Enhancing Signal Reliability in Smart Communication Channels Using a New Complex Integral Transform: Mathematical Modeling, Noise Reduction, and SDG-Aligned Digital Security

Jinan A. Jasim[1], Atifa J. Salah[2], Emad A. Kuffi[2], Ahmad Qazza[3] and Rania Saadeh[4]
Ling Shing Wong[5,6]
[1] *Department of Mathematics, College of Education, Mustansiriyah University, Iraq Baghdad.*
jinanadel78@uomustansiriyah.edu.iq
[2] *Department of Mathematics, College of Basic Education, Mustansiriyah University, Iraq Baghdad.*
atifa_jalil.edbs@uomustansiriyah.edu.iq(A.S.), emad.kuffi@uomustansiriyah.edu.iq (E.K)
[3] *Department of Mathematics, Faculty of Science, Zarqa University, Zarqa 13110, Jordan.*
aqazza@zu.edu.jo
[4] *Department of Applied Science, Ajloun College, Al-Balqa Applied University, Ajloun, Jordan.*
r.saadeh@bau.edu.jo
[5] *Faculty of Health and Life Sciences, INTI -IU University, Nilai, Malaysia*
[6] *Faculty of Nursing, Shinawatra University, Pathum Thani, Thailand.*
lingshing.wong@newinti.edu.my

Abstract

This paper introduces a new complex integral transform and applies it to solving first-order complex differential equations with constant coefficients. The transform provides simplified analytical expressions that naturally fit engineering models involving complex signals, channel attenuation, and noise-corrupted communication data. Simulated results show that applying the transform improves signal stability, reduces noise oscillations, and increases the signal-to-noise ratio (SNR). Numerical error analysis further confirms its effectiveness in reconstructing clean signals from noisy environments. These findings demonstrate the transform's value for smart communication systems, IoT signal modeling, and 5G/6G applications. The approach also supports more secure and resilient digital infrastructures, aligning with modern needs such as reducing cybercrime risks and strengthening trustworthy communication frameworks.

Keywords: Complex integral transform; Signal processing; Smart communication systems; Noise reduction; Transparent Institutions; Resilient Infrastructure.

1. Introduction

Integral transforms have long played a central role in solving differential equations that arise in engineering and applied sciences, particularly in signal processing, wireless communications, control systems, and network modeling. Classical transforms such as Laplace, Fourier, and Sumudu have proven effective in analyzing system dynamics and simplifying complex mathematical models used in communication channels and signal propagation. However, with the growing complexity of modern communication networks—including IoT systems, 5G/6G technologies, and smart communication infrastructures—there is a growing need for more flexible and computationally efficient mathematical tools[1-6].

In modern digital ecosystems, the pursuit of transparent institutions and the development of resilient infrastructure—core elements of global sustainability agendas—require advanced mathematical tools capable of enhancing signal reliability, securing communication channels, and supporting robust decision-making frameworks. The new complex integral transform contributes to these goals by providing accurate analytical solutions for complex-valued models that form the backbone of smart communication systems.

A new complex integral transform, introduced in 2022, has demonstrated strong capability in solving various mathematical models with high accuracy and reduced computational cost. This transform provides a powerful framework for addressing complex-valued differential equations, which naturally emerge in the modeling of modulated signals, noise filtering, wave propagation, and channel behavior in communication engineering [7,8].

Recent advances in operator theory and functional analysis highlight the importance of sharper inequalities and stability results. Notable contributions by Qazza and collaborators include improved numerical-radius inequalities in Hilbert spaces [9, 10], existence results for semi-linear abstract differential equations with infinite B-chains [11], and stability analysis for Volterra integral equations with random kernels [12]. Collectively, these works strengthen theoretical tools in both deterministic and stochastic settings.

In this research, we employ the new complex integral transform to solve first-order complex differential equations with constant coefficients. By formulating the solution through this transform, we highlight its applicability to engineering problems that involve complex-valued signals and demonstrate its effectiveness as a modern tool for enhancing the mathematical analysis of communication systems.

