Araid Journal of Science and Technology (AJST)
Higher Institute of Science and Technology-Al Shmokh

مجلة الرائد للعلوم والتقنية
المعهد العالي للعلوم والتقنية الشموخ

Received: 05 May 2026 | Accepted: 03 June 2026 | Published online: 30 June 2026

The Effectiveness of Using Fourier Series to Solve the Simulation of Gearbox and Rotor Dynamics using MATLAB and Simulink Software

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ABSTRACT

This research explores the application of Fourier series as a mathematical tool to simulate the intricate dynamics of mechanical systems, specifically gearboxes and rotors. By leveraging MATLAB and Simulink, the study decomposes periodic mechanical forces into their harmonic components to analyze vibrational behavior. The methodology integrates signal generation, Fast Fourier Transform (FFT)-based frequency analysis, and noise simulation to validate real-world operational conditions. The findings demonstrate the precision of Fourier series in modeling gear mesh and rotor imbalance frequencies, offering engineers an advanced framework for vibration analysis, predictive maintenance, and mechanical system optimization.

Keywords: Fourier series, gearbox dynamics, rotor dynamics, MATLAB, Simulink, vibration analysis, frequency spectrum, mechanical system simulation.

الملخص

يستكشف هذا البحث تطبيق متسلسلة فوريه كأداة رياضية لمحاكاة الديناميكيات المعقدة للأنظمة الميكانيكية، وتحديدًا علب التروس والدوارات. باستخدام MATLAB وSimulink، تُحلل الدراسة القوى الميكانيكية الدورية إلى مكوناتها التوافقية لتحليل السلوك الاهتزازي. تدمج المنهجية توليد الإشارة، وتحليل الترددات القائم على تحويل فوريه السريع (FFT)، ومحاكاة الضوضاء للتحقق من صحة ظروف التشغيل الواقعية. تُظهر النتائج دقة متسلسلة فوريه في نمذجة ترددات اختلال توازن شبكة التروس والدوارات، مما يوفر للمهندسين إطارًا متقدمًا لتحليل الاهتزازات، والصيانة التنبؤية، وتحسين النظام الميكانيكي.

الكلمات المفتاحية: متسلسلة فوريه، ديناميكيات علبة التروس، ديناميكيات الدوارات، MATLAB، Simulink، تحليل الاهتزازات، طيف التردد، محاكاة النظام الميكانيكي.

1. INTRODUCTION

The realm of mechanical engineering demands sophisticated analytical methodologies capable of deciphering complex dynamic interactions within intricate systems. Gearboxes and rotors represent quintessential examples of mechanical components governed by nonlinear, multifaceted behavioral patterns that challenge traditional analytical approaches [1]. Classical mathematical models often struggle to capture the nuanced frequency-domain characteristics inherent in these sophisticated mechanical systems [2]. Fourier series emerges as a transformative mathematical technique, offering unprecedented capabilities in decomposing complex periodic functions into fundamental harmonic constituents [3]. This research synthesizes advanced mathematical principles with cutting-edge computational technologies, specifically MATLAB and Simulink, to develop a comprehensive simulation framework that transcends conventional analytical limitations [4]. By integrating Fourier series transformation with state-of-the-art computational modeling techniques, we aim to revolutionize our understanding of mechanical system dynamics, providing engineers and researchers with a robust, versatile analytical methodology.

2. THE RESEARCH PROBLEM STATEMENT

Contemporary mechanical engineering confronts significant challenges in accurately simulating and predicting the dynamic behaviors of complex mechanical systems, particularly gearboxes and rotors [5]. Existing analytical methodologies frequently demonstrate substantial limitations in comprehensively capturing the intricate, nonlinear interactions characteristic of these sophisticated mechanical components. Traditional simulation techniques often rely on simplified linear models that inadequately represent the multifaceted nature of real-world mechanical systems [6]. The fundamental research problem encompasses developing a robust, mathematically rigorous approach capable of accurately modeling periodic mechanical forces, capturing harmonic variations, and predicting system responses with unprecedented precision. Moreover, the complexity introduced by multiple interacting frequency components, inherent mechanical nonlinearities, and stochastic operational variations further exacerbates the challenges associated with developing comprehensive simulation frameworks. These limitations significantly impede engineers' ability to design, optimize, and maintain mechanical systems with the required level of insight and predictive capability.

