IAES International Journal of Artificial Intelligence (IJ-AI)
Vol. 14, No. 3, June 2025, pp. 2433~2443
ISSN: 2252-8938, DOI: 10.11591/ijai.v14.i3.pp2433-2443

An adaptive window function based on enhanced cuckoo search optimization for finite impulse response filter design

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Article Info

Article history:

Received May 13, 2024
Revised Nov 21, 2024
Accepted Jan 27, 2025

Keywords:

FIR filter
Optimization
Signal processing
Spectral characteristics
Window function

ABSTRACT

This study introduced a modern approach involving an adaptive window function with the enhanced cuckoo search optimization (ECSO) algorithm for optimizing the finite impulse response (FIR) filter design by dynamically adjusting window parameters. This proposed method enhanced spectral performance, and improved accuracy, resolution, and reliability in spectral analysis. A mathematical model was developed for the adaptive window function, and the original cuckoo search optimization (CSO) algorithm was enhanced through adaptive step-size adjustment. Results demonstrated better spectral characteristics with narrower main lobes, lower sidelobes, and enhanced stopband attenuation, indicating computational efficiency, versatility, and robustness. Comparative analysis showed that the adaptive window function outperformed Kaiser, Gaussian, Tukey, and Chebyshev windows, exhibiting superior frequency selectivity, uniform amplitude response within the passband, and improved signal fidelity with reduced interference from neighboring frequency bands. Additionally, it demonstrated lower leakage factors, indicating reduced spectral leakage and better confinement of signal energy within the desired frequency range. This advancement in FIR filter design holds promise for various signal processing tasks and real-time applications, marking a significant milestone in signal processing innovation.

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1. INTRODUCTION

In signal processing, accurate spectral analysis is paramount for understanding the underlying characteristics of signals and extracting meaningful information. Window functions play a critical role in spectral analysis by shaping the frequency content of signals during transformation processes such as the Fourier transform. These are mathematical functions that are used to taper the impulse response of the filter to minimize certain undesirable characteristics, such as spectral leakage and ripple in the frequency domain. Spectral leakage occurs due to the inherent periodicity of the discrete Fourier transform (DFT) applied to finite-length signals. The DFT implicitly assumes that the signal repeats infinitely, leading to discontinuities at the signal boundaries, which manifests as leakage. Window functions are designed to mitigate spectral leakage by tapering the signal towards zero at its edges, reducing discontinuities, and suppressing side lobes in the frequency domain. Hence, the selection of window function significantly affects the trade-off between the main lobe width and the level of sidelobes in the frequency response of digital filters.

The heavy interest in improving the spectral characteristics of window functions provides new avenues for various signal processing applications. Traditional window functions exhibit spectral leakage, where energy from the main lobe spills into adjacent frequency bins, leading to inaccuracies in frequency estimation and distortion of spectral content. Improving spectral characteristics helps minimize spectral leakage, resulting in more accurate spectral representations. Spectral characteristics affect the frequency resolution of signal analysis techniques such as fourier transform and spectrogram analysis. Optimizing window functions to have narrower main lobes and lower side lobes, frequency resolution can be enhanced, enabling the differentiation of closely spaced frequency components in the signal that contain fine spectral structures that require high-resolution analysis. Improving spectral characteristics of window functions can result in better acquisition of these fine structures, allowing for detailed analysis and interpretation of signal features. In many engineering systems and real-time signal processing applications, accurate spectral analysis is essential for system design, performance evaluation, and deployment. Improving spectral characteristics ensures that the analysis results reflect the true characteristics of the signals under investigation.

