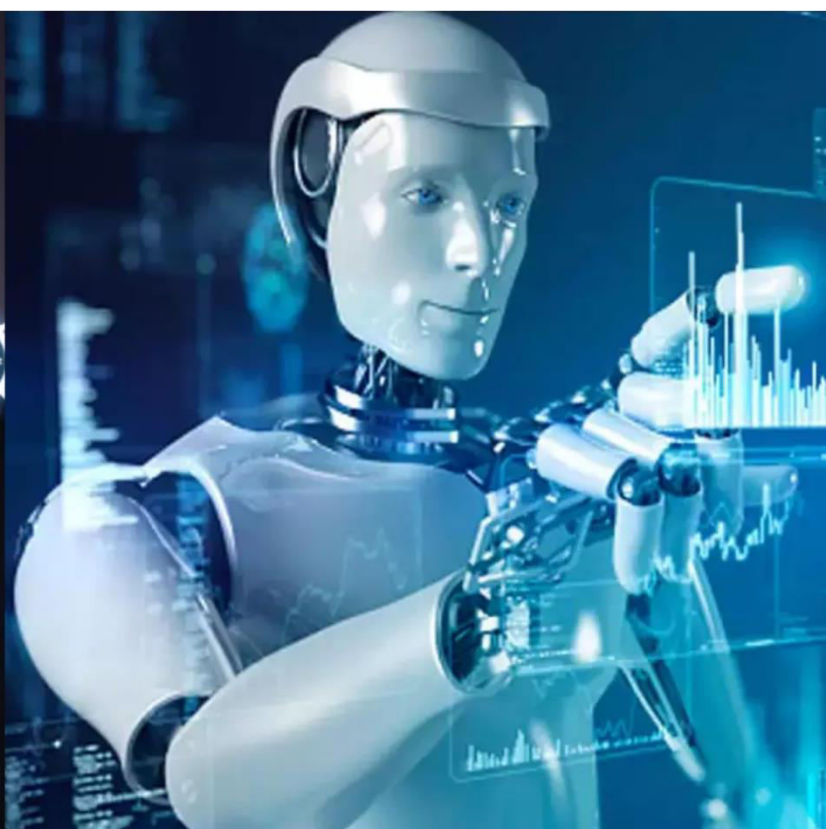




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A Study of Fractional Sumudu and Fourier Transformation: A Review

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ABSTRACT: This review paper provides a detailed overview of the Fractional Sumudu–Fourier Transformation, focusing on its development, mathematical framework, and research progress. Integral transforms such as the Sumudu, Fractional Sumudu, and Fourier transforms are essential tools for simplifying differential and integral equations. The study discusses their definitions along with fractional, conformable, and fuzzy extensions, which help model memory effects and uncertainty in complex systems. Key properties, including linearity, differentiation, integration, inverse transforms, and convolution, are examined across different transform types. The paper also reviews various fractional calculus approaches and transformation techniques used in recent studies for solving fractional differential equations. While these methods show strong potential in theoretical analysis and applied fields such as engineering and signal processing, existing work is largely limited to mathematical formulations. Important research gaps include the lack of a unified Fractional Sumudu–Fourier framework, limited real-world applications, and insufficient development of numerical and computational methods. The paper concludes by highlighting future research directions aimed at strengthening theoretical models and expanding their practical use in science and engineering.

KEYWORDS: Sumudu Transform, Fractional Sumudu Transform, Fourier Transform, Fractional Calculus.

I. INTRODUCTION

Mathematics provides several techniques for simplifying complex problems, among which integral transforms play an important role. These transforms help convert difficult mathematical expressions from one form into another, making it easier to solve differential equations, integral equations, and boundary value problems. Because of their problem-solving ability, integral transforms are widely used in mathematics, engineering, physics, and many applied sciences.

One such useful transform is the Sumudu Transform, which has become increasingly important owing to its effectiveness in solving mathematical and engineering problems. Similar to the Laplace Transform, it simplifies complicated equations; however, it offers additional advantages, such as preserving the original unit of the function and handling initial conditions more conveniently. These features make the Sumudu Transform a valuable mathematical tool in several scientific and engineering applications.