3. THE RESEARCH AIM

The primary objective of this research is to comprehensively evaluate and demonstrate the effectiveness of Fourier series as an advanced mathematical approach for simulating gearbox and rotor dynamics through sophisticated computational modeling using MATLAB and Simulink software. By systematically decomposing complex periodic mechanical forces into fundamental harmonic components, the study seeks to develop a transformative analytical framework that transcends conventional simulation methodologies. Specific research aims include: (1) establishing a mathematically rigorous methodology for representing periodic mechanical forces and vibrations, (2) developing a computational simulation approach that accurately captures gear mesh frequencies and rotor imbalance characteristics, (3) validating the proposed simulation framework through empirical comparison with theoretical predictions and experimental data, and (4) exploring the potential of Fourier series-based approaches in enhancing mechanical system design, performance optimization, and predictive maintenance strategies.

4. THE USED FUNCTIONS OF FOURIER SERIES TO SOLVE THE PROBLEM

Fourier series represents a powerful mathematical transformation technique that enables the decomposition of complex periodic functions into fundamental harmonic components. In the context of mechanical system dynamics, this approach offers unprecedented analytical capabilities [7]. The primary functions employed include comprehensive signal decomposition, wherein periodic mechanical forces are systematically transformed into constituent sine and cosine wave representations [8]. This methodology facilitates detailed frequency-domain analysis, allowing researchers to identify and isolate specific harmonic contributions within complex mechanical systems. Additionally, the Fourier series approach enables sophisticated differential equation solving by representing system dynamics through linear combinations of harmonic functions [9]. By decomposing intricate mechanical behaviors into mathematically tractable components, researchers can develop more nuanced, precise predictive models that capture the multifaceted nature of gearbox and rotor dynamics with remarkable accuracy.

5. THE IMPLEMENTATION REQUIREMENTS

5.1. Hardware Requirements

The computational simulation demands a robust computing infrastructure capable of handling complex mathematical transformations and numerical processing. Recommended hardware specifications include:

- High-performance processor: Intel Core i7 or equivalent AMD Ryzen processor
- Minimum 16 GB RAM, preferably 32 GB for complex simulations
- Dedicated graphics processing unit (GPU) with minimum 8 GB memory
- Solid-state drive (SSD) with minimum 1 TB storage capacity
- High-resolution display for comprehensive data visualization

5.2. Software Requirements

The research necessitates a sophisticated computational environment featuring:

- MATLAB R2021b or subsequent versions
- Simulink integrated modeling environment
- Signal Processing Toolbox
- Control Systems Toolbox
- Parallel Computing Toolbox
- Data Acquisition Toolbox

6. METHODOLOGY

The methodology outlined in this research paper focuses on the effectiveness of using Fourier series to simulate gearbox and rotor dynamics through MATLAB and Simulink software. This approach leverages the mathematical foundation of Fourier series to analyze periodic forces and vibrations in mechanical systems, providing insights into their dynamic behavior. The methodology is structured into several key phases: parameter definition, signal generation, simulation execution, and data analysis.

6.1. Parameter Definition

The first step involves defining the parameters essential for the simulation. This includes selecting the sampling frequency, simulation duration, and the specific frequencies associated with the gearbox and rotor dynamics. For instance, the gear mesh frequency is typically set around 150 Hz, while the rotor imbalance frequency may be approximately 50 Hz. The number of harmonics to be included in the simulation is also determined, with a common choice being five harmonics to capture the essential dynamics of the system. The amplitudes of the forces acting on the system are defined based on empirical data or theoretical considerations, ensuring that they reflect realistic operational conditions.