Window functions are extensively used to resolve the trade-offs between various aspects of filter performance, including frequency response characteristics, spectral leakage, and time-domain properties. These are essential tools in the design of finite impulse response (FIR) filters and are widely used in applications such as signal processing [1], communications, audio processing [2], and image processing. Window functions are employed to truncate the infinite impulse response (IIR) of an ideal filter to obtain a finite-length impulse response suitable for practical implementation. However, traditional window functions like rectangular, Hamming, Hanning, and Blackman have inherent limitations that vary across specific applications such as the spectral characteristics that includes spectral leakage, poor frequency resolution, and high side lobe levels, which can distort the analysis results and hinder the interpretation of signal features. Several studies were conducted using fixed window functions such as rectangular, Hamming [3], Hanning, and Blackman [4] to analyze the spectral characteristics of these window functions in the design of FIR filter models. However, some limitations arise because of uncontrolled parameters due to its closed-form expression. For these reasons, various papers have explored adjustable window functions such as the well-known Kaiser and Gaussian [5], raised semi-ellipse windows [6], and other proposed variable window functions as presented in the works of [7]–[13]. Additionally, comparative studies were also conducted using combinations of existing window functions such as the works of [10] which is a combination of Blackman-Harris, Hamming, and Gaussian window, the hybrid of Blackman and Lanczos [14], combination of Hamming, Blackman-Harris, Chebwin, and Kaiser [11], and the product of Hamming and Gaussian to provide better suppression in the stopbands than single implementation designs. Furthermore, new and improved window functions were also presented in several literatures such as the study of [13] concatenation of trigonometric functions, and semi-ellipse window [15]. Although these combinations and modifications have enhanced the traditional window functions and increased the performance of digital filter design because of the adjustable parameters that control the trade-offs and manipulate the impulse response, still the window function should be specifically tailored to the requirement of the specific application to achieve optimal results. However, tailoring it to meet the design requirement has always been a challenge for designers to achieve optimum filter performance. The recent approach introduces metaheuristic optimization techniques in FIR filter designs such as those presented in the review papers of [16], [17] has gained popularity in the field of digital filter design. Some of these studies use ant colony optimization [18], firefly algorithm [19], grasshopper optimization [20], [21], whale optimization [22] to determine the optimal values of the filter coefficients to achieve desirable impulse response. However, reducing the error between the actual response and the desired response remains a challenge.

To address this gap, an adaptive window functions that dynamically adjust its parameters to optimize spectral characteristics based on the characteristics of the input signal is proposed in this study. This adaptive approach that is based on the integration of the enhanced cuckoo search optimization (ECSO) algorithm offers the potential to enhance spectral performance by tailoring the window function to better match the signal properties, leading to improved accuracy, resolution, and reliability in spectral analysis. This study generally aims to develop an adaptive window function based on ECSO for improved FIR filter design. Specifically, this study aims to i) derive the mathematical model for the adaptive window function; ii) develop the algorithm for the ECSO; iii) evaluate the spectral characteristics of the adaptive window function optimized through comparative simulation; iv) validate the results through FIR filter design. This study introduced an innovative approach by proposing an adaptive window function for FIR filter design, leveraging the ECSO algorithm. This proposed methodology offers several significant contributions to the field of signal processing.

The integration of the ECSO algorithm that efficiently optimizes window function parameters is presented in this study to enhance the filter design process. Unlike traditional fixed window functions, this adaptive approach dynamically adjusts its parameters based on the input signal, ensuring optimal performance for specific applications. This adaptability addresses traditional limitations and improves FIR filter design, resulting in better frequency response characteristics, reduced spectral leakage, and improved time-domain properties. The advancements significantly impact applications requiring precise spectral analysis, such as communications, audio processing, and image processing, facilitating more accurate system design, performance evaluation, and deployment.

2. PROPOSED METHOD

2.1. The adaptive window function

In order to design a window function that is tailored to the specific signal an adaptive window function is proposed in this study. The proposed adaptive window function is composed of two terms which are the Gaussian function which is widely used due to its smooth and symmetric properties and a cosine term which introduces oscillation within the window function.

$$Gaussian\ envelop(n) = exp\left(-\alpha \cdot \left(\frac{n-\frac{N-1}{2}}{N}\right)^2\right) \tag{1}$$

The term in (1) represents a Gaussian envelope that controls the decay of the window function towards its edges to minimize spectral leakage and achieve good frequency response characteristics. To make the window function adaptable, an additional parameter α is incorporated in the equation which determines the width of the window.

$$Cosine\ oscillation\ (n)\ = cos\ \beta\left(\frac{n-\frac{N-1}{2}}{N}\right) \tag{2}$$

Oscillations within the window function can help in shaping the frequency response and controlling sidelobe levels. The parameter β controls the frequency of these oscillations. This term represented in (2) introduces the ripples in the window function.

$$\frac{n-\frac{N-1}{2}}{N} \tag{3}$$

The term in (3) normalizes the time index n to ensure that the window is symmetric around its midpoint and within the range of $[0,1]$ where $\frac{N-1}{2}$ represents the center of the window. The adjustable parameters α and β that allow the window function can be specifically tailored to meet specific requirements such as side lobe suppression, transition bandwidth, and stopband attenuation through the manipulation of its main lobe width and sidelobe ripples. Hence, when two components are multiplied together the resulting expression will be in general form $w_A\ [n]$ can be expressed as (4).