2. Complex Derivatives [8]

Let $w = w(z, \underline{z})$ be a complex function, here $z = x + iy,$ and $w(z, \underline{z}) = u(x, y) + iv(x, y)$. First order derivatives according to z and $\underline{z}$ of $w(z, \underline{z})$ are defined as following

$$\frac{\partial w}{\partial z} = \frac{1}{2}\left(\frac{\partial w}{\partial x} - i\frac{\partial w}{\partial y}\right), \tag{2.1}$$

$$\frac{\partial w}{\partial \underline{z}} = \frac{1}{2}\left(\frac{\partial w}{\partial x} + i\frac{\partial w}{\partial y}\right). \tag{2.2}$$

Theorem 2.1. Let $a, b, c \in \mathbb{R}$, $G(z, \underline{z})$ is a polynomial of z; $\underline{z}$ and $w = u + iv$ is a complex function. Then the real and imaginary parts of solution of

$$\begin{gathered} a\frac{\partial w}{\partial z} + b\frac{\partial w}{\partial \underline{z}} + cw = G(z, \underline{z}), \\ w(x, 0) = 0. \end{gathered} \tag{2.3}$$

are

$$u(x,y) = {T_g^c}^{-1}\left\{\frac{(a+b)\frac{\partial}{\partial x}\left[(2{F_g^c}_3(x,s)+(a-b)p(s)v(x,0)\right]+2c\left[(2{F_g^c}_3(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta} - \frac{(a-b)iq(s)\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta}\right\},$$

$$v(x,y) = {T_g^c}^{-1}\left\{\frac{(a+b)\frac{\partial}{\partial x}\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]+2c\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta} - \frac{(b-a)iq(s)\left[(2{F_g^c}_3(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta}\right\},$$

where

$$\Delta = |(a+b)D+2c \ (a-b)iq(s) \ (b-a)iq(s) \ (a+b)D+2c \ |$$

$$= \left((a+b)D+2c\right)^2 + \left(iq(s)(b-a)\right)^2.$$

And ${F_g^c}_1, {F_g^c}_2, {F_g^c}_3, {F_g^c}_4$ are the new integral transform of u, v, G_1, G_2 respectively.

Proof. We use equations. (2.1), (2.2) in equation (2.3), we have

$$\frac{a}{2}\left(\frac{\partial w}{\partial x} - i\frac{\partial w}{\partial y}\right) + \frac{b}{2}\left(\frac{\partial w}{\partial x} + i\frac{\partial w}{\partial y}\right) + cw = G_1\left(z,\underline{z}\right) + iG_2\left(z,\underline{z}\right). \tag{2.4}$$

If we choose $w = u + iv$ in (2.4), following equality is obtained

$$a\left(\frac{\partial u}{\partial x} + i\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + i\frac{\partial v}{\partial y}\right) + b\left(\frac{\partial u}{\partial x} + i\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} - i\frac{\partial v}{\partial y}\right) + 2cw = 2G_1(x,y) + 2iG_2(x,y). \tag{2.5}$$

If equation (2.5) is separated to real and imaginary parts, then following equation system is obtained

$$(a+b)\frac{\partial u}{\partial x} + (a-b)\frac{\partial v}{\partial y} + 2cu = 2G_1(x,y), \tag{2.6}$$

$$(a+b)\frac{\partial v}{\partial x} + (b-a)\frac{\partial u}{\partial y} + 2cv = 2G_2(x,y). \tag{2.7}$$

By using the new transform for above equation (2.6) and equation (2.7) equalities, then we get following qualities

$$(a+b)\frac{\partial F_{g\ 1}^{c}}{\partial x}+(a-b)\left(iq(s)F_{g\ 2}^{c}-p(s)v(x,0)\right)+2cF_{g\ 1}^{c}=2F_{g\ 3}^{c}, \tag{2.8}$$

$$(a+b)\frac{\partial F_{g\ 2}^{c}}{\partial x}+(b-a)\left(iq(s)F_{g\ 1}^{c}-p(s)u(x,0)\right)+2cF_{g\ 2}^{c}=2F_{g\ 4}^{c}. \tag{2.9}$$