Another important area of study is Fractional Calculus, which extends the traditional concept of differentiation and integration to fractional or non-integer orders. Unlike classical calculus, fractional calculus can better represent systems that exhibit memory and hereditary effects. Owing to this ability, it has been successfully applied to model complex systems, such as viscoelastic materials, diffusion processes, and dynamic control systems.

Likewise, the Fourier Transform is a powerful mathematical technique used to study the frequency behaviour of functions and signals. It helps to break complex signals into simpler frequency components, making analysis easier in areas such as signal processing, heat transfer, image processing, communication systems, and quantum mechanics.

The integration of Fractional Sumudu and Fourier Transforms offers a promising approach for solving complex problems involving both fractional-order dynamics and frequency-domain analysis. This combination may provide more accurate and efficient mathematical models for various engineering and scientific applications in the future. Therefore, this review paper focuses on examining the development, mathematical properties, applications, and

research gaps associated with the Fractional Sumudu-Fourier Transformation, while also identifying possible directions for future research.

II. DEVELOPMENT OF FRACTIONAL SUMUDU FOURIER TRANSFORM

2.1 ORIGIN AND DEFINITION OF THE SUMUDU TRANSFORM:

The Sumudu transform was introduced by G.K. Watugala in 1993. It was developed as an alternative to Laplace transform. The main aim was to solve differential equation without changing the units of the original function. It is widely use in engineering, control system and applied mathematics.

Definition: Using the relationship with the Laplace transform, the definition of the Sumudu transform can be expressed as:

$$F(u) = S\{f(t)\} = \frac{1}{u} \int_0^{\infty} e^{-\frac{t}{u}} f(t) dt$$

Where:

- $f(t)$ – original function in the time domain.
- $F(u)$ – transformed function
- u – transformed parameter (variable)
- t – variable

2.2 EXTENSION OF THE FRACTIONAL SUMUDU TRANSFORMATION

The fractional extension of the Sumudu transform expands the classical transform to handle fractional-order functions and their corresponding differential equations. This is especially useful in fractional calculus, where derivatives and integrals are not limited to whole numbers. This extension helps solve complex problems while preserving important features, such as unit consistency.

Mathematical Formulation: The Fractional Sumudu Transform of a function $f(t)$ is denoted by $S_{\alpha}\{f(t)\} = F_{\alpha}(s)$ and is defined by

$$S_{\alpha}\{f(t)\}(s) = \frac{1}{s} \sqrt{\frac{1 - i \cot \alpha}{2\pi i}} \int_{-\infty}^{\infty} f(t) e^{\frac{1}{2}[(t^2 + \frac{1}{s^2}) \cot \alpha - \frac{2t}{s} \operatorname{cosec} \alpha]} dt$$

where:

- α = fractional order or rotation angle
- $i = \sqrt{-1}$
- s = transform variable

2.3 ORIGIN AND DEFINITION OF FOURIER TRANSFORMATION

In the early 19th century, Joseph Fourier showed that complex patterns, such as heat flow, can be broken down into simple sine and cosine waves. He later extended this idea to all types of functions, forming the basis of the Fourier Transform, a key tool used across science and engineering.

Mathematical Formulation: The Fourier transformation of a function $f(t)$ is defined as

$$F(p) = \int_{-\infty}^{\infty} f(x) e^{-ipx} dx$$

where:

- x – transformation variable
- p – parameter

2.4 ORIGIN AND DEFINITION OF THE FRACTIONAL SUMUDU-FOURIER TRANSFORM

The fractional Sumudu – Fourier Transform is a double integral transform that combine fractional Sumudu and Fourier transform, allowing simultaneous analysis of the memory effect in the time and frequency behaviours in space.