$$w_A\ [n] = exp\left(-\alpha \cdot \left(\frac{n-\frac{N-1}{2}}{N}\right)^2\right) \cdot cos\ \beta\left(\frac{n-\frac{N-1}{2}}{N}\right) \tag{4}$$

Where $w_A[n]$ is the value of the window function at index n. α is the parameter that controls the width of the Gaussian function. β is the parameter that controls the frequency of the cosine modulation which determines the number of ripples. N represents the length of the window and is used to normalize the time index n

2.2. The enhanced cuckoo search optimization algorithm

The cuckoo search optimization (CSO) algorithm is a metaheuristic optimization algorithm inspired by the brood parasitism of certain cuckoo species. While CSO has proven to be effective for various optimization problems, there are several modifications and enhancements proposed in this study to improve its performance by using dynamic scaling factors or adaptive control parameters to regulate the step size. ECSO algorithm includes mechanisms for adapting the step size of Levy flights dynamically based on the local landscape of the search space. This allows for more efficient exploration and exploitation of the solution space compared to the original CSO, which typically uses a fixed step size.

3. METHODOLOGY

3.1. Comparative simulation of the adaptive window function

The spectral efficiency of window functions refers to their ability to shape the frequency response of a signal when multiplied with it in the time domain. To determine the spectral efficiency of the proposed window function it has been compared with common adjustable window functions such as Kaiser, Gaussian, Turkey, and Chebyshev windows in terms of main lobe width [23], ripple ratio [15], relative sidelobe attenuation, and leakage factor [24]. Moreover, a comparison of the magnitude response in the time and frequency domain was also determined at a certain window length for comparative evaluation of the spectral characteristics.

3.2. Comparative performance analysis of FIR filter using the adaptive window function

Different filter models were designed using Kaiser, Gaussian, Turkey, and Chebyshev windows to further evaluate the efficiency of the proposed adaptive window function in terms of mean square error (MSE), signal-to-noise ratio (SNR), and total harmonic distortion (THD) to assess its deviation from the ideal response. Likewise, the magnitude response was also analyzed to determine the filter characteristics in terms of passband ripples, transition bandwidth, and minimum stopband attenuation. The filter models were designed using the given specifications as shown in Table 1.

Table 1. Filter specification

Filter parameter	Value
Passband frequency	0 to 200 Hz
Stopband frequency	300 to 500 Hz
Passband ripple	0.1 dB
Stopband attenuation	60 dB
Transition width	$0.2\,\pi$
Filter length	100
Sampling frequency	10.00 Hz
Filter type	Bandpass

3.3. Mathematical structure of the enhanced cuckoo search optimization

The ECSO algorithm is designed to optimize FIR filter design by integrating an adaptive window function into its structure. This process involves a series of steps that symmetrically refine filter coefficients to achieve an optimal frequency response. The following sections outlines the key mathematical steps in ECSO, from initialization to iteration, ensuring that the optimization effectively balances different performance metrics.

3.3.1. Initialization

The optimization process begins by initializing a population of candidate solutions, referred to as nests. Each candidate solution represents a set of FIR filter coefficients that will be refined throughout the optimization process. Additionally, the algorithm initializes key parameters, such as the step size (α) and window shape parameter (β), which influence the adaptive window function used in shaping the frequency response. This initialization phase establishes the foundation for the optimization process by defining the search space and controlling the degree of exploration.

Initialization: initialize a population of candidate solutions (nests). Where each candidate solution $X_i = (x_{i1}, x_{i2}, \ldots, x_{id})$ represents a set of FIR filter coefficients. Initialize parameters for the adaptive window function: step-size α and window shape parameter β.

3.3.2. Objective function

To guide the optimization process, an objective function is defined to evaluate the quality of candidate solutions. The objective function considers multiple performance metrics, including main lobe width, sidelobe attenuation, passband ripple, and stopband attenuation. Each of these metrics is weighted to ensure that the optimization prioritizes different aspects of filter performance based on design requirements. By formulating the objective function in this manner, the algorithm can effectively assess and compare candidate solutions.

