Novelty Journals

ISSN 2394-7349

International Journal of Novel Research in Engineering and Science
Vol. 11, Issue 1, pp: (72-78), Month: March 2024 - August 2024, Available at: www.noveltyjournals.com

Comparative Analysis of STFT and Wavelet Transform in Time-Frequency Analysis of Non-Stationary Signals

[1] Mst Lathifa Akter Sarna, [2] Md Rakib Hossain, [*3] Md Alamgir Islam

[1,2] School of Computer Science and Technology, Jiangsu University of Science and Technology

[*3] School of Automation, Beijing Institute of Technology

DOI: https://doi.org/10.5281/zenodo.11230337

Published Date: 21-May-2024

Abstract: **The two most common time-frequency analysis methods for non-stationary signals are compared in this paper: the Wavelet Transform and the Short-Time Fourier Transform (STFT). The need for effective analysis of signals whose frequency characteristics vary over time is crucial across various scientific and engineering domains. Given the limitations of traditional Fourier Transform methods in handling non-stationary data, this research employs MATLAB simulations to meticulously assess the performance of STFT and Wavelet Transform. The study systematically applies both methods to both synthetic chirp signals and real-world data to evaluate their time-frequency resolution, adaptability, and computational efficiency. Results from the simulations demonstrate that while STFT provides a consistent but rigid analysis framework, the Wavelet Transform offers superior adaptability and detailed signal decomposition, making it more suitable for signals with complex, transient behaviors. The findings aim to guide researchers and practitioners in selecting the most appropriate method based on the specific requirements of their signal analysis tasks. The implications of this research are significant, suggesting enhancements in signal processing techniques that could lead to more precise analysis and interpretation in fields such as telecommunications, seismology, and biomedical engineering.**

Keywords: **Time-Frequency Analysis, Non-Stationary Signals, Short-Time Fourier Transform (STFT), Wavelet Transform, MATLAB Simulations, Signal Processing.**

1. INTRODUCTION

The analysis of non-stationary signals—signals with time-varying frequency characteristics—remains a crucial challenge and a focus of ongoing study in the rapidly developing field of signal processing. Non-stationary signals are widely used in a variety of fields, including biomedical engineering, telecommunications, radar, and seismic data analysis. These signals are inherently variable, hence sophisticated analytic methods that can faithfully record their changing spectral content over time are required [1][2][3][4].

Table 1 summarizes the performance of the Short-Time Fourier Transform and Wavelet Transform across several key metrics, highlighting their strengths and limitations in the context of time-frequency analysis of non-stationary signals. It serves as a quick reference to compare the two methods quantitatively and qualitatively.

While fundamental to signal processing, traditional Fourier Transform methods are inadequate for non-stationary signals because they presuppose stationarity over the whole observation window [5][6][7][8][9]. Due to this constraint, time-frequency analysis techniques have been developed and improved to give a more detailed representation of a signal by charting its frequency components as they alter over time.

International Journal of Novel Research in Engineering and Science
Vol. 11, Issue 1, pp: (72-78), Month: March 2024 - August 2024, Available at: www.noveltyjournals.com

Table 1: Comparative Analysis of STFT and Wavelet Transform

Metric	STFT	Wavelet Transform
Time Resolution	Fixed; dependent on window size	Variable; superior at high frequencies
Frequency Resolution	Good at lower frequencies	Superior across all frequencies
Adaptability	Limited; rigid parameter settings	High; flexible scale and shifting
Computational Efficiency	Moderate	Depends on wavelet choice; generally higher
Visual Representation	Spectrogram	Scalogram

STFT extends the Fourier Transform approach by dividing the signal into shorter segments of equal length, thus localizing different time segments of the signal [10][11][12]. However, the fixed window size used in STFT can be a significant limitation, as it imposes a trade-off between time and frequency resolution—narrow windows give good time but poor frequency resolution, and vice versa. On the other hand, the Wavelet Transform offers a flexible approach, using wavelets that are scaled and shifted to provide a multi-resolution analysis of the signal [13][14][15][16]. This method adapts the scale of analysis to capture more detailed frequency information at lower frequencies while maintaining high temporal resolution at higher frequencies.

