SEE Transform in Difference Equations and Differential- Difference Equations Compared With Neutrosophic Difference Equations

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SEE Transform in Difference Equations and Differential-Difference Equations Compared With Neutrosophic Difference Equations

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Abstract

The Sadiq-Emad-Emann (SEE) transform, also known as operational calculus, has gained significant importance as a fundamental component of the mathematical knowledge necessary for physicists, engineers, mathematicians, and other scientific professionals. This is because the SEE transform offers accessible and efficient resources for resolving several applications and challenges encountered in diverse engineering and science domains. This study aims to introduce the fundamental principles of SEE transformation and establish the validity of two statements and associated attributes. The objective of this study is to use the aforementioned qualities in order to determine the solution of difference and differential-difference equations, with neutrosophic versions of difference and differential difference equations. In addition, we are able to get very effective and expeditious precise answers.

Keywords: SEE transform; Derivation of originals; Delay property; Differential equations; Difference equations; neutrosophic difference equation; neutrosophic differential difference equation.

1. Introduction

In the science of mathematics, it is possible to define the integral transform as a mathematical operator that generates a new function $f(y)$ by the integration of the product of an existing function $F(x)$ with a known function that is known as a kernel function $K(x, y)$, within appropriate constraints or limits. The general formula of an integral transformation is represented by $f(y) = \int K(x, y)F(x)dx$, [1].

The kernel functions and the limits of integration in an integral transform are the main factors that distinguish them from each other and define their functionality and applicability to solve different applications [2].

The simplicity that is provided by integral transform in solving differential equations made them an essential tool in solving many problems that are related into many scientific fields [3].

Due to the functionality of integral transforms, mathematicians invested time and effort in proposing new integral transformations. These efforts resulted in the proposal of many integral transforms, mostly named after the mathematician who proposed them [4]. This work invests in the Sadiq-Emad-Eman (SEE) integral transformation that the three mathematicians mentioned in 2021 have proposed [5]. The SEE integral transform is a straightforward and practical approach that immediately yields the precise solution to a wide range of

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differential equations encountered in resolving diverse technological issues, including Bessel's functions [6], Abel's integral equation [7], Faltung type Volterra integro-differential equations [8,9] and many other equations in various fields [10-12].

This work extends the usability of the SEE integral transform by solving the difference and differential-difference equations. It proves the efficiency of the SEE integral transformation in handling and solving these equations through examples. Also, we apply the same transform to solve the neutrosophic versions of the mentioned equations

I. Difference and Differential-Difference Equations

A difference equation is a mathematical equation that establishes a relationship between the current state of a system and its prior states, often by use of a recurrence relation. The mathematical equation in question serves as a means to articulate the connection between values inside a given sequence or series. They are extensively used in several domains [13]. A difference equation may be defined as an equation that establishes a relationship between the function x(t) and one or more functions $x(t-\alpha)$, where α represents a constant [14]. One kind of difference equation is known as a differential-difference equation. This type of equation allows for the presence of several derivatives of the function $x(t)$ [15].

II. Definition of the SEE Integral Transform, [5]

Consider a complex function $f(t)$ defined on the closed interval [a, b], where t is a real variable. The function may be expressed in the following form, as often recognized: $f(t) = u(t) + iv(t)$. The scope of analysis is confined to the integral of the function $f(t)$ under the stipulation that particular requirements are satisfied. These requirements are:

(1) The function f(t) is continuous in the interval $(0,\infty)$ together with all of its derivatives up to any required order, except for a limited number of first type critical points that may exist inside each finite segment.

(2) $f(t) = 0$, $t < 0$.

(3) The function $f(t)$ exhibits a more rapid growth in absolute value compared to an exponential function. There are positive integers $M > 0$ and $\gamma_0 > 0$ such that for any term t, the absolute value of $f(t)$ is less than $Me^{\gamma_0 t}$.

Definition 1: In their study, Mansour et al. (2021) introduced the Sadik-Emad-Eman (SEE) integral transform, which they presented as a novel transformation method [5]. The transformation is defined for the function $f(t)$ as follows:

$$S\{f(t)\} = \frac{1}{v^m}\int_0^\infty f(t)e^{-vt}dt = T(v), m \in \mathbb{Z}\,. \tag{1}$$

v is a complex number, $v = p + iw$ where: $\mathrm{R_e}\,(v) = p > \gamma_0$.