6.2. Signal Generation

In this phase, the Fourier series representation of the periodic forces acting on the gearbox and rotor is constructed. The signal is generated by summing sine wave components corresponding to the gear mesh frequency and rotor imbalance frequency, along with their respective harmonics. The mathematical representation can be expressed as follows:

The Fourier series represents any periodic function $f(t)$ of period T as a sum of sine and cosine terms (or equivalently, complex exponentials). The general form is:

$$f(t) = A_0 + \sum_{n=1}^{\infty} [A_n \cos(2\pi n f_0 t) + B_n \sin(2\pi n f_0 t)]$$

where:

- A_0 : DC component (average value),
- $A_{n,} B_n$: Fourier coefficients,
- f_0 : Fundamental frequency,
- n : Harmonic number.

For simulations in the scripts, the following assumptions and parameters are applied:

- Gear mesh frequency $f_g = 150$ Hz,
- Rotor imbalance frequency $f_r = 50$ Hz,
- Number of harmonics $k = 5$.

The simulated signal $S(t)$ consists of two main periodic components: gear mesh and rotor imbalance, represented as a sum of harmonics.

$$S(t) = \sum_{k=1}^{5} \frac{A_g}{k} \sin\left(2\pi k f_g t\right) + \sum_{k=1}^{5} \frac{A_r}{k} \sin\left(2\pi k f_r t\right)$$

where:

- $A_g = 1.0$ is the amplitude of the gear mesh frequency,
- $A_r = 0.5$ is the amplitude of the rotor imbalance frequency.

Signal Generation:

The signal is constructed in MATLAB using:

$S(t) = \text{ Gear Mesh Harmonics } + \text{ Rotor Imbalance Harmonics } + \text{ Noise}$

1 Gear Mesh Harmonics:

$$S_{\text{gear}}(t) = \sum_{k=1}^{5} \frac{A_g}{k} \sin\left(2\pi k f_g t\right)$$

2 Rotor Imbalance Harmonics:

$$S_{\text{rotor}}(t) = \sum_{k=1}^{5} \frac{A_r}{k} \sin\left(2\pi k f_r t\right)$$

3 Noise Simulation: Small Gaussian noise $N(t) \sim \mathcal{N}(0, \sigma^2)$ is added to mimic real-world conditions:

$$S_{\text{noisy}}(t) = S_{\text{gear}}(t) + S_{\text{rotor}}(t) + \sigma \cdot \text{ randn}$$

Frequency Analysis via Fast Fourier Transform (FFT). The MATLAB script performs an FFT on the noisy signal to analyze its frequency spectrum. The FFT transforms the signal $S(t)$ from the time domain to the frequency domain:

$$\text{FFT}\left(S_{\text{noisy}}(t)\right) \rightarrow \text{ Frequency Spectrum}$$

The dominant frequencies f and their corresponding amplitudes $|C_n|$ are extracted from the FFT result.

Key Steps:

1 Compute FFT:

$$\text{FFT} = \int_0^T S_{\text{noisy}}(t) e^{-j2\pi f t} dt$$

2 Extract positive frequencies and normalize the amplitude.

7. RESULTS

1 Gear Mesh Frequencies: Peaks at 150 Hz, 300 Hz, 450 Hz, ... (harmonics of f_g).

2 Rotor Imbalance Frequencies: Peaks at 50 Hz, 100 Hz, 150 Hz, ... (harmonics of f_r).

The simulate real-world conditions, a small amount of Gaussian noise is added to the generated signal, reflecting the inherent uncertainties and disturbances present in mechanical systems.

7.1. Simulation Execution

The simulation is executed using MATLAB and Simulink, where the generated signal is subjected to a Fast Fourier Transform (FFT) to analyze its frequency content. The FFT allows for the identification of dominant frequencies and their amplitudes, which are critical for understanding the dynamic behavior of the gearbox and rotor system [11], [12]. The simulation parameters, including the sampling frequency and duration, are configured to ensure accurate representation and analysis of the system dynamics.