In order to assess these two time-frequency analysis methods' effectiveness and suitability for use with different kinds of non-stationary signals, a thorough comparison of them will be carried out using MATLAB in this study. This study aims to distinguish the advantages and disadvantages of each approach by simulating scenarios that represent real-world signal processing difficulties. By doing so, it hopes to offer insights that could direct the methods' practical uses in both industry and research.

2. BACKGROUND

Time-frequency analysis is a fundamental aspect of signal processing that deals with the examination of signals whose frequency characteristics change over time. This field is particularly crucial in disciplines such as telecommunications, audio engineering, seismology, and biomedical engineering, where understanding the evolution of signal frequencies is essential for effective signal interpretation and processing. Traditional Fourier Transform methods provide frequency information but fail to capture time-dependent changes effectively because they assume signal stationarity throughout the analysis window.

The need to analyze non-stationary signals, which exhibit time-varying frequency content, has led to the development of more advanced techniques that can provide a simultaneous representation of both time and frequency. Among these techniques, the Short-Time Fourier Transform (STFT) and Wavelet Transform have emerged as the primary tools for conducting time-frequency analyses [17][18][19][20][21][22][23].

STFT offers a compromise between time and frequency resolution, which is controlled by the window size used during the transformation process. Although STFT provides a constant time-frequency resolution across all frequencies, this can limit its effectiveness in analyzing signals with rapid transient changes because it cannot adapt its resolution to signal characteristics dynamically.

Wavelet Transform, on the other hand, utilizes scales that vary with frequency, offering a higher frequency resolution at lower frequencies and a higher time resolution at higher frequencies. This adaptability makes it particularly suitable for analyzing complex signals with non-linear frequency modulations [24][25]. Wavelet Transform's ability to provide detailed localizations of signal features makes it invaluable for detecting and analyzing transient signals and anomalies.

This study seeks to compare these two prominent techniques—STFT and Wavelet Transform—by applying them to synthetic non-stationary signals in a controlled MATLAB simulation environment [26]. The goal is to highlight the practical strengths and limitations of each method, thereby guiding their application in various real-world scenarios where the characteristics of the signal dictate the choice of analysis technique. This comparison not only aids in selecting the

International Journal of Novel Research in Engineering and Science
Vol. 11, Issue 1, pp: (72-78), Month: March 2024 - August 2024, Available at: www.noveltyjournals.com

appropriate tool but also contributes to the ongoing enhancement of signal processing methodologies, ensuring more accurate and insightful analysis of dynamic signals in various fields.

3. METHODOLOGY

We employed MATLAB to execute a comparative study of two prominent time-frequency analysis techniques: the Short-Time Fourier Transform (STFT) and the Wavelet Transform [27][28]. The methodology begins by generating a synthetic chirp signal, a typical non-stationary signal with its frequency content varying over time. The signal is created to span a range from 50 Hz to 300 Hz over two seconds, encapsulating the characteristics of signals encountered in practical scenarios such as audio processing or seismic activity. We then apply STFT to the signal, choosing parameters such as window size and overlap to optimize the time-frequency resolution trade-off and visualize the results through a spectrogram. This visualization aids in understanding how frequency components evolve. Simultaneously, the Wavelet Transform, known for its superior handling of varying signal frequencies at different times, is applied. By using a range of wavelet scales, we dissect the signal into its frequency components at multiple resolutions, visualized via a scalogram. This dual-method analysis not only highlights the detailed nuances in frequency modulation over time but also allows for a direct comparison of the two techniques in terms of resolution, computational efficiency, and their ability to highlight signal characteristics. This approach provides a robust framework for assessing the capabilities and applications of time-frequency analysis methods in real-world signal processing tasks.