Define objective function values $f(\mathrm{X}, \alpha, \beta)$ which evaluates the fitness of the filter considering both the filter coefficients and the frequency response shaped by the adaptive window function. The objective function can be a weighted sum of these performance metrics: main lobe width (MLW), sidelobe attenuation (SLA), passband ripple (PBR), and stopband attenuation (SBA), and w are the weights that balance the importance of each metric.

$$f(\mathrm{X},\alpha,\beta) = w_1 \cdot MLW(\mathrm{X},\alpha,\beta) + w_2 \cdot SLA(\mathrm{X},\alpha,\beta) + w_3 \cdot PBR(\mathrm{X},\alpha,\beta) + w_4 \cdot SBA(\mathrm{X},\alpha,\beta) \quad (5)$$

3.3.3. Adaptation and Lévy flights

The ECSO algorithm employs an adaptive step-size mechanism to enhance convergence. The step size (α) is adjusted dynamically based on the difference between the best solution found so far and the current solution. This adaptive approach ensures that the algorithm explores the search space efficiently while focusing on promising regions. Additionally, the algorithm uses Lévy flights, a stochastic search strategy that enables candidate solutions to undergo long-distance jumps. This mechanism prevents premature convergence and enhances the algorithm's ability to escape local optima. Adjust the step-size α adaptively based on the current iteration t and the best solution found so far as in (6).

$$\alpha^{(t+1)} = \alpha^{(t)} \times \ exp\left(\frac{f(X_{best}) - f(X_i)}{f(X_{best})}\right) \quad (6)$$

3.3.4. Lévy flights

Lévy flights play a crucial role in generating new candidate solutions. These flights simulate a random walk behavior where step sizes are drawn from a Lévy distribution. This distribution is known for its heavy-tailed properties, which allow for both local and global exploration. By incorporating Lévy flights, the algorithm ensures a balance between exploiting good solutions and exploring new regions of the search space. Generate new candidate solutions using Lévy flights, which simulate the random walk behavior with step sizes drawn from a Lévy distribution as in (7).

$$X_i^{(t+1)} = X_i^{(t)} + \alpha^{(t)} \cdot \ L\acute{e}vy\ (\lambda) \quad (7)$$

3.3.5. Filter coefficients and adaptive window

Once new candidate solutions are generated, the adaptive window function is applied to refine the filter coefficients. The window function, parameterized by α and β, plays a critical role in shaping the frequency response of the FIR filter. This step ensures that the optimized filter coefficients are not only mathematically optimal but also practical for real-world applications.

Apply the adaptive window function to the filter coefficients as in (8).

$$h_{windowed} = X_i^{(t+1)} \cdot w(\alpha,\beta) \quad (8)$$

Here, $w(\alpha,\beta)$ is the adaptive window function parameterized by $\alpha\ and\ \beta$.

3.3.6. Evaluation and selection

After applying the adaptive window function, the new candidate solutions undergo fitness evaluation. The objective function is recalculated to assess the performance of the updated filter coefficients. To maintain diversity in the population, a fraction of the worst-performing solutions is replaced with new random solutions. This selection mechanism prevents premature convergence and ensures that the optimization continues to explore potential improvements.

Fitness evaluation: evaluate the objective function for each new candidate solution $X_i^{(t+1)}$ as in (9).

$$f\left(X_i^{(t+1)},\alpha^{(t+1)},\beta\right) = w_1 \cdot MLW\left(X_i^{(t+1)},\alpha^{(t+1)},\beta\right) + w_2 \cdot SLA\left(X_i^{(t+1)},\alpha^{(t+1)},\beta\right) + \\ w_3 \cdot PBR(X_i^{(t+1)},\alpha^{(t+1)},\beta) + w_4 \cdot SBA(X_i^{(t+1)},\alpha^{(t+1)},\beta) \quad (9)$$

Selection: replace a fraction of ρ_α of the worst solutions with new random solutions to maintain diversity in the population.

3.3.7. Iteration

The entire process from generating new solutions to evaluating and selecting candidates is repeated iteratively until convergence criteria are met. The algorithm continues refining the filter coefficients until it identifies an optimal solution that meets the desired performance metrics. By iterating through this structured optimization framework, the ECSO algorithm enhances FIR filter design through systematic exploration and adaptation. Repeat the process of generating new solutions, evaluating the objective function, and updating the population until the convergence criteria are met.

3.4. The FIR filter design algorithm

The presented algorithm in Figure 1 outlines the process of designing an FIR bandpass filter using the adaptive window function based on the ECSO algorithm, incorporating the mechanisms for exploration, exploitation, and adaptation to find the optimal filter coefficients that meet the desired filter specifications in Table 1. The adaptive window function is applied to the filter coefficients obtained from Lévy flights to shape the frequency response of the filter according to the desired characteristics. This ensures that the parameters of the adaptive window function (α and β) are adjusted appropriately based on the desired filter response. The objective function evaluates the fitness of the filter considering both the filter coefficients and the frequency response shaped by the adaptive window function.