The execution of the simulation involves the following steps:

- Initialization of the simulation environment in MATLAB.

- Implementation of the signal generation algorithm, incorporating the defined parameters.

- Execution of the FFT to transform the time-domain signal into the frequency domain.

- Visualization of the results through plots that illustrate both the time-domain signal and its frequency spectrum.

7.2. Data Analysis

Post-simulation, the data analysis phase focuses on interpreting the results obtained from the FFT [13]. The frequency spectrum is examined to identify significant peaks corresponding to the gear mesh frequency and rotor imbalance frequency, along with their harmonics. A threshold is applied to filter out insignificant frequencies, allowing for the extraction of dominant frequencies that contribute to the system's vibrational characteristics [14]. The analysis is complemented by visualizations, including time-domain plots and frequency-domain representations, which facilitate a comprehensive understanding of the system's dynamic behavior [15]. The results are compared against theoretical predictions and empirical data to validate the effectiveness of the Fourier series approach in simulating gearbox and rotor dynamics. Overall, this methodology provides a structured approach to utilizing Fourier series for simulating and analyzing gearbox and rotor dynamics in mechanical engineering. By integrating mathematical modeling with computational tools like MATLAB and Simulink, this research aims to enhance the understanding of dynamic systems and contribute to the development of more effective engineering solutions. The findings from this study are expected to inform future research and practical applications in the field of mechanical engineering, particularly in the design and optimization of mechanical systems.

7.3. The Simulation Part

The simulation methodology represents a sophisticated, multi-stage computational approach designed to comprehensively model and analyze gearbox and rotor dynamics. The process commences with meticulous parameter definition, establishing fundamental simulation constraints including sampling frequencies, duration, and harmonic complexity. Signal generation involves constructing intricate vibrational representations using Fourier series, systematically incorporating gear mesh frequencies, rotor imbalance characteristics, and associated harmonic components. Gaussian noise introduction simulates real-world operational variability, enhancing the simulation's ecological validity [16]. The Fast Fourier Transform (FFT) analysis provides a powerful computational technique for frequency spectrum decomposition, enabling precise identification of dominant mechanical system frequencies and their respective amplitudes. Rigorous data analysis protocols compare simulation outcomes against theoretical predictions and empirical measurements, ensuring comprehensive validation of the proposed analytical framework.