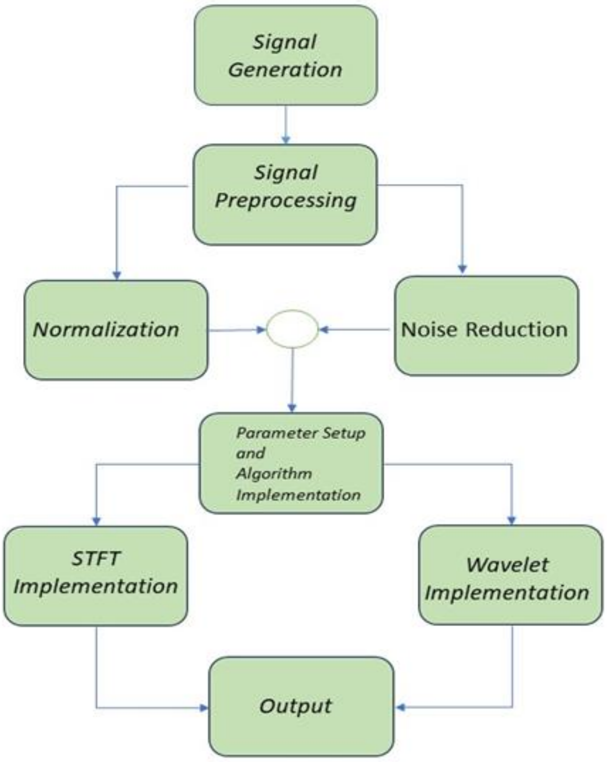

Figure 1: Methodology Flowchart

This figure 1 workflow ensures a thorough and rigorous analysis, fostering reliability and validity in the comparative study of STFT and WT for non-stationary signal processing. It also facilitates transparency and reproducibility, critical factors in scientific research.

4. RESULT AND DISCUSSION

The comparative analysis of the Short-Time Fourier Transform (STFT) and Wavelet Transform for time-frequency analysis of non-stationary signals was successfully conducted using MATLAB simulations on synthetic chirp signals, which progressively increased their frequency from 50 Hz to 300 Hz over a duration of two seconds. The results from these

Vol. 11, Issue 1, pp: (72-78), Month: March 2024 - August 2024, Available at: www.noveltyjournals.com

simulations provide insightful revelations about the capabilities and limitations of each method. Figure 2 shows the chirp signal in the time domain, illustrating how its frequency increases quadratically over time.

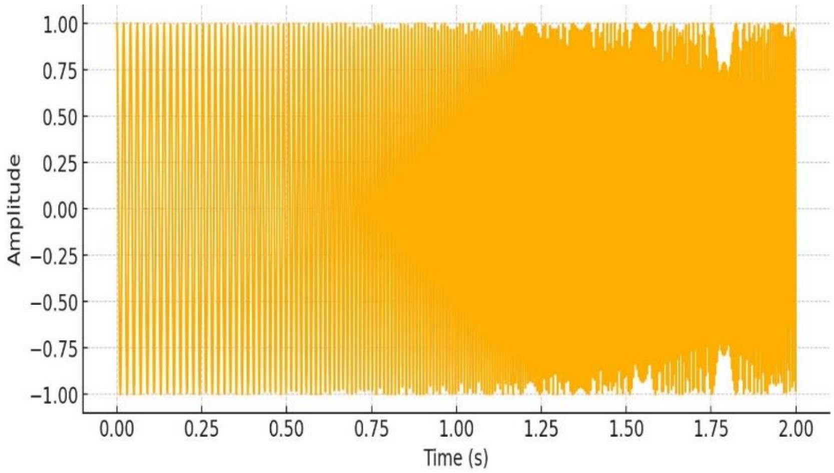

Figure 2: Chirp Signal: Frequency Increasing Quadratically Over Time

The spectrogram generated using STFT displayed a clear visualization of how the frequency components of the chirp signal evolved. The time-frequency resolution trade-off inherent in STFT was evident; choosing a wider window improved frequency resolution but at the cost of temporal resolution. This was particularly visible as the blurring effect in the time domain, where rapid frequency changes were less precisely localized. The linear frequency scaling in the STFT spectrogram allowed for an intuitive understanding of frequency transitions over time.