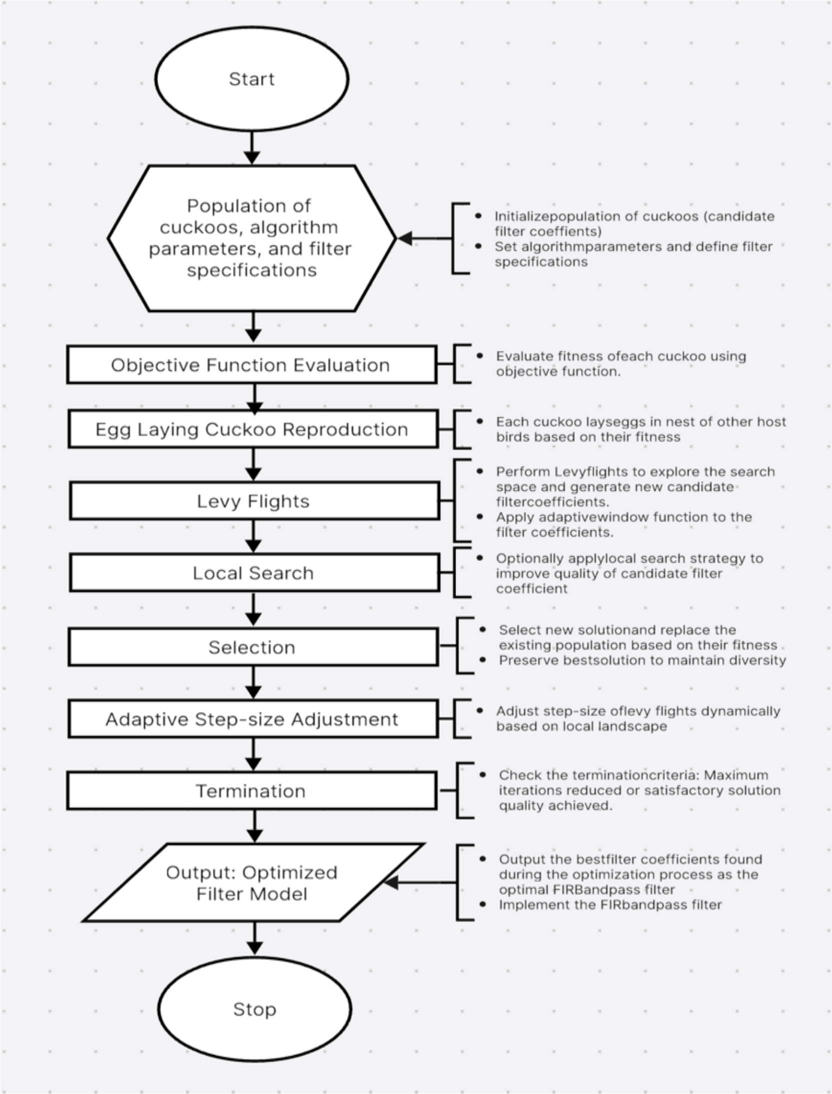

Figure 1. Flowchart of the FIR bandpass filter design algorithm

4. SIMULATION RESULTS

4.1. Spectral characteristics of the window function

Results of the comparative simulations as shown in Figure 2 illustrate that the proposed window function based on the ECSO algorithm is designed to adaptively shape its frequency response to meet specific design requirements. Afridi *et al.* [11] reported that by adjusting the two variables, designers can optimize the trade-off between the filter’s transition width and side lobe attenuation. This case was also observed in the suggested window function, thus allowing it to yield its unique shape, which is determined by the parameters α and β and optimized using the ECSO algorithm which balances the main lobe width, sidelobe level, and transition characteristics according to the optimization criteria. Results further revealed that the Kaiser window exhibits a main lobe with relatively low sidelobe levels which offers a trade-off between main lobe width and sidelobe attenuation that is controlled by the parameter β which is also dominantly observed in the studies conducted by [5], [25].

