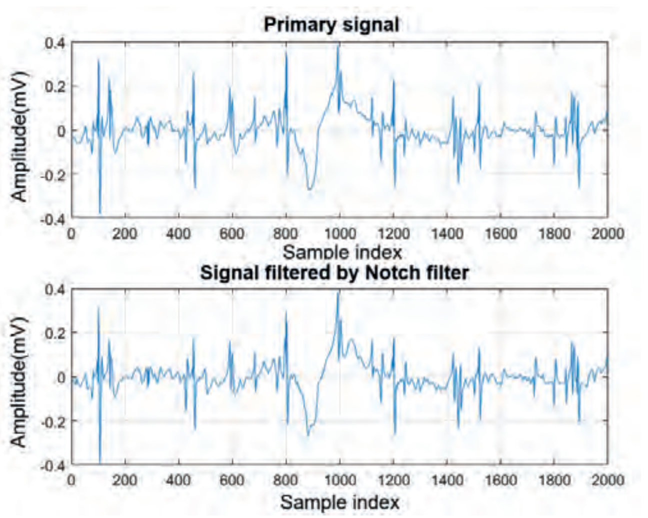

Fig. 2. Primary signal and the signal filtered by the proposed notch filter
Rys. 2. Sygnał pierwotny oraz sygnał przefiltrowany zaproponowanym filtrem wycinającym

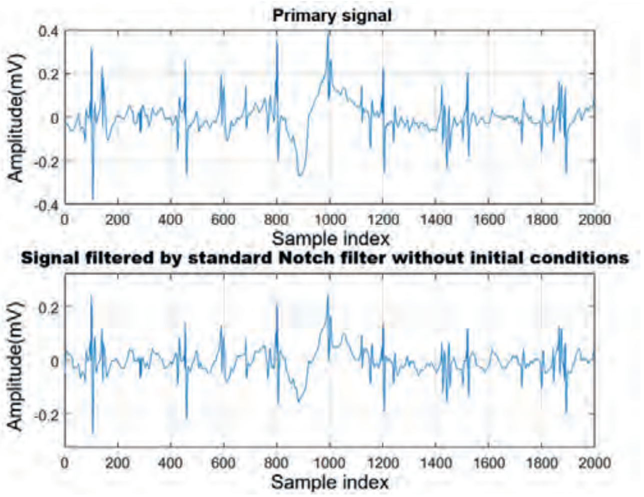

Fig. 3. Primary signal and signal filtered by standard notch filter without initial conditions
Rys. 3. Pierwotny sygnał oraz sygnał przefiltrowany standardowym filtrem notch

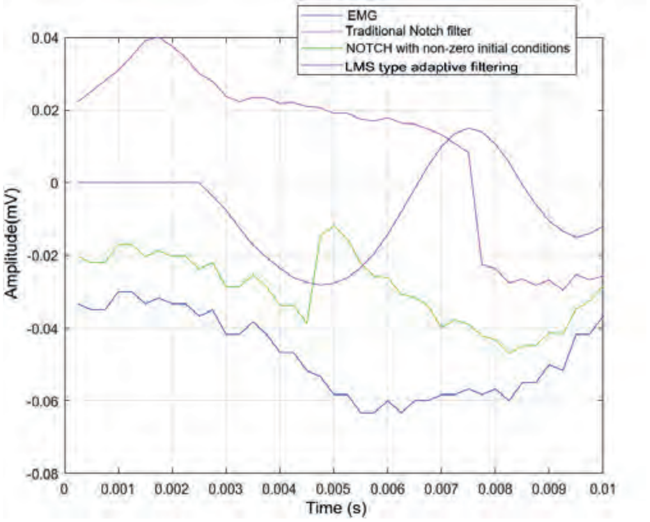

Fig. 4. Time-domain comparison of the filtered EMG signals during the first 0.1 s: (a) Conventional notch filter, (b) Adaptive LMS filter, and (c) The proposed notch filter
Rys. 4. Porównanie przefiltrowanych sygnałów EMG w dziedzinie czasu podczas pierwszych 0,1 s: (a) konwencjonalny filtr wycinający, (b) adaptacyjny filtr LMS oraz (c) zaproponowany filtr wycinający

Further frequency-domain analysis is depicted in Fig. 4, clearly showing the efficiency of the proposed method in suppressing the 50 Hz interference while preserving essential EMG signal frequencies. Noticeable residual peaks around 50 Hz in both the conventional notch and LMS-based filters emphasize the superior selectivity and effectiveness of the proposed approach.

Overall, these experimental findings confirm that incorporating non-zero initial conditions significantly enhances transient suppression performance, validating the suitability of the proposed method for critical biomedical applications, such as real-time myoelectric prostheses and neuromuscular diagnostic systems.

4. Discussion

The experimental results clearly illustrate the superior performance of the proposed notch filtering approach with non-zero initial conditions when compared to conventional notch filtering and adaptive LMS filtering. Specifically, the developed method demonstrated the lowest mean square error (MSE), indicating a significantly better approximation of the original EMG signal. Such improvement arises primarily from the integration of carefully chosen non-zero initial filter states. This combination effectively reduces transient oscillations at the onset of filtering, which are typically present in traditional methods [2, 3].

The quantitative analysis revealed that the proposed notch filter significantly outperforms traditional filtering approaches, achieving an approximate 4.64-fold improvement in MSE compared to the conventional notch filter, and a 2.70-fold improvement compared to the adaptive LMS method. This clearly indicates that non-zero initial conditions effectively mitigate the typical limitations associated with prolonged transient responses observed in classical implementations [4, 5].