Mathematical Formulation: The Fractional Sumudu - Fourier Transform, where Sumudu part acts on variable t and Fourier part acts on variable x is represented as:

$$FrSFT \{f(t, x)\} = F_{\alpha}(s, p) = \frac{1}{s} \sqrt{\frac{1 - i \cot \alpha}{2\pi i}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(t, x) e^{\frac{1}{2}[(t^2 + \frac{1}{s^2}) \cot \alpha - \frac{2t}{s} \operatorname{cosec} \alpha]} e^{-ipx} dt dx$$

where:

- $f(t, x)$ – Original function of time t and space x
- s – Sumudu transform variable
- p – Frequency variable
- α – Fractional parameter
- $\cot \alpha, \operatorname{cosec} \alpha$ – Trigonometric function defining fractional behaviour

2.5 ORIGIN AND DEFINITION OF THE FUZZY FRACTIONAL SUMUDU TRANSFORM

The Fuzzy fractional Sumudu transform is obtained from combining the basic Sumudu transform with ideas from fractional calculus and fuzzy logic. It was created to better handle real – world problem where there is both uncertainty and effect that depend on past behaviour.

Mathematical Formulation: For a fuzzy valued function $\tilde{f}(t)$, the fuzzy fractional Sumudu transform of order $\beta > 0$ is defined as:

$$S_{\beta}[\tilde{f}(t)](u) = \int_0^{\infty} \frac{\tilde{f}(ut)t^{\beta-1}}{\Gamma(\beta)} e^{-t} dt$$

where:

- $\tilde{f}(t)$: Fuzzy-valued function
- u : Transform variable
- $\beta > 0$: Fractional order
- $\Gamma(\beta)$: Gamma function
- The kernel $\frac{t^{\beta-1}}{\Gamma(\beta)} e^{-t}$ generalizes the classical transform

2.6 ORIGIN AND DEFINITION OF CONFORMABLE FRACTIONAL SUMUDU TRANSFORM

The conformable fractional Sumudu transform originated from extending the classical Sumudu transform using fractional calculus to include memory effects in mathematical model.

Mathematical Formulation: The conformable fractional Sumudu transform of f can be generalized as follows:

$$S_{\alpha}[f(x)] = F_{\alpha}(u) = \frac{1}{u} \int_0^{\infty} e^{-\frac{x^{\alpha}}{au}} f(x) d_{\alpha}x$$

where:

- $d_{\alpha}x = x^{\alpha-1}dx$, $0 < \alpha < 1$ and provided that the integral exists.

III. MATHEMATICAL PROPERTY

Below, we discuss some common mathematical properties:

Property	Common Purpose	Classical Sumudu Transform	Fractional Sumudu Transform	Conformable Fractional Sumudu Transform
Linearity Property	Simplify mathematical expression and calculation	$S[af + bg] = aF(u) + bG(u)$	$S_\alpha[af + bg] = aF_\alpha(u) + bG_\alpha(u)$	$S_\alpha[af + bg] = aF_\alpha(u) + bG_\alpha(u)$
Differentiation Property	Simplifies differential equation	$\frac{S[f'(t)]}{F(u) - f(0)} = \frac{1}{u}$	$S_\alpha[D^\alpha f] = \frac{F_\alpha(u)}{u^\alpha}$	$S_\alpha[T_\alpha f] = \frac{F_\alpha(u)}{u^\alpha}$
Integration Property	Solve integral problem	$S(\int f) = uF(u)$	$S_\alpha[I^\alpha f] = u^\alpha F_\alpha(u)$	$S_\alpha[I_\alpha f] = u^\alpha F_\alpha(u)$
Inverse Transform	Recover original function	$f(t) = S^{-1}[F(u)]$	$f(x) = S_\alpha^{-1}[F_\alpha(u)]$	$f(x) = S_\alpha^{-1}[F_\alpha(u)]$
Convolution Property	Solve system equation	$S[f * g] = uF(u)G(u)$	$S_\alpha[f * g] = u^\alpha F_\alpha(u)G_\alpha(u)$	$S_\alpha[f * g] = u^\alpha F_\alpha(u)G_\alpha(u)$
Relation with Laplace transform	Improve mathematical analysis	$F(u) = L[f(t)]_{(s=\frac{1}{u})}$	$F_\alpha(u) = L_\alpha[f(x)]_{(s=\frac{1}{u})}$	$F_\alpha(u) = L_\alpha[f(x)]_{(s=\frac{1}{u})}$
Kernel Behaviour	To transform complex function to simple form.	Standard exponential	Fractional exponential/ Mittag-Leffler	Modified exponential (Conformable derivative based)

The above table provided a simple comparison of the main mathematical properties used in the Sumudu Transform, Fractional Sumudu Transform, and Conformable Fractional Sumudu Transform. Common properties such as linearity, differentiation, integration, inverse transformation, and convolution are found in all three methods. However, their forms change depending on the type of transform used. The classical Sumudu Transform follows ordinary calculus, whereas the fractional and conformable forms are modified to solve more complex problems. Even with these differences, all methods primarily aim to simplify mathematical equations and facilitate problem-solving.