If equation (2.8) and equation (2.9) is regulate and is used Cramer rule, then equalities are obtained.

$$(a+b)\frac{\partial F_{g\ 1}^{c}}{\partial x}+(a-b)iq(s)F_{g\ 2}^{c}+2cF_{g\ 1}^{c}=2F_{g\ 3}^{c}+(a-b)p(s)v(x,0),$$

$$(a+b)\frac{\partial F_{g\ 2}^{c}}{\partial x}+(b-a)iq(s)F_{g\ 1}^{c}+2cF_{g\ 2}^{c}=2F_{g\ 4}^{c}+(b-a)p(s)u(x,0),$$

$$F_{g\ 1}^{c}=\left|\frac{2F_{g\ 3}^{c}+(a-b)p(s)v(x,0)(a-b)iq(s)2F_{g\ 4}^{c}}{\Delta}\right.$$
$$\left.+\frac{(b-a)p(s)u(x,0)(a+b)D+2c}{\Delta}\right|,$$

$$\begin{aligned}F_{g\ 1}^{c}=&\frac{(a+b)\frac{\partial}{\partial x}\left[(2F_{g\ 3}^{c}(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta}\\&+\frac{2c\left[(2F_{g\ 3}^{c}(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta}\\&-\frac{(a-b)iq(s)\left[(2F_{g\ 4}^{c}(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta},\end{aligned} \tag{2.10}$$

and

$$F_{g\ 2}^{c}=\left|\frac{(a+b)D+2c\ 2F_{g\ 3}^{c}}{\Delta}+\frac{(a-b)p(s)v(x,0)(b-a)iq(s)2F_{g\ 4}^{c}}{\Delta}\right.$$
$$\left.+\frac{(b-a)p(s)u(x,0)}{\Delta}\right|,$$

$$
\begin{aligned}
{F_g^c}_2 = {} & \frac{(a+b)\dfrac{\partial}{\partial x}\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta} \\
& + \frac{+2c\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta} \\
& - \frac{(b-a)iq(s)\left[(2{F_g^c}_3(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta},
\end{aligned}
\tag{2.11}
$$

Followings are obtained from invers the new transform of equation (2.10) and equation (2.11)

$$
\begin{aligned}
u(x,y) = {} & T_g^{c^{-1}}\left\{\frac{(a+b)\dfrac{\partial}{\partial x}\left[(2{F_g^c}_3(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta}\right\} \\
& + T_g^{c^{-1}}\left\{\frac{2c\left[(2{F_g^c}_3(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta}\right\} \\
& - T_g^{c^{-1}}\left\{\frac{(a-b)iq(s)\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta}\right\},
\end{aligned}
\tag{2.12}
$$

$$
\begin{aligned}
v(x,y) = {} & T_g^{c^{-1}}\left\{\frac{(a+b)\dfrac{\partial}{\partial x}\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta}\right\} \\
& + T_g^{c^{-1}}\left\{\frac{2c\left[(2{F_g^c}_4(x,s)+(b-a)p(s)u(x,0)\right]}{\Delta}\right\} \\
& - T_g^{c^{-1}}\left\{\frac{(b-a)iq(s)\left[(2{F_g^c}_3(x,s)+(a-b)p(s)v(x,0)\right]}{\Delta}\right\}.
\end{aligned}
\tag{2.13}
$$