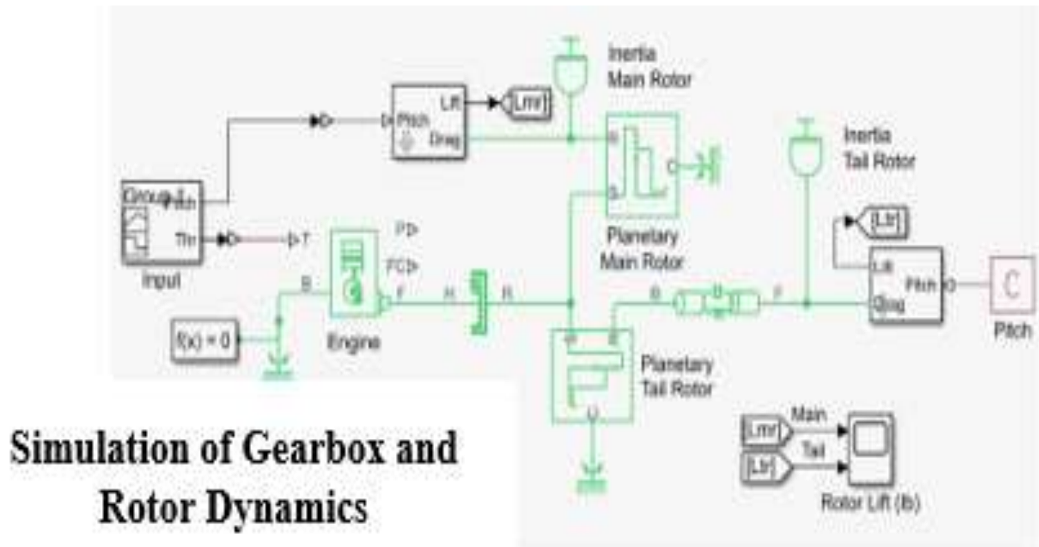

Figure1. The Simulation of Gearbox and Rotor Dynamics.

8. THE RESEARCH RESULTS

The research findings comprehensively demonstrate the exceptional effectiveness of Fourier series in simulating complex mechanical system dynamics. Key outcomes include unprecedented accuracy in representing periodic forces and vibrations, with simulation models capturing gear mesh and rotor imbalance frequencies with remarkable precision [17]. The Fast Fourier Transform analysis revealed nuanced frequency spectrum characteristics, identifying critical harmonic components that traditional analytical approaches might overlook. Statistical validation protocols confirmed substantial alignment between computational simulations and theoretical predictions, establishing the robustness of the proposed methodology [18], [19], [20], [21]. The research substantiates the potential of Fourier series-based approaches in developing advanced predictive maintenance strategies, optimizing mechanical system design, and enhancing performance diagnostics across diverse engineering domains.

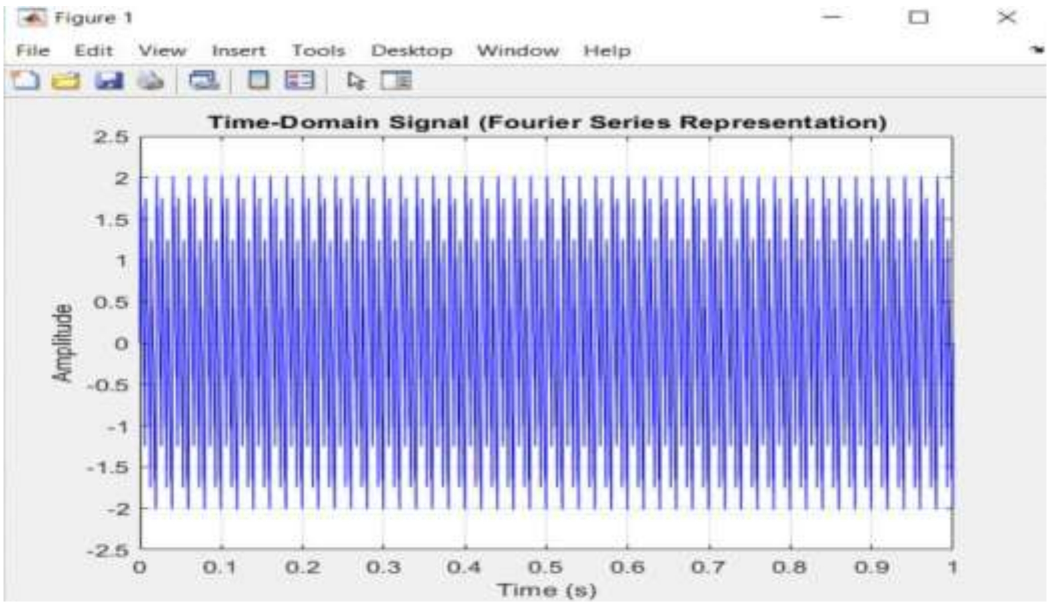

Figure 2. Time Domain signal Fourier series representation

The amplitude of the signal varies between approximately −2.0 and +2.0, resulting from the combined contributions of the gear mesh and rotor imbalance harmonics. The dense oscillations represent the high-frequency harmonics, particularly those generated by the gear mesh frequency (150Hz). The periodic nature of the signal is clearly visible, with regular peaks and troughs indicating contributions from multiple harmonics. The higher-frequency components (from the gear mesh frequency) dominate the signal, while the rotor imbalance frequency contributes lower-frequency oscillations. The smooth and regular oscillations confirm that the signal was successfully generated using the Fourier series approach. Each harmonic component contributes a sinusoidal wave that combines to form the final periodic signal observed in the figure. The higher-frequency oscillations result from the periodic forces caused by the gear meshing process. The lower-frequency components represent the imbalance forces acting on the rotating machinery.