IV. METHOD AND MATHEMATICAL TECHNIQUE USED

The selected research papers mainly use different methods of fractional calculus, such as the Caputo derivative, Riemann–Liouville derivative, and conformable fractional derivative, to solve fractional differential equations more effectively. These methods help in understanding complex mathematical systems that cannot be solved easily using ordinary calculus.

Several transformation techniques, including the Sumudu Transform, Fractional Sumudu Transform (FST), Conformable Fractional Sumudu Transform (CFST), and Fuzzy Fractional Sumudu Transform (FFST), are used to convert difficult equations into simpler forms. This makes mathematical calculations easier and improves problem-solving methods. Some studies also apply fuzzy theory, graph theory, and matrix methods to manage uncertainty and study graph-based signals.

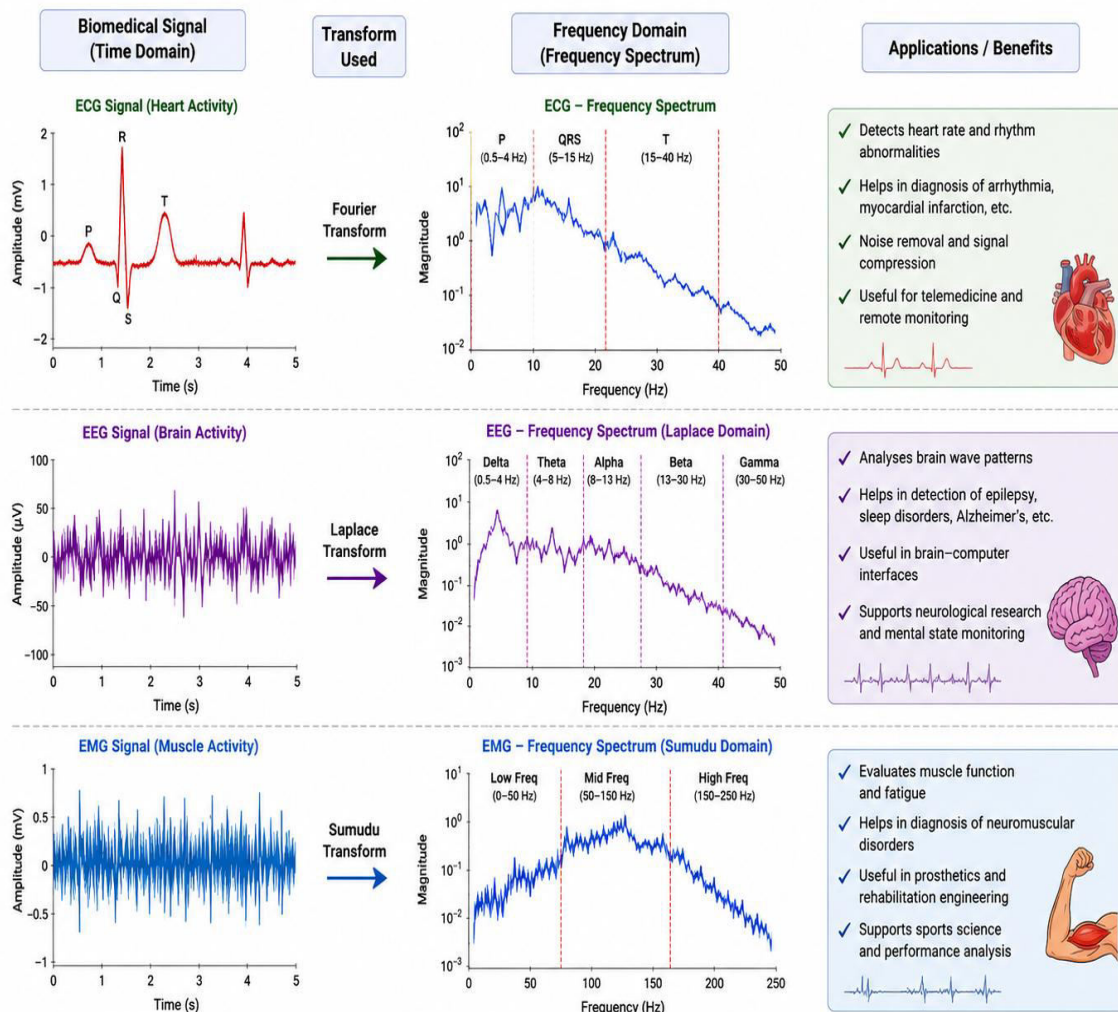
In addition, important mathematical properties such as linearity, inverse transform, differentiation, integration, shifting, and convolution are discussed to improve the understanding of these transforms. Many studies also compare these methods with the Laplace Transform and Fuzzy Laplace Transform to check their effectiveness. Finally, example