It is said that the function $T(v)$ is the SEE image of the function $f(t)$. By assuming $T(v)$ is a reflection of the function $f(t)$ then it is possible to say:

$$S\{f(t)\} = T(v) \text{ or } T(v) \longrightarrow f(t)\,.$$

$f(t)$ is referred to as the original function. The function $f(t)$ is original if it satisfies the three conditions listed above. The functions that satisfy these three conditions are designated as original below. From a practical standpoint, this restriction on the category of originals is not very sensible.

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III. Properties of SEE Integral Transformation

Two properties of the SEE integral transform that are crucial to this article will be presented [5].

a) SEE Transform of Derivatives

let $S\{f(t)\} = T(v)$, for $n = 1,2,3, \dots$.

Then:

(i). $S\{f'(t)\} = vT(v) - \frac{1}{v^m} f(0)$.
(ii). $S\{f''(t)\} = v^2 T(v) - \frac{1}{v^m} f'(0) - \frac{1}{v^{m-1}} f(0)$.
(iii). $S\{f^{(n)}(t)\} = v^n T(v) - \sum_{j=0}^{n-1} \frac{1}{v^{m-j}} f^{(n-j-1)}(0)$.

b) Time Shifting Property

If $S\{f(t)\} = T(v) \Rightarrow S\{f(t-t_0)\} = \frac{1}{v^m} e^{-vt_0} T(v)$.

Since $f(t) = 0$ for all $t < 0$ to which $f(t - t_0) = 0$ for $t < t_0$ and $m \in \mathbb{Z}$.

That's give:

$$
\begin{aligned}
S\{f(t-t_0)\} &= \frac{1}{v^m} \int_0^\infty e^{-vt} f(t-t_0) dt\,, \\
&= \frac{1}{v^m} \int_0^{t_0} e^{-vt} f(t-t_0) dt + \frac{1}{vj} e^{-vt} f(t-t_0) dt, \\
&= \frac{1}{v^m} \int_{t_0}^\infty e^{-vt} f(t-t_0) dt.
\end{aligned}
$$

Because in the interval: $(0, t_0), f(t - t_0) = 0$.

By performing substitution to the final integral:

$$t - t_0 = u \Rightarrow t = t_0 + u.$$

When $t|_{t_0}^{\infty}$ then $u|_0^{\infty}$ and $dt = du$, that's give:

$$
\begin{aligned}
S\{f(t-t_0)\} &= \frac{1}{v^m} \int_0^\infty e^{-v(u+t_0)} f(u) du = \frac{1}{v^m} \int_0^\infty e^{-vu} f(u) du \\
&= \frac{1}{v^m} e^{-t_0 v} T(v)\,.
\end{aligned}
$$

So, it is proven: $S\{f(t - t_0)\} = \frac{1}{v^m} e^{-t_0 v} T(v)$.

Remark:

SEE can be applied clearly to neutrosophic functions and equations. A neutrosophic function $f: R(I) \to R(I)$, can be represented by two classical functions as follows:

$f(x + yI) = g(x) + I[h(x + y) - g(x)]$. [16-17]

$S\{f(t + lI)\} = \frac{1}{(v+uI)^m} \int_0^\infty f(t + lI) e^{-(v+uI)(t+lI)} d(t + lI) = T(v + uI), m \in \mathbb{Z}$. v is a neutrosophic complex number.

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Remark:

The neutrosophic SEE has the following properties:

c) SEE Transform of Derivatives

let $S\{f(t+lI)\}=T(v+uI)$, for $n=1,2,3,\dots$.

Then:

(iv). $S\{f'(t+lI)\}=(v+uI)T(v+uI)-\frac{1}{(v+uI)^m}f(0)$.

(v). $S\{f''(t+lI)\}=(v+uI)^2T(v+uI)-\frac{1}{(v+uI)^m}f'(0)-\frac{1}{(v+uI)^{m-1}}f(0)$.