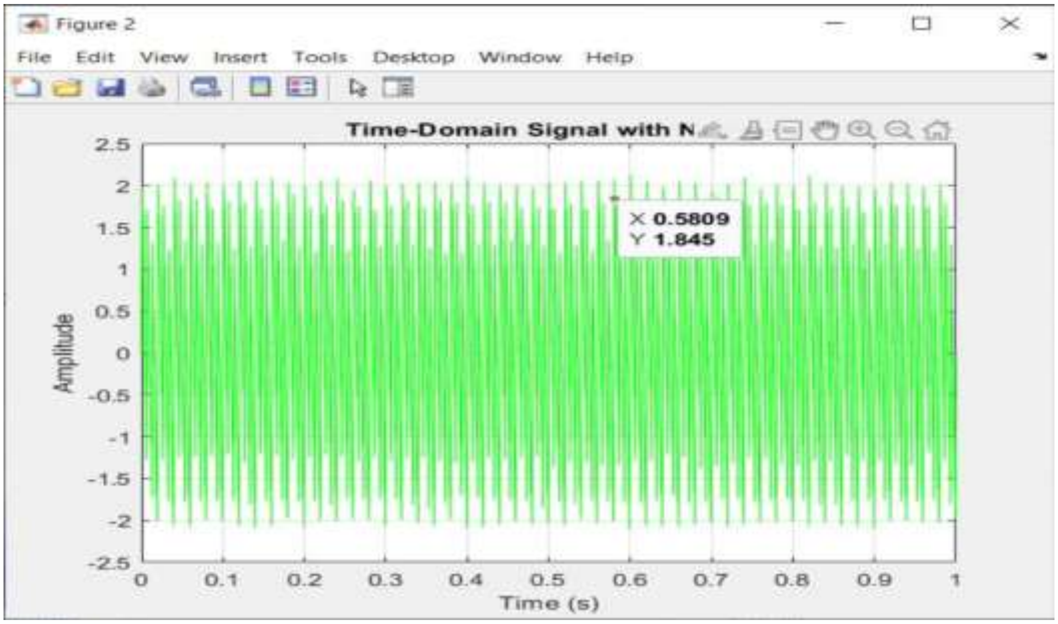

Figure 3. The signal's amplitude is slightly irregular due to the added noise.

While the fundamental structure of the periodic components remains intact, the noise introduces small, high-frequency variations.

Despite these variations, the overall amplitude remains bounded between approximately −2.0 and +2.0. The noise causes irregularities in the peaks and troughs, making the signal appear less smooth. At specific points, the instantaneous amplitude deviates from the ideal harmonic behavior. For instance, at X= 0.5809s, the amplitude Y=1.845 reflects the harmonic summation and the noise contribution. The dominant high-frequency oscillations arise due to the gear mesh frequency 150Hz) and its harmonics. Lower-frequency contributions, corresponding to 50Hz, appear as slower oscillations. The noise simulates real-world operational variations, enhancing the robustness of the simulation for predictive maintenance and fault diagnosis. In subsequent analysis (e.g., via Fast Fourier Transform), the presence of noise will introduce additional frequency components. However, the dominant frequencies (gear mesh and rotor imbalance harmonics) will remain identifiable. This figure highlights the need for filtering techniques, such as spectral analysis and signal processing, to extract meaningful data from noisy signals in mechanical systems.