problems, numerical methods, and graphical analysis are used to show the practical usefulness of these techniques in solving mathematical and real-world problems [01], [06], [07], [08], [09], [10].

V. APPLICATION DISCUSSED IN PREVIOUS RESEARCH

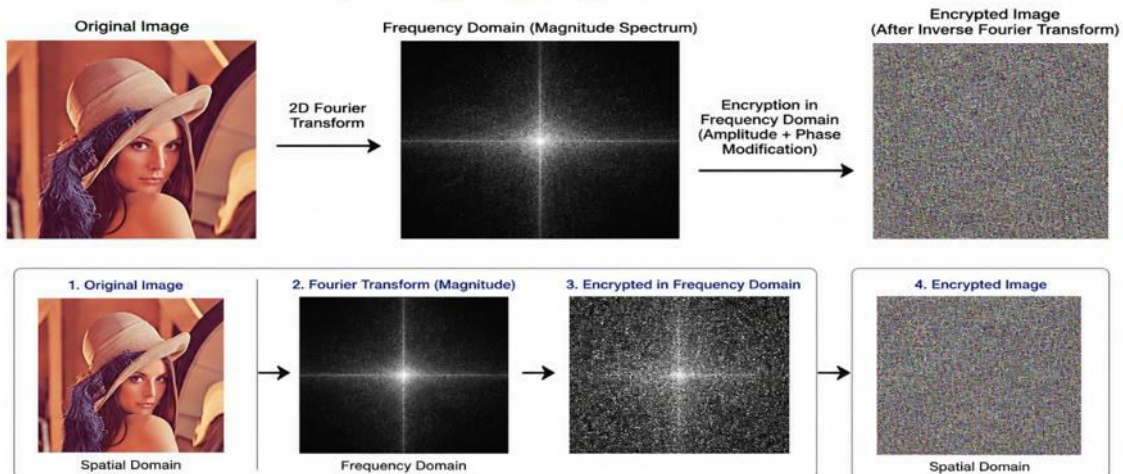
- Used to solve ordinary, fractional, and fuzzy differential equations, making complex problems easier to handle.
- Supports analysis of diffusion, wave, and transport phenomena, including irregular or non-standard behaviour.
- Simplifies complicated mathematical expressions and integral equations for easier computation.
- Widely applied in engineering fields, particularly in control systems and system analysis.
- Useful in biomedical applications, such as analysing ECG, EEG, and other medical signals.
- Supports real-world modelling, where exact data may be incomplete or uncertain.
- Useful in studying viscoelastic materials, especially for time-dependent stress–strain analysis.
- Enables handling of uncertainty and imprecision through fuzzy mathematical approaches.
- Applied in signal processing and network-based data analysis, including graph-related systems.
- Visual representation of image encryption using Integral transformation in Cryptography.