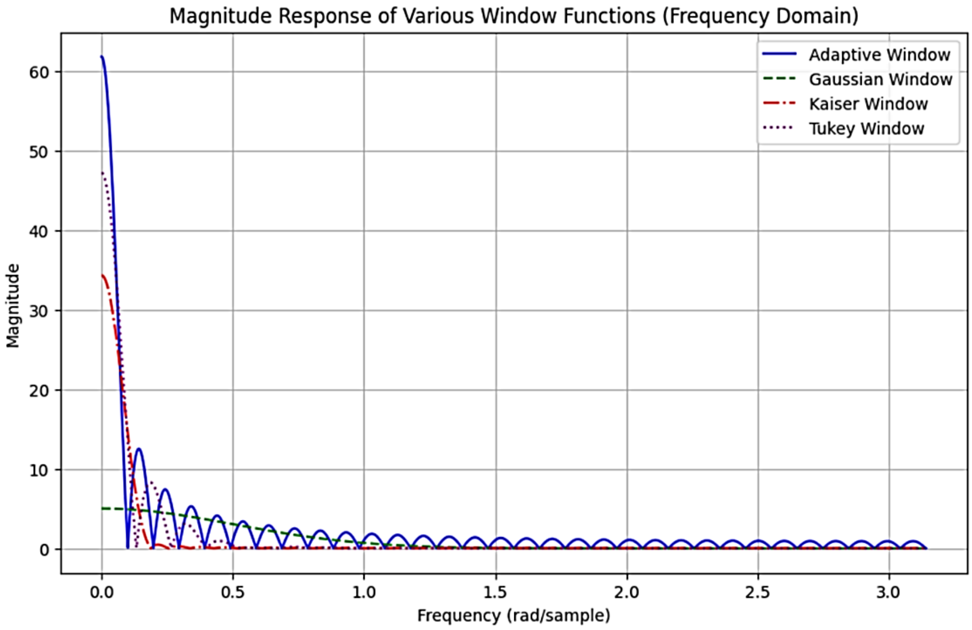

Figure 2. Frequency domain response of different window functions

Likewise, the Gaussian window has a smooth and symmetric shape with rapid attenuation of sidelobes and shows a smooth main lobe with very low sidelobes. The Chebyshev window achieved an extremely sharp transition between passband and stopband with high sidelobe suppression and showed a narrow main lobe with a very steep transition and extremely low sidelobes which indicates excellent frequency domain characteristics but potentially at the cost of a wider main lobe. However, the Tukey window which combines the characteristics of the rectangular and Hann (raised cosine) windows exhibits moderate sidelobe levels which offer the balance between main lobe width and sidelobe attenuation.

Figure 3 illustrates the time domain response of the adaptive window function, showcasing its remarkable localization around the central peak, indicative of minimal signal spreading. Its adaptability enables precise manipulation of the window shape, resulting in well-defined mainlobes and minimal sidelobes. Compared to other adjustable window functions presented in [6], the raised semi-ellipse window function excels in reducing sidelobes, but the adaptive window function achieves comparable sidelobe suppression while maintaining superior control over main lobe width and transition characteristics, thus providing a more balanced spectral performance. Likewise, the proposed window function exhibits superior time-domain characteristics, making it ideal for applications necessitating precise temporal resolution and minimal signal distortion. The Kaiser window demonstrates acceptable localization around the central peak but may feature slightly broader main lobes and higher sidelobes than the adaptive window function, potentially distorting signals with sharp transitions. The Gaussian window offers a smooth time-domain response with a well-defined central peak but may have broader main lobes and higher sidelobes compared to the adaptive window function, particularly for signals requiring precise representation. The Tukey window allows customization of main lobe width and sidelobe levels but may not achieve the same level of localization and sidelobe suppression as the adaptive window function, especially for signals with strict temporal precision requirements.

The Chebyshev window excels in sidelobe attenuation. But may introduce ripples in the time-domain response, affecting signal fidelity. The results confirmed that the adaptive window function provides precise control over window shape, minimizing signal spreading and ensuring well-defined main lobes with suppressed sidelobes, making it the preferred choice for applications requiring accurate signal representation while minimizing distortion.