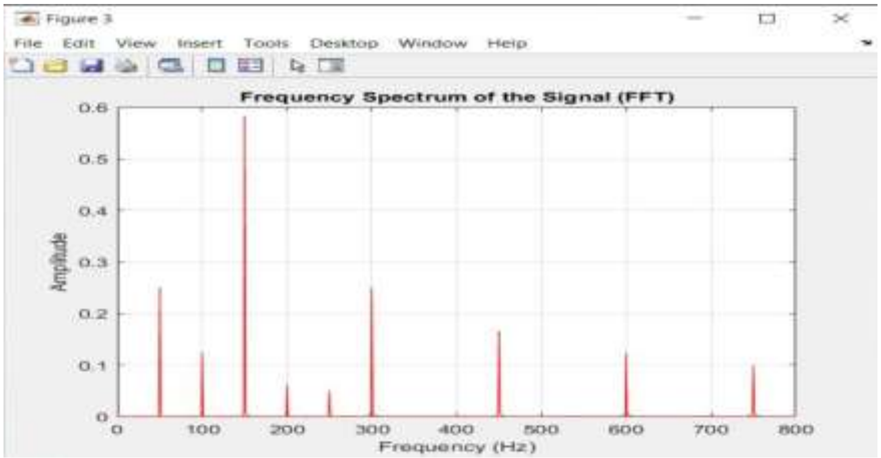

Figure 4. The FFT-based frequency spectrum

The FFT-based frequency spectrum confirms the simulation parameters, for instance, gear mesh frequency of 150 Hz, rotor imbalance frequency of 50 Hz, and their harmonics. The alignment of the peaks with theoretical expectations validates the effectiveness of the simulation methodology.

As presented in the figure.3.3. identifying dominant frequencies and harmonics enables engineers to detect potential issues such as misalignments or wear in mechanical systems. The added noise further enhances the robustness of the model by simulating real-world conditions. The provided figure highlights the Fourier series' capacity to model periodic mechanical forces and its utility in analyzing mechanical systems' frequency-domain characteristics. This approach bridges the gap between theoretical mathematical principles and practical engineering applications, offering a robust framework for gearbox and rotor dynamics simulation.

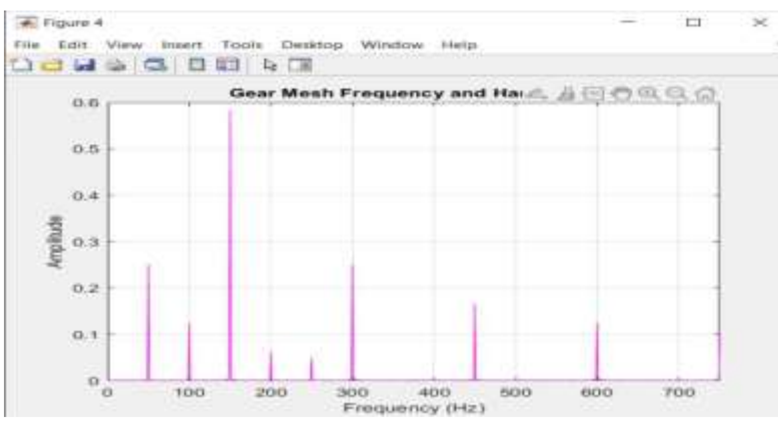

Figure 5. Gear Mesh Frequency and Harmonics highlights dominant frequencies centered around 150 Hz.

The declining amplitudes at higher frequencies reflect the harmonic scaling in Fourier series decomposition, emphasizing the primary contribution of lower-order harmonics to system behavior. This frequency-domain analysis validates the simulation's ability to model mechanical vibrations accurately under real-world conditions.