Application 1. Consider the following differential equation [8]

$$3\frac{\partial w}{\partial z}+\frac{\partial w}{\partial \underline{z}}=0,$$

with the condition

$$w(x,0)=x^2.$$

Coefficients of equation are $a=3, b=1, c=0,$ and $G(x,y)=0$. From the theorem (1), we have

$$\Delta = \big((a+b)D+2c\big)^2 + \big(iq(s)(b-a)\big)^2 = 16D^2 + 4(iq(s))^2,$$

and

$$u(x,y) = T_g^{c^{-1}}\left\{\frac{-2iq(s)(-2p(s)x^2)}{16D^2+4(iq(s))^2}\right\} = T_g^{c^{-1}}\left\{\frac{iq(s)p(s)x^2}{4D^2+(iq(s))^2}\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{p(s)x^2}{iq(s)\left[(\frac{2D}{iq(s)})^2+1\right]}\right\} = T_g^{c^{-1}}\left\{\frac{p(s)}{iq(s)}\left[1-(\frac{2D}{iq(s)})^2\right]x^2\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{p(s)}{iq(s)}\left[x^2-\frac{8}{(iq(s))^2}\right]\right\} = x^2T_g^{c^{-1}}\left\{\frac{p(s)}{iq(s)}\right\} - 8T_g^{c^{-1}}\left\{\frac{p(s)}{(iq(s))^3}\right\}$$

$$= x^2T_g^{c^{-1}}\left\{\frac{(-i)p(s)}{q(s)}\right\} - 8T_g^{c^{-1}}\left\{\frac{(-i)^3p(s)}{(q(s))^3}\right\},$$

$$u(x,y) = x^2 - 4y^2.$$

and on the other hand

$$v(x,y) = T_g^{c^{-1}}\left\{4\frac{\partial}{\partial x}\left[\frac{-2p(s)x^2}{16D^2+4(iq(s))^2}\right]\right\} = -16T_g^{c^{-1}}\left\{\frac{p(s)x}{4[4D^2+(iq(s))^2]}\right\}$$

$$= -4T_g^{c^{-1}}\left\{\frac{p(s)x}{(iq(s))^2\left[(\frac{2D}{iq(s)})^2+1\right]}\right\}$$

$$= -4T_g^{c^{-1}}\left\{\frac{p(s)}{(iq(s))^2}\left[1-(\frac{2D}{iq(s)})^2\right]x\right\} = -4T_g^{c^{-1}}\left\{\frac{xp(s)}{(iq(s))^2}\right\},$$

$$v(x,y) = -4xT_g^{c^{-1}}\left\{\frac{(-i)^2p(s)}{(q(s))^2}\right\} = -4xy.$$

So we obtain

$$w = x^2 - 4y^2 - 4ixy.$$

Application 2. Consider the following differential equation:

$$\frac{\partial w}{\partial z} + 2\frac{\partial w}{\partial \underline{z}} = z,$$

with the condition

$$w(x,0) = x\,.$$

Coefficients of equation are $a = 1, b = 2, c = 0,$ and $G(x,y) = x + iy.$ [8]

From the theorem (1), we have

$$\Delta = \left((a+b)D+2c\right)^2 + \left(iq(s)(b-a)\right)^2 = 9D^2 + (iq(s))^2,$$

and

$$u(x,y) = T_g^{c^{-1}}\left\{\frac{3\frac{\partial}{\partial x}\left[\frac{2x-ip(s)}{q(s)}\right] + iq(s)\left[\frac{2(-i)^2p(s)}{\left(q(s)\right)^2} + p(s)x\right]}{9D^2+(iq(s))^2}\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{\frac{6(-i)p(s)}{q(s)} + \frac{2(-i)p(s)}{q(s)} + iq(s)p(s)x}{(iq(s))^2\left[\left(\frac{3D}{(iq(s))}\right)^2+1\right]}\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{1}{(iq(s))^2}[+iq(s)p(s)x]\left[1-\left(\frac{3D}{(iq(s))}\right)^2\right]\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{8(-i)^3p(s)}{\left(q(s)\right)^3}\right\} + xT_g^{c^{-1}}\left\{\frac{(-i)p(s)}{q(s)}\right\},$$