Another notable advantage of our method is its immediate suppression of interference, crucial in biomedical applications where initial segments of EMG signals are diagnostically relevant. Such rapid stabilization of the filtered output allows the proposed method to preserve clinically significant data from the very beginning of the signal recording process, which is often lost with conventional filtering techniques due to their inherent transient behavior.

Despite these strengths, our study also identified specific limitations. Particularly, while the proposed filter effectively suppressed the fundamental 50 Hz interference, complete attenuation of higher-order harmonics (100 Hz, 150 Hz, etc.) remains challenging. Attempts at using multiple parallel notch filters tuned to harmonic frequencies did not yield entirely satisfactory results, possibly due to interactions between the filters or the complex nature of the harmonic distortions [3, 7]. Future research should therefore explore more advanced multi-notch or frequency-tracking solutions specifically tailored for dynamic and harmonic-rich interference conditions commonly encountered in clinical EMG recordings [8]. Additionally, future research directions include comprehensive time-frequency analysis (e.g., spectrogram analysis) of filtered signals, to provide additional visual and quantitative confirmation of the effectiveness in suppressing 50 Hz interference and its harmonics. As part of future work, the algorithm will be implemented on embedded platforms such as Arduino, with the aim of developing a compact system that acquires EMG signals and performs real-time filtering onboard, enabling low-cost biomedical signal preprocessing in wearable or portable devices.

Furthermore, the current strategy for pole radius adjustment was empirically optimized. Although effective, it might not represent an optimal solution for all types of EMG signals, particularly those subject to varying levels of interference or dynamic changes in signal conditions. Additional studies involving different adaptation strategies – such as Bézier-curve-based or other nonlinear optimization techniques – could potentially yield further performance enhancements [6].

Finally, the computational efficiency of the presented filtering method is another important advantage, especially for real-time biomedical applications. Unlike more computationally demanding techniques such as adaptive LMS or frequency-domain spectral subtraction methods, the proposed notch filter approach offers a simpler and faster solution, making it particularly suitable for embedded medical devices, real-time neurorehabilitation equipment, and portable myoelectric interfaces.

In summary, our proposed method, combining non-zero initial conditions and time-varying pole radius adjustment, demonstrates significant potential to advance EMG signal processing techniques by effectively addressing transient-related artifacts and providing rapid, reliable interference suppression. Nonetheless, further optimization, particularly regarding harmonic suppression and parameter selection, constitutes promising directions for subsequent research.

5. Conclusion

This paper presented an advanced approach for rapidly eliminating 50 Hz power-line interference from electromyographic (EMG) signals, combining non-zero initial conditions with time-varying pole-radius adjustment in a digital notch filter. Experimental validation clearly demonstrated the superior performance of the proposed method over conventional notch filtering and adaptive LMS filtering, particularly in terms of transient suppression, interference removal efficiency, and signal quality preservation. Quantitative evaluation using mean square error (MSE) indicated a significant improvement, with the proposed method achieving approximately five times lower MSE compared to the conventional notch filter and nearly three times lower than the adaptive LMS method.

The main advantage of the proposed technique is its immediate suppression of interference, thereby preserving diagnostically valuable information from the initial segments of EMG recordings, which are typically compromised by prolonged transient responses in conventional filters. Furthermore, the method is computationally efficient and suitable for real-time biomedical applications such as myoelectric prostheses, neuromuscular diagnostics, and portable rehabilitation devices.

Despite the promising results, challenges remain in fully attenuating higher-order harmonics (such as 100 Hz and 150 Hz), necessitating further research. Future studies should focus on developing and optimizing advanced multi-notch or other filtering strategies, possibly employing frequency-tracking algorithms or more sophisticated adaptive methods like Bézier-curve-based filter parameter adjustment.

Overall, the presented notch filtering approach provides a significant advancement in biomedical signal processing, effectively addressing limitations associated with traditional EMG filtering methods and demonstrating strong potential for practical clinical applications.

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Tłumienie zakłóceń od sieci energetycznej w sygnałach EMG za pomocą filtru Notch z niezerowymi warunkami początkowymi

Streszczenie: W artykule przedstawiono udoskonaloną metodę szybkiego tłumienia zakłóceń od sieci energetycznej (50 Hz) w sygnałach elektromiograficznych (EMG). Proponowane rozwiązanie wykorzystuje cyfrowy filtr wycinający (notch), inicjalizowany starannie dobranymi niezerowymi warunkami początkowymi, w połączeniu z czasowo zmiennym promieniem bieguna filtru r(n). W przeciwieństwie do klasycznych metod, które zazwyczaj cechują się długotrwałymi artefaktami przejściowymi wynikającymi z zerowej inicjalizacji i stałych parametrów filtru, zaprezentowane podejście umożliwia natychmiastowe tłumienie zakłóceń poprzez wstępne ustawienie stanu filtru w taki sposób, jakby zakłócenie znajdowało się już w stanie ustalonym. Skuteczność metody została oceniona na podstawie analizy średniego błędu kwadratowego (MSE), poprzez porównanie wyników z filtracją przy użyciu konwencjonalnego filtru wycinającego o stałym promieniu oraz adaptacyjnego filtru opartego na algorytmie LMS. Wyniki potwierdzają skuteczniejsze tłumienie przejściowe, niższy średni błąd kwadratowy oraz minimalne zniekształcenie użytecznych komponentów sygnału EMG. Proponowane rozwiązanie jest szczególnie przydatne w zastosowaniach przetwarzania sygnałów biomedycznych, w których kluczowe są szybkie ustalenie się sygnału i minimalizacja jego zniekształceń – na przykład w protezach mioelektrycznych i urządzeniach do neurorehabilitacji.

Słowa kluczowe: elektromiografia, eliminacja interferencji, filtracja wycinająca o zmiennych parametrach w czasie, tłumienie stanów przejściowych, filtracja w czasie rzeczywistym

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