Applications of Integral Transforms in Biomedical Signal Analysis



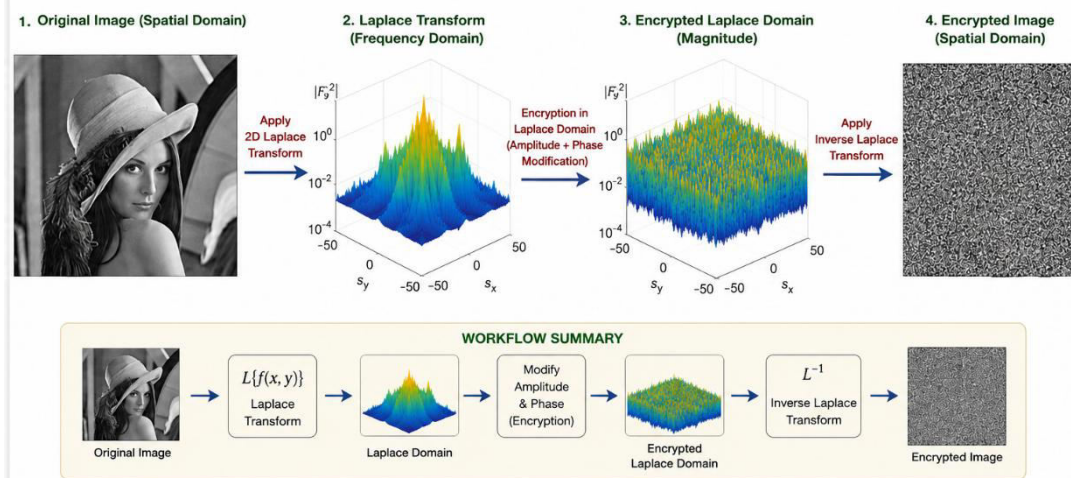
(a) Fourier transform-based image Encryption:

Image Encryption Using Fourier Transform



(b) Laplace transform-based image Encryption:

Image Encryption Using Laplace Transform



VI. SOME RESULT AND FINDING

- **Development of Useful Mathematical Properties:**
The studies developed important properties such as linearity, differentiation, integration, inverse transform, shifting, and convolution, which made Sumudu-based transforms more useful for solving mathematical problems. [01], [07], [08], [09].
- **Simplifying Complex Equations:**
Different forms of the Sumudu Transform were found helpful in converting difficult fractional and differential equations into simpler algebraic forms, making them easier to solve. [01], [07], [08], [09], [10].
- **Connection with Other Transforms:**
Several studies showed a strong relationship between the Sumudu Transform and Laplace Transform, including fuzzy and conformable forms, proving their effectiveness in problem-solving. [01], [07], [08], [09].
- **Extension to New Fields and Practical Use:**
The transforms were successfully applied in areas like graph signal processing, engineering, and fractional models, showing accurate and reliable results through practical examples and simulations. [06], [10].

VII. COMPARISON WITH ANOTHER TRANSFORM

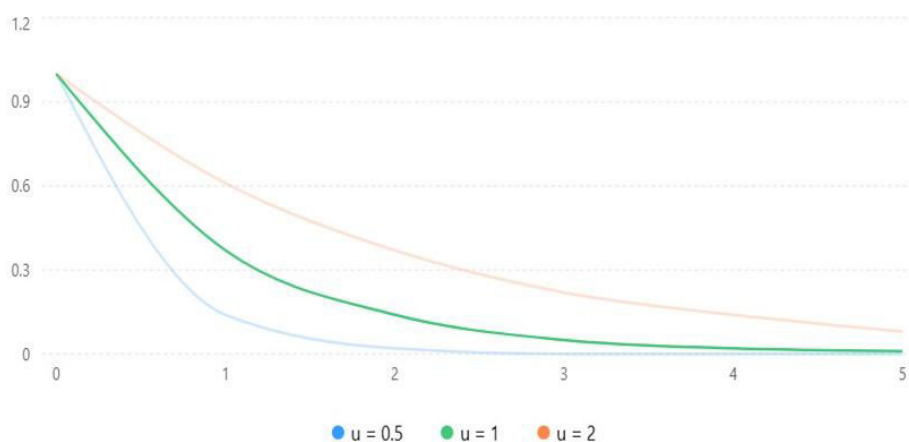
Here we discussed the comparison of Sumudu transform, Laplace transform and Fourier transform with each other