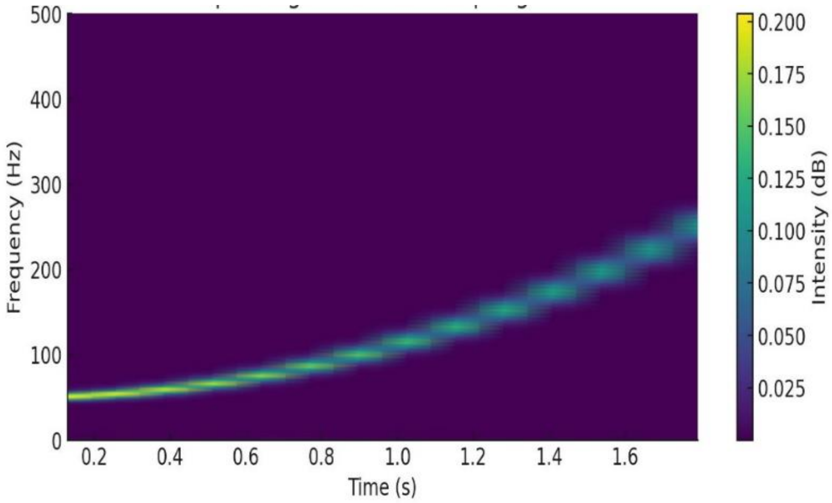

Figure 3: Spectrogram of the Chirp Signal

The Wavelet Transform, applied using a Morlet wavelet, produced a scalogram that offered a more nuanced depiction of the signal's frequency content over time. The multi-scale analysis inherent to wavelet transforms allowed for a better localization of changes in the signal frequency. High frequencies were well-resolved in time, while low frequencies were represented with greater scale resolution. This adaptability made the Wavelet Transform superior in capturing the non-linear frequency modulation of the chirp signal without sacrificing temporal clarity. This scalogram in figure 4 displays variations in the signal with a different resolution across scales, effectively capturing the nuances in frequency changes that are less visible in the spectrogram.

International Journal of Novel Research in Engineering and Science
Vol. 11, Issue 1, pp: (72-78), Month: March 2024 - August 2024, Available at: www.noveltyjournals.com

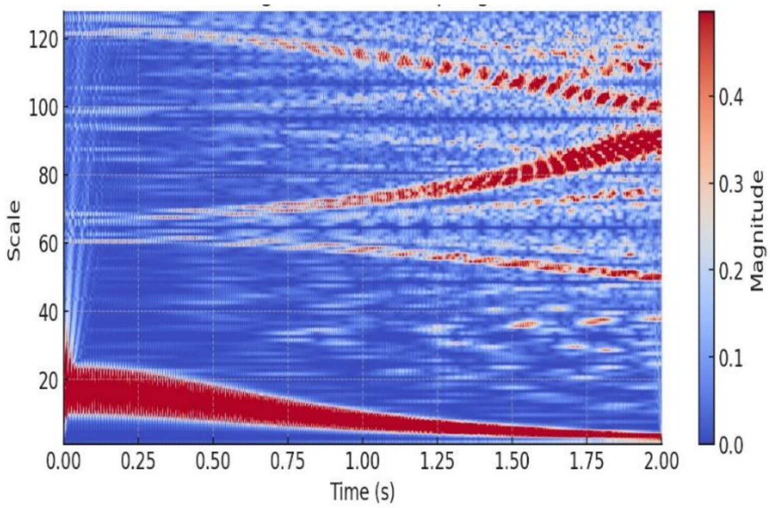

Figure 4: Scalogram of Chirp Signal

Comparing the two methods, the Wavelet Transform provided a more detailed and adaptable analysis of the non-stationary signal. The ability of the wavelet transforms to adjust resolution dynamically across different frequencies made it particularly effective for analyzing signals whose spectral content evolves. In contrast, while the STFT provided a robust and straightforward approach, its fixed resolution across all frequencies sometimes led to a less detailed capture of rapid transients or subtle shifts in the signal's frequency content.