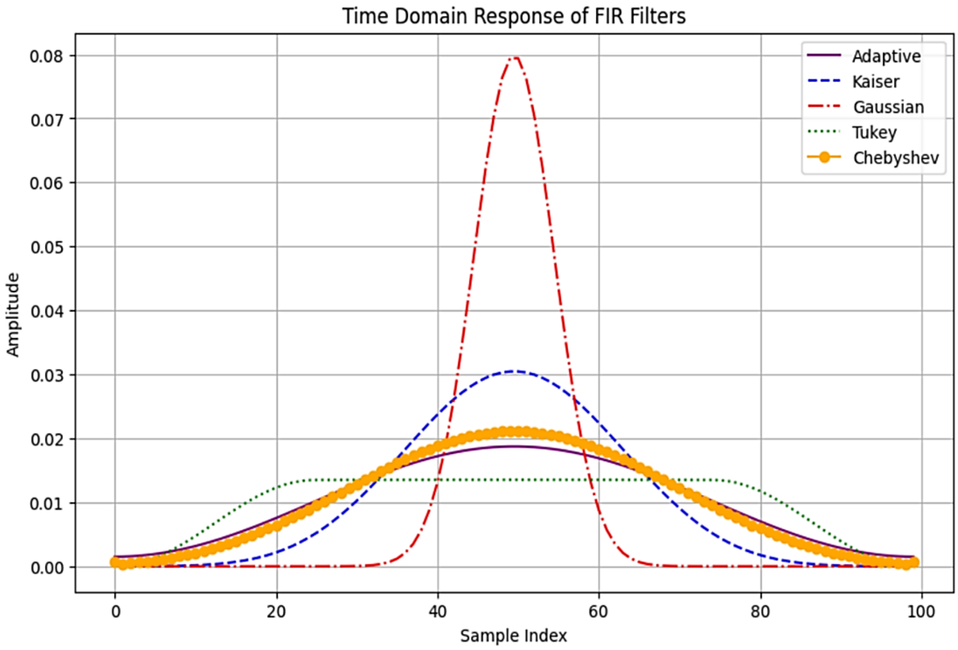

Figure 3. Time domain response of different window functions

Table 2 compares the spectral properties of the adaptive window function, emphasizing its dominance over traditional adjustable windows like Kaiser, Gaussian, Tukey, and Chebyshev. The adaptive window offers precise control over the main lobe width, surpassing Kaiser and Gaussian windows, which offer lesser flexibility. It minimizes passband ripple, ensuring superior signal fidelity compared to Chebyshev windows. While Kaiser and Gaussian windows provide smoother passband but may not match the ripple reduction of the adaptive window. The adaptive window achieves comparable sidelobe attenuation as compared with the traditional windows as shown in the results obtained. Chebyshev windows exhibit similar sidelobe suppression but may compromise the passband ripple. The adaptive window was able to minimize spectral leakage as evidenced by the low leakage factor, enhancing frequency localization, and reducing interference compared to other windows with higher leakage levels, leading to potential signal distortion.

Table 2. Comparison of the spectral properties of the different window function

Window function	Mainlobe width (Hz)	Ripple ratio (dB)	Sidelobe attenuation (dB)	Leakage factor
Kaiser	2,307.75	32.77	1.0	7.86
Gaussian	5,958.36	22.52	1.0	21.63
Turkey	1,263.29	49.49	1.0	4.14
Chebyshev	1,621.39	46.00	1.0	5.29
Adaptive window function	1,452.29	18.74	1.0	4.68

4.2. FIR bandpass filter characteristics

4.2.1. Spectral properties

The magnitude response of the FIR filter designed using the adaptive window function was illustrated in Figure 4 and compared with filters designed using Kaiser, Gaussian, Turkey, and Chevyshev windows. The Kaiser window exhibits a smooth and symmetric shape with a gradual tapering towards the edges which is characterized by a parameter (β) that controls the trade-off between main lobe width and sidelobe levels. Meanwhile, the Kaiser window shows a smooth curve that gradually decreases towards the edges, indicating a tapering effect. Likewise, the Gaussian window has a bell-shaped curve with rapid decay towards zero at the edges which offers excellent sidelobe suppression and smooth transition characteristics. Moreover, the Tukey window combines characteristics of the rectangular and Hann (raised cosine) windows that have a flat top region with tapered edges, controlled by a parameter (α) that determines the ratio of the flat top to the tapering towards the edges offering a balance between main lobe width and sidelobe levels.