Basis	Sumudu Transform	Laplace Transform	Fourier Transform
Definition	$S\{f(t)\} = \frac{1}{u} \int_0^{\infty} f(t) e^{-\frac{t}{u}} dt$	$L\{f(t)\} = \int_0^{\infty} f(t) e^{-st} dt$	$F\{f(t)\} = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt$
Variable Used	u	s	ω (frequency)
Unit Preservation	Preserve units	Does not preserve	Does not preserve
Interval	0 to ∞	0 to ∞	$-\infty$ to ∞
Domain Conversion	Time to Similar domain	Time to complex frequency	Time to frequency
Main Applications	Differential equation, fractional calculus	Engineering, circuits, control system	Signal and image processing
Relationship	Related to Laplace	General form	Special case of Laplace ($s = i\omega$)

The Sumudu, Laplace, and Fourier transforms are all important tools for converting functions into different domains. The Sumudu transform preserves units and is useful for fractional calculus, the Laplace transform is widely used in engineering and differential equations, while the Fourier transform is best suited for signal and frequency analysis. Each transform differs mainly in its variable, application area, and domain of transformation.

VIII. GRAPHICAL BEHAVIOUR OF INTEGRAL TRANSFORM KERNELS

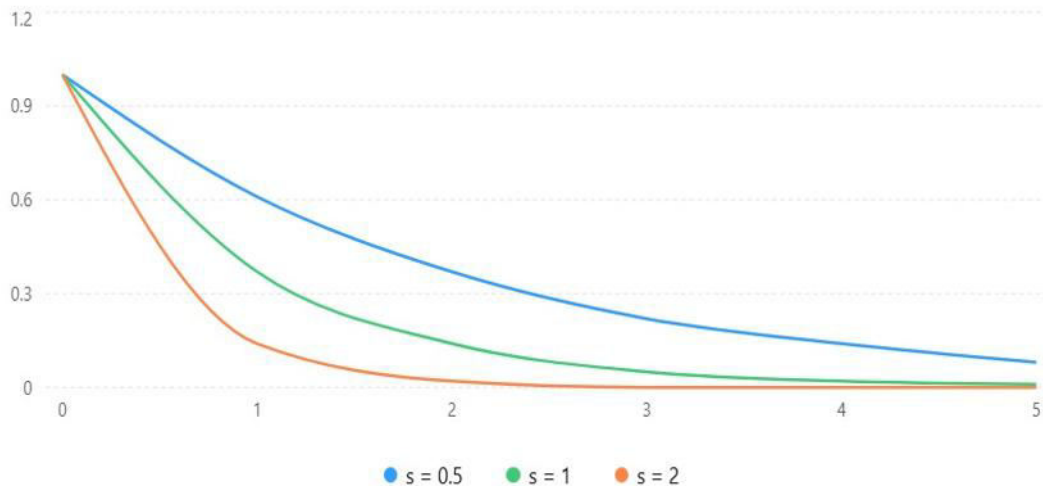
Sumudu Transformation Kernel: Graphical illustration of the Sumudu transformation kernel for different values of parameter u .



The graph shows that the Sumudu transformation kernel decreases as the variable increases. Smaller values of u make the kernel decreases faster, while larger values make it decreases more slowly. This shows that the parameter u affects the behaviour of the transformation.

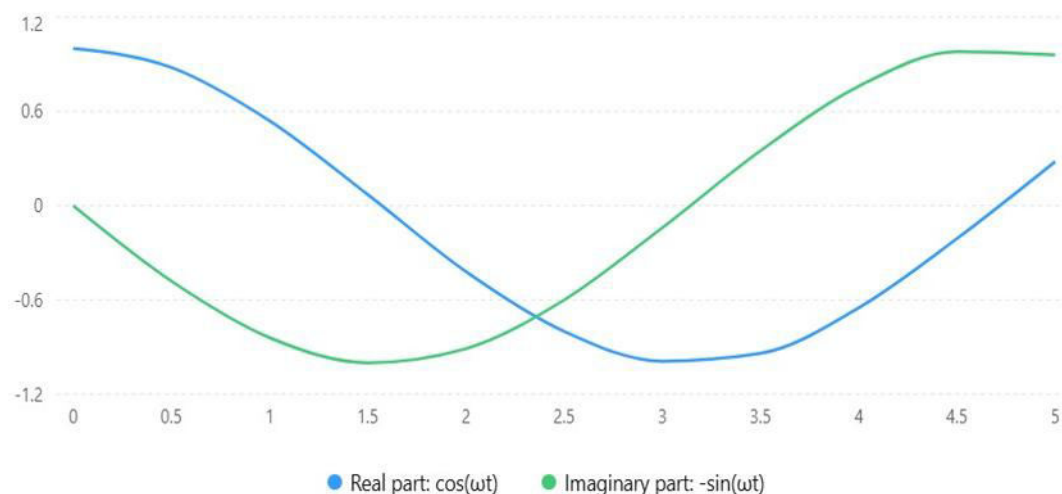
Laplace Transformation Kernel:

Graphical illustration of the Laplace transformation kernel for different values of parameter s



From the above graph, it can be observed that the kernel gradually decreases as the variable increases. Larger values of s cause a faster decay, whereas smaller values resulting in a slower decrease in the kernel.

Fourier Transformation Kernel: Graphical illustration of the Fourier transformation kernel showing its real and imaginary oscillatory components.



The graph shows that the Fourier transformation kernel has a wave like pattern. The real part behaves like a cosine wave, while the imaginary part behaves like a sine wave, making the Fourier transform useful for studying signal and frequencies.

IX. RESEARCH GAPS

- **Need to Develop a Combined Fractional Sumudu–Fourier Transformation:**
Most studies have focused on the Sumudu Transform, Fractional Sumudu Transform, or Fractional Fourier Transform separately. However, very little work has been done on combining these transforms into a Fractional Sumudu–Fourier Transformation, which can be an important area for future research. [06], [07], [08], [09], [10].
- **Limited Use in Real-Life Applications:**
Current research mainly focuses on mathematical theory and solving equations. There is still less work on using these transforms in practical areas such as signal processing, image analysis, engineering systems, and other real-world problems. More application-based studies are needed. [01], [06], [07], [08], [09].
- **Lack of Numerical and Modern Computational Methods:**
Very few studies discuss numerical methods, computer-based techniques, or AI-supported approaches for solving complex fractional problems using these transforms. This creates an opportunity for future researchers to develop better computational methods. [01], [06], [09], [10].
- **Limited Research on Complex and Multidimensional Problems:**
Most existing work deals with simple mathematical models. More research is needed to apply these transforms to multidimensional models, fuzzy systems, and complex fractional differential equations for better problem-solving. [01], [06], [07], [08], [09].
- **Need for Comparison with Other Integral Transforms:**
There are not enough studies comparing these transforms with other important integral transforms like the Laplace Transform and Fourier Transform. Such comparisons can help understand their advantages, limitations, and practical usefulness. [01], [06], [07], [08], [09].

X. FUTURE SCOPE

Based on the reviewed studies, there is significant scope for further development in the field of Fractional Sumudu–Fourier Transformation. Most existing research focuses mainly on theoretical properties and solving mathematical equations, while limited attention has been given to practical and real-world applications. Future studies may focus on developing a combined Fractional Sumudu–Fourier Transform to improve the analysis of systems involving both fractional behaviour and frequency-based characteristics.

In addition, more research can be carried out in areas such as signal processing, image processing, biomedical engineering, communication systems, and artificial intelligence. Numerical techniques and software-based implementation using MATLAB or Python may also improve the practical use of these transforms. Furthermore, comparative studies with other integral transforms may help identify their strengths and broader applications in mathematics and engineering.

XI. CONCLUSION

The Fractional Sumudu–Fourier Transformation is an emerging mathematical tool that combines the advantages of fractional calculus with frequency-domain analysis. The studies reviewed indicate that it has strong potential for solving complex problems involving memory effects, uncertainty, and fractional-order systems. Its theoretical foundations have been developed through various extensions of the Sumudu and Fourier transforms, providing useful techniques for analysing and simplifying differential equations.

Despite these advances, most existing research remains focused on mathematical theory, with limited attention given to practical applications and computational methods. Future work should concentrate on developing a unified Fractional Sumudu–Fourier framework, efficient numerical techniques, and real-world applications in fields such as engineering, signal processing, and biomedical sciences. Further comparative studies with other integral transforms may also help to better understand its strengths and expand its range of applications.

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