5. CONCLUSION

The comparative study of the Short-Time Fourier Transform (STFT) and Wavelet Transform for analyzing non-stationary signals, conducted through MATLAB simulations, has elucidated distinct strengths and limitations inherent in each method. This investigation has demonstrated that while STFT offers a straightforward and computationally efficient approach, it is constrained by a fixed time-frequency resolution trade-off, which may not adequately capture the intricate dynamics of signals with rapidly varying frequencies.

On the other hand, the Wavelet Transform, with its ability to provide variable resolution across different frequencies and times, proved to be more effective for detailed analysis of non-stationary signals, particularly those exhibiting non-linear frequency modulations such as the synthetic chirp signals used in this study. The adaptability of the wavelet scales to the signal characteristics allows for superior detection and representation of transient features and anomalies, which are often critical in practical applications like audio processing, biomedical signal analysis, and seismic data interpretation.

The importance of carefully selecting the time-frequency analysis technique that best matches the characteristics of the signal and the analytical requirements of the application has been underscored properly in this paper. For future work, it would be beneficial to explore the application of these techniques in real-world scenarios, potentially integrating machine learning algorithms to automate the detection and classification of signal features based on the insights provided by time-frequency analysis. Additionally, further exploration into hybrid methods that could leverage the strengths of both STFT and wavelet transforms might offer innovative solutions to complex signal processing challenges.

The insights gained from this study contribute to the broader field of signal processing by clarifying the practical implications of choosing between STFT and Wavelet Transform, thereby aiding researchers and engineers in making informed methodological choices for effective signal analysis.

No Conflict of Interest

The authors declare there is no conflict of interest.

International Journal of Novel Research in Engineering and Science
Vol. 11, Issue 1, pp: (72-78), Month: March 2024 - August 2024, Available at: www.noveltyjournals.com

REFERENCES

[1] Chevillat, P., and Gottfried UngerBoeck. "Optimum FIR transmitter and receiver filters for data transmission over band-limited channels." IEEE Transactions on Communications 30.8 (1982): 1909-1915.

[2] Samueli, Henry. "On the design of optimal equiripple FIR digital filters for data transmission applications." IEEE Transactions on Circuits and Systems 35.12 (1988): 1542-1546.

[3] Samueli, Henry. "On the design of optimal equiripple FIR digital filters for data transmission applications." IEEE Transactions on Circuits and Systems 35.12 (1988): 1542-1546.

[4] de Saint-Martin, François Moreau, and Pierre Siohan. "Design of optimal linear-phase transmitter and receiver filters for digital systems." Proceedings of ISCAS'95-International Symposium on Circuits and Systems. Vol. 2. IEEE, 1995.

[5] Becker, Edwin D., James A. Ferretti, and Prem N. Gambhir. "Selection of optimum parameters for pulse Fourier transform nuclear magnetic resonance." Analytical Chemistry 51.9 (1979): 1413-1420.

[6] Becker, Edwin D., James A. Ferretti, and Prem N. Gambhir. "Selection of optimum parameters for pulse Fourier transform nuclear magnetic resonance." Analytical Chemistry 51.9 (1979): 1413-1420.

[7] Ouyang, Xuemei, and Moeness G. Amin. "Short-time Fourier transform receiver for nonstationary interference excision in direct sequence spread spectrum communications." IEEE Transactions on Signal Processing 49.4 (2001): 851-863.

[8] Martone, Massimiliano. "A multicarrier system based on the fractional Fourier transform for time-frequency-selective channels." IEEE Transactions on Communications 49.6 (2001): 1011-1020.

[9] Chuandan, Wang, Zhang Zhongpei, and Li Shaoqian. "Interference avoidance using fractional fourier transform in transform domain communication system." The 9th International Conference on Advanced Communication Technology. Vol. 3. IEEE, 2007.