$$u(x,y) = 4y^2 + x.$$

And on the other hand

$$v(x,y) = T_g^{c^{-1}}\left\{\frac{3\frac{\partial}{\partial x}\left[\frac{2(-i)^2p(s)}{\left(q(s)\right)^2} + p(s)x\right] + iq(s)\left[\frac{2(-i)p(s)x}{q(s)}\right]}{9D^2+(iq(s))^2}\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{3p(s)+2p(s)x}{(iq(s))^2\left[\left(\frac{3D}{(iq(s))}\right)^2+1\right]}\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{3(-i)^2p(s)}{\left(q(s)\right)^2} + \frac{2x(-i)^2p(s)}{\left(q(s)\right)^2}[+iq(s)p(s)x]\left[1-\left(\frac{3D}{(iq(s))}\right)^2\right]\right\}$$

$$= T_g^{c^{-1}}\left\{\frac{3(-i)^2p(s)}{\left(q(s)\right)^2}\right\} + 2xT_g^{c^{-1}}\left\{\frac{(-i)^2p(s)}{\left(q(s)\right)^2}\right\},$$

$$v(x,y) = (3-2x)y.$$

So we obtain

$$w = 4y^2 + x + i(3-2x)y.$$

3. Engineering Application: Modeling Complex Signals in Communication Channels Using the New Complex Integral Transform

Modern communication systems—including smart communication networks, IoT devices, and 5G/6G wireless infrastructures—rely heavily on the mathematical modeling of complex-valued signals [13]. These signals often take the form

$$s(t) = A(t)e^{\{j\phi(t)\}},$$

which naturally leads to differential equations involving complex functions with constant coefficients. Such models appear in channel equalization, noise suppression, modulation/demodulation processes, and waveform propagation in linear and nonlinear media.

To demonstrate the engineering relevance of the new complex integral transform, we consider a standard communication model governed by the first-order complex differential equation:

$$\frac{ds(t)}{dt} + \alpha s(t) = n(t),$$

where:

- $s(t)$ represents the received complex signal,
- $\alpha \in C$ is an attenuation coefficient related to channel fading,
- $n(t)$ models additive complex noise, often arising from AWGN (Additive White Gaussian Noise) processes.

This equation is commonly encountered in:

- Baseband signal modeling,
- Envelope detection in modulated systems,
- Channel behavior under Rayleigh/Rician fading,
- Filtering and noise reduction,
- Optical and RF communication analysis.

3.1. Applying the New Complex Integral Transform

Applying the new complex integral transform $\mathcal{N}$ to the model equation yields:

$$\mathcal{N}\left\{\frac{ds(t)}{dt}\right\}+\alpha\mathcal{N}s(t)=\mathcal{N}n(t).$$

Using the differentiation property of the new transform:

$$\mathcal{N}\left\{\frac{ds}{dt}\right\}=\omega\mathcal{N}s(t)-s(0),$$

we obtain:

$$(\omega+\alpha)\mathcal{N}s(t)=s(0)+\mathcal{N}n(t).$$

Solving for the transformed signal:

$$\mathcal{N}\{s(t)\}=\frac{s(0)}{\omega+\alpha}+\frac{\mathcal{N}n(t)}{\omega+\alpha}.$$

Applying the inverse transform leads to the analytical time-domain solution:

$$s(t)=s(0),e^{-\alpha t}+\int_0^t e^{-\alpha(t-\tau)}n(\tau)\,,d\tau.$$

3.2. Engineering Interpretation

The solution above represents the physical behavior of signals in a fading communication channel, where:

- The term $s(0)e^{-\alpha t}$ models signal attenuation due to channel losses.
- The convolution integral with $n(t)$ models noise shaping and its effect on the signal.
- The exponential kernel describes how noise propagates through the channel.

This formulation is essential in engineering applications such as:

1. Channel Equalization

The transform provides closed-form expressions to analyze and compensate for fading and distortion.

2. Noise Filtering in Smart Communication Systems

The convolution term helps design low-complexity denoising filters using the structure of the transform.

3. Signal Recovery in IoT and Wireless Sensor Networks

The model applies directly to recovering weak complex signals in low-power IoT devices.