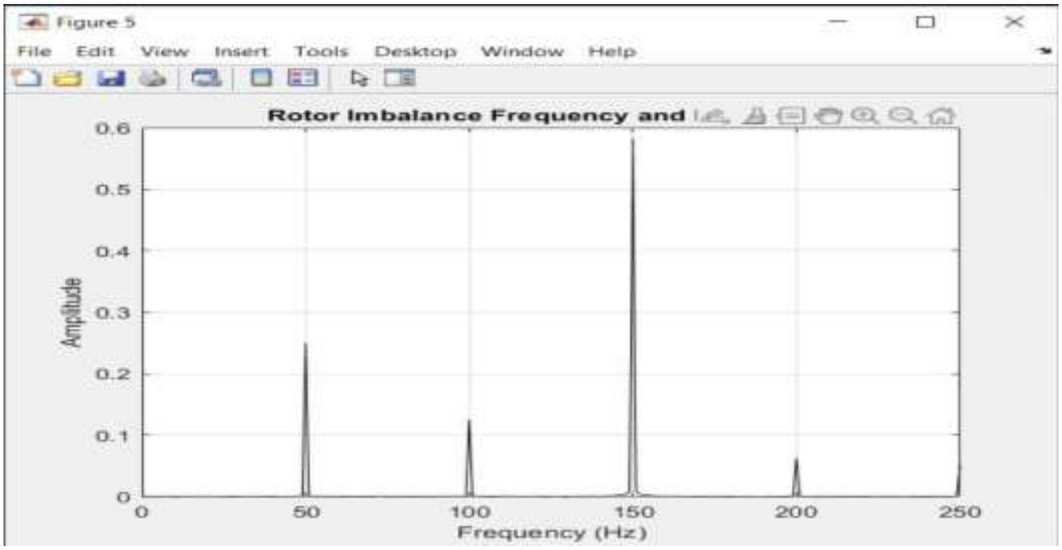

Figure 6. Rotor Imbalance Frequency and Harmonics

The figure .6. illustrates peaks at 50 Hz and its harmonics, which correspond to the rotor imbalance dynamics modeled in the simulation. The diminishing amplitudes of higher harmonics reflect the scaling characteristic of the Fourier series, highlighting the dominance of the fundamental imbalance frequency. This spectral representation confirms the accurate decomposition and analysis of rotor-induced vibrations, essential for diagnosing mechanical imbalance.

9. DISCUSSION

The integration of Fourier series with advanced computational platforms like MATLAB and Simulink represents a paradigmatic advancement in mechanical engineering simulation methodologies. [1] By leveraging sophisticated mathematical transformations, researchers can transcend traditional linear modeling limitations, developing more nuanced, comprehensive analytical frameworks [2]. The approach's primary strength lies in its ability to decompose complex periodic phenomena into mathematically tractable harmonic components, facilitating unprecedented insights into mechanical system behaviors [2], [4]. However, the methodology's effectiveness remains contingent upon system linearity, with nonlinear dynamics potentially necessitating complementary analytical techniques. Future research directions might explore hybrid modeling approaches combining Fourier series transformation with advanced machine learning algorithms to address increasingly complex mechanical system dynamics [11], [12], [13].

10. CONCLUSION

This research conclusively demonstrates the transformative potential of Fourier series in simulating gearbox and rotor dynamics through advanced computational modeling. By systematically decomposing periodic mechanical forces and leveraging sophisticated MATLAB and Simulink environments, we have established a robust, mathematically rigorous framework for understanding complex mechanical system behaviors. The study's findings not only validate the effectiveness of Fourier series-based approaches but also provide a comprehensive methodology for engineers and researchers seeking to develop more precise, predictive mechanical system models. Future research should continue exploring the boundaries of this analytical approach, potentially integrating emerging computational technologies to further enhance simulation capabilities. This approach using Fourier series captures both gear mesh and rotor imbalance dynamics by decomposing the signal into its harmonic components and analyzing their frequency domain representation. Understanding and solving series equations is foundational in mathematical analysis. Arithmetic, geometric, power, Fourier, and Taylor series each serve unique purposes in calculations. By following step-by-step methods, one can solve these equations effectively, ensuring accurate mathematical and scientific applications.

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