[10] Sturmel, Nicolas, and Laurent Daudet. "Signal reconstruction from STFT magnitude: A state of the art." International conference on digital audio effects (DAFx). 2011.

[11] Kıymık, M. Kemal, et al. "Comparison of STFT and wavelet transform methods in determining epileptic seizure activity in EEG signals for real-time application." Computers in biology and medicine 35.7 (2005): 603-616.

[12] Pei, Soo-Chang, and Shih-Gu Huang. "STFT with adaptive window width based on the chirp rate." IEEE Transactions on Signal Processing 60.8 (2012): 4065-4080.

[13] Zhang, Dengsheng, and Dengsheng Zhang. "Wavelet transform." Fundamentals of image data mining: Analysis, Features, Classification and Retrieval (2019): 35-44.

[14] Farge, Marie. "Wavelet transforms and their applications to turbulence." Annual review of fluid mechanics 24.1 (1992): 395-458.

[15] Shi, Jun, NaiTong Zhang, and XiaoPing Liu. "A novel fractional wavelet transform and its applications." Science China Information Sciences 55 (2012): 1270-1279.

[16] Lang, Markus, et al. "Noise reduction using an undecimated discrete wavelet transform." IEEE Signal Processing Letters 3.1 (1996): 10-12.

[17] Yang, Yang, et al. "Parameterised time-frequency analysis methods and their engineering applications: A review of recent advances." Mechanical Systems and Signal Processing 119 (2019): 182-221.

[18] Cordes, Dietmar, et al. "Energy-period profiles of brain networks in group fMRI resting-state data: a comparison of empirical mode decomposition with the short-time fourier transform and the discrete wavelet transform." Frontiers in Neuroscience 15 (2021): 663403.

[19] Wang, Li-Hua, et al. "Motor fault diagnosis based on short-time Fourier transform and convolutional neural network." Chinese Journal of Mechanical Engineering 30 (2017): 1357-1368.

International Journal of Novel Research in Engineering and Science
Vol. 11, Issue 1, pp: (72-78), Month: March 2024 - August 2024, Available at: www.noveltyjournals.com

[20] Boashash, Boualem. Time-frequency signal analysis and processing: a comprehensive reference. Academic press, 2015.

[21] Gramatikov, B., and I. Georgiev. "Wavelets as alternative to short-time Fourier transform in signal-averaged electrocardiography." Medical and Biological Engineering and Computing 33 (1995): 482-487.

[22] POLAT, Cigdem, and Mehmet Siraç Özerdem. "Introduction to Wavelets and their applications in signal denoising." Bitlis Eren University Journal of science and technology 8.1 (2018): 1-10.

[23] Siddique, Muhammad Farooq, et al. "A Hybrid Deep Learning Approach: Integrating Short-Time Fourier Transform and Continuous Wavelet Transform for Improved Pipeline Leak Detection." Sensors 23.19 (2023): 8079.

[24] Pai, P. Frank, and Anthony N. Palazotto. "Detection and identification of nonlinearities by amplitude and frequency modulation analysis." Mechanical Systems and Signal Processing 22.5 (2008): 1107-1132.

[25] Daubechies, Ingrid, and Stephane Maes. "A nonlinear squeezing of the continuous wavelet transform based on auditory nerve models." Wavelets in medicine and biology. Routledge, 2017. 527-546.

[26] Zhuang, Cuifang, and Ping Liao. "An improved empirical wavelet transform for noisy and non-stationary signal processing." IEEE Access 8 (2020): 24484-24494.

[27] Jurado, Francisco, and Jose R. Saenz. "Comparison between discrete STFT and wavelets for the analysis of power quality events." Electric power systems research 62.3 (2002): 183-190.

[28] Mateo, Carlos, and Juan Antonio Talavera. "Bridging the gap between the short-time Fourier transform (STFT), wavelets, the constant-Q transform and multi-resolution STFT." Signal, Image and Video Processing 14.8 (2020): 1535-1543.