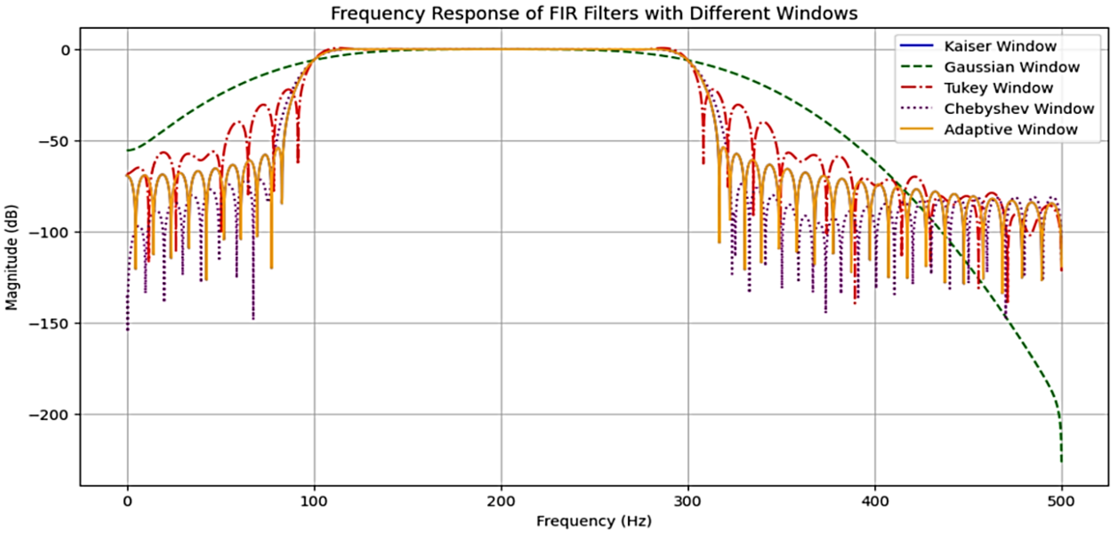

Figure 4. Magnitude response of the FIR bandpass filter designed using different window functions

4.2.2. Performance evaluation

The performance evaluation of the filter models is presented in Table 3 which depicts the filter characteristics of the FIR bandpass filter designed using the adaptive window and different adjustable window functions. The FIR bandpass filter designed using the adaptive window (ECSO-based) exhibits the lowest MSE similar to Kaiser and Chebyshev windows. Likewise, the adaptive window function obtained a THD value of 8.2 which is the lowest among other windows, indicating superior accuracy and lower distortion compared to other filters. The Kaiser window filter also performs well in terms of MSE and THD but has a higher leakage factor as compared with the adaptive window filter. The Gaussian, Tukey, and Chebyshev window filters show higher MSE and THD values compared to the adaptive and Kaiser window filters. The adaptive window filter also demonstrates the highest SNR, indicating better preservation of signal quality relative to noise. Lastly, the results of the comparison validate that the integration of optimization algorithms such as those presented in [19] improves the spectral characteristics of digital FIR filters. Therefore, for this specific application, the adaptive window filter designed using the ECSO algorithm appears to be the most suitable choice due to its superior performance in terms of accuracy, distortion reduction, and signal preservation.

Table 3. Comparison of the filter characteristics of the different window function

Window function	MSE	SNR	THD	Leakage factor
Kaiser	10	8.6	8.6	7.68
Gaussian	15	12.4	12.4	21.63
Turkey	20	15.3	15.3	4.14
Chebyshev	10	9.2	10.32	5.29
Adaptive window function	10	16.3	8.2	4.68

5. CONCLUSION

This study promoted a promising advancement in FIR filter design and signal processing by leveraging an adaptive window function integrated with the ECSO algorithm. Results demonstrated substantial improvements in spectral performance optimization through mathematical modeling, algorithm development, and comparative simulation. Likewise, the efficiency of the proposed approach in achieving narrower main lobes, lower sidelobe levels, and enhanced stopband attenuation was revealed. The adaptive window function based on the ECSO framework tended to have narrower main lobes compared to traditional window functions like Kaiser, Gaussian, Tukey, and Chebyshev. This narrower main lobe width indicated better frequency selectivity, enabling more precise filtering of desired frequency components. It achieved lower passband ripple compared to other adjustable window functions, meaning it could maintain a more uniform amplitude response within the passband, resulting in better signal fidelity for frequencies within the passband range and providing improved sidelobe attenuation. This implied that it could suppress unwanted frequency components outside the main lobe more effectively, leading to cleaner signal extraction and reduced interference from neighboring frequency bands. Lastly, the adaptive window function tended to exhibit lower leakage factors, indicating reduced spectral leakage, which meant it could better confine signal energy within the desired frequency range, minimizing spectral leakage into adjacent frequency bins.

FUNDING INFORMATION

The authors would like to express their sincere gratitude to Cavite State University for the financial support provided through the Small-Scale CvSU Research Grant (SS-CRG), which made this research possible. Likewise, the authors would like to extend our appreciation to the CvSU Knowledge Management Center for their invaluable assistance in processing the publication support. Their support and guidance have been instrumental in the successful completion of this study.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis

I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting

Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [NAF], upon reasonable request.

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