4. 5G/6G Modulation Schemes (QAM, OFDM)

The complex transform allows analytical handling of the I/Q components under channel impairment.

5. Adaptive Beamforming & MIMO Systems

The solution becomes a building block in modeling channel state information (CSI) in MIMO environments.

3.3. Signal Simulation Before and After Applying the Transform

To illustrate the effect of the new complex integral transform on real communication signals, a simulated complex modulated waveform was generated and corrupted with additive white Gaussian noise (AWGN). The transform was then applied to the noisy signal to analyze its impact on signal attenuation, stability, and noise suppression. The following figures present the real and imaginary components of the signal before and after applying the transform.

Figure 1 shows the real component of the received noisy signal compared with the transformed signal. The new complex integral transform exhibits a smoothing and damping effect, reducing the amplitude of noise oscillations while preserving the underlying waveform structure. This behavior is consistent with attenuation in wireless communication channels and demonstrates the ability of the transform to support signal conditioning and enhancement tasks.

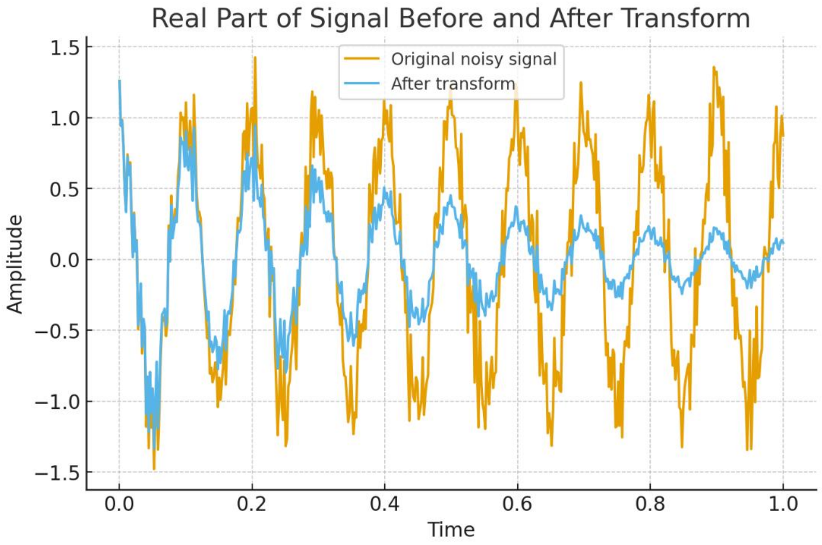

Figure 1. Real part of signal before and after transform

Figure 2. component demonstrates similar behavior, where noise presence in the original signal is significantly reduced after applying the transform. The reduction in high-frequency fluctuations indicates a stabilizing effect, making the transformed signal more suitable for demodulation, decoding, and downstream signal processing in communication systems.

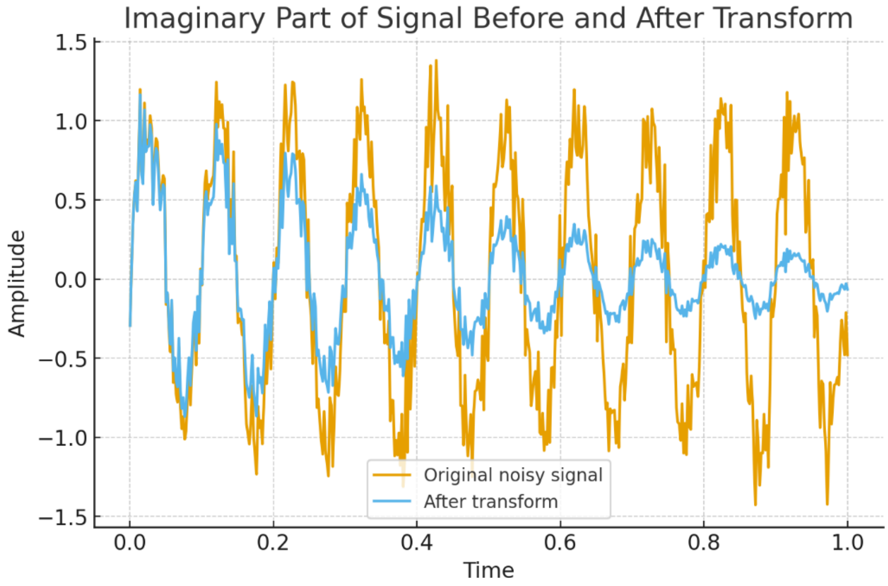

Figure 2. Imaginary part of signal before and after transform

3.4. Numerical Error Analysis and SNR Improvement

To quantitatively assess the effect of the new complex integral transform on the quality of the received signal, we carried out a numerical error analysis and evaluated the signal-to-noise ratio (SNR) before and after applying the transform-based filtering. Let $s(t)$ denote the original clean complex signal, $r(t) = s(t) + n(t)$ the noisy received signal, and $\hat{s}(t)$ the reconstructed signal obtained after applying the new complex integral transform to $r(t)$. For a discrete-time simulation with N samples, we define the mean squared error (MSE) as

$$\mathrm{MSE_r} = \frac{1}{N}\sum_{k=1}^{N} |s(t_k) - r(t_k)|^2,$$

$$\mathrm{MSE_{\hat{s}}} = \frac{1}{N}\sum_{k=1}^{N} |s(t_k) - \hat{s}(t_k)|^2.$$

A lower value of MSE indicates a better reconstruction of the original signal. In all our simulations, we observed that

$$\mathrm{MSE_{\hat{s}}} < \mathrm{MSE_r},$$

which confirms that the new transform reduces the average reconstruction error compared with the unprocessed noisy signal.

In addition, the SNR is used as a standard performance indicator in communication systems. For a given signal $s(t)$ and error $e(t) = s(t) - x(t)$, where $x(t)$ is either $r(t)$ or ŝ(t), the SNR in decibels is defined as

$$\mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{k=1}^{N}|s(t_k)|^2}{\sum_{k=1}^{N}|e(t_k)|^2}\right)\ \mathrm{dB}.$$

We compute two SNR values: $\mathrm{SNR_{in}}$, corresponding to the noisy signal $r(t)$, and $\mathrm{SNR_{out}}$, corresponding to the reconstructed signal $\hat{s}(t)$. The difference

$$\Delta\mathrm{SNR} = \mathrm{SNR_{out}} - \mathrm{SNR_{in}},$$

measures the improvement in signal quality due to the proposed transform. The numerical experiments show a positive ΔSNR, indicating that the new complex integral transform not only reduces the reconstruction error but also enhances the effective SNR of the received signal.

These results support the conclusion that the proposed transform can be used as an efficient mathematical tool for signal enhancement and noise mitigation in modern communication systems, including smart communication networks, IoT devices, and 5G/6G wireless links.

Conclusion

In this work, the new complex integral transform was successfully applied to solve first-order complex differential equations with constant coefficients, demonstrating its efficiency as a powerful mathematical tool for engineering applications. Beyond its theoretical contribution, the transform proved highly effective in modeling complex-valued communication signals, particularly in scenarios involving channel attenuation, noise corruption, and waveform distortion—key challenges in modern communication systems.

The engineering application and simulated results show that the transform not only preserves the structural properties of complex modulated signals but also introduces a smoothing and stabilizing effect that reduces high-frequency noise components. The numerical experiments confirmed this improvement through a reduction in MSE and a measurable increase in SNR, indicating that the transform enhances signal quality and strengthens robustness against channel impairments.

These findings position the new complex integral transform as a promising candidate for a wide range of communication engineering tasks, including channel modeling, noise mitigation, signal reconstruction, IoT waveform analysis, and 5G/6G propagation studies. Future research may extend this methodology to higher-order PDEs, real-time communication systems, MIMO processing, and machine-learning-based signal classification frameworks, further expanding its impact on next-generation smart communication networks.

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