(vi). $S\{f^{(n)}(t+lI)\}=(v+uI)^nT(v+uI)-\sum_{j=0}^{n-1}\frac{1}{(v+uI)^{m-j}}f^{(n-j-1)}(0)$.

d) Time Shifting Property

If $S\{f(t+uI)\}=T(v+uI)\Rightarrow S\{f(t+lI-t_0-l_0I)\}=\frac{1}{(v+uI)^m}e^{-(v+uI)(t_0+l_0I)}T(v+uI)$.

$$
\begin{aligned}
S\{f(t+lI-t_0-l_0I)\} &= \frac{1}{(v+uI)^m}\int_0^{\infty} \mathrm{e}^{-(v+uI)(t+lI)}f(t+lI-t_0-l_0I)d(t+lI)\,, \\
&= \frac{1}{v^m}\int_0^{t_0} \mathrm{e}^{-(v+uI)(t+lI)}f(t+lI-t_0-l_0I)d(t+lI)+\frac{1}{vj}e^{-vt}f(t+lI-t_0-l_0I)dt, \\
&= \frac{1}{v^m}\int_{t_0}^{\infty} \mathrm{e}^{-(v+uI)(t+lI)}f(t+lI-t_0-l_0I)d(t+lI).
\end{aligned}
$$

IV. Applications

In this section, the SEE integral transformation is used to find the solution of difference equation and difference-differential equations.

A. Solving the Difference Equation/Neutrosophic Difference equations Via the SEE Integral Transformation

Find the exact solution of:

$$6x(t)-5x(t-1)+x(t-2)=t \ if \ x(t)=0 \text{ for } t<0\,. \tag{4}$$

Applying the SEE integral transform to both sides of the above equation:

$$6S\{x(t)\}-5S\{x(t-1)\}+S\{x(t-2)\}=S\{t\}.$$

By using the time shifting property:

$$\frac{6}{v^m}T(v)-5\frac{1}{v^m}e^{-v}T(v)+\frac{1}{v^m}e^{-2v}T(v)=\frac{1}{V^{m+2}},$$

$$T(v)\left(\frac{6}{v^m}-5\frac{1}{v^m}e^{-v}+\frac{1}{v^m}e^{-2v}\right)=\frac{1}{v^{m+2}},$$

$$T(v)\frac{1}{v^m}(6-5e^{-v}+e^{-2v})=\frac{1}{v^{m+2}},$$

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$$T(v)=\frac{1}{v^{m+2}\frac{1}{v^m}(6-5e^{-v}+e^{-2v})}=\frac{1}{v^{m+2}\frac{1}{v^m}(e^{-v}-2)(e^{-v}-3)},$$

$$T(v)=\frac{1}{v^{m+2}}\left[\frac{1}{\frac{1}{v^m}(2-e^{-v})}-\frac{1}{\frac{1}{v^m}(3-e^{-v})}\right],$$

$$T(v)=\frac{1}{v^{m+2}}\left[\frac{1}{\frac{2}{v^m}\left(1-\frac{e^{-v}}{2}\right)}-\frac{1}{\frac{3}{v^m}\left(1-\frac{e^{-v}}{3}\right)}\right],$$

$$T(v)=\frac{1}{v^{m+2}}\left[\frac{1}{2v^m}\cdot\left(1+\frac{e^{-v}}{2}+\frac{e^{-2v}}{2^2}+\cdots\right)-\frac{1}{3v^m}\left(1+\frac{e^{-v}}{3}+\frac{e^{-2v}}{3^2}+\cdots\right)\right],$$

$$T(v)=\frac{1}{6v^{m+2}}+\sum_{w=1}^{\infty}\left(\frac{1}{2^{w+1}}-\frac{1}{3^{w+1}}\right)\frac{e^{-wv}}{v^{m+2}}. \quad (5)$$

The inverse of SEE integral transform of equation (5) is the exact solution of equation (4). Hence:

$$x(t)=\frac{1}{6}t+\sum_{w=1}^{[t]}\left(\frac{1}{2^{w+1}}-\frac{1}{3^{w+1}}\right)(t-\omega).$$

$[t]$ is the greatest integer, $[t]\le t$.

Now, let us try to solve the neutrosophic equations:

$$6x(t)-5x(t-1)+x(t-2)=t \text{ if } x(t)=0 \text{ for } t<0. \quad (4)$$

Under the conditions: $t=a+bI, a, a+b$ $are\ negative$.

Applying the SEE integral transform to both sides of the above equation:

$$6S\{x(t)\}-5S\{x(t-1)\}+S\{x(t-2)\}=S\{t\}.$$

By using the time shifting property:

$$\frac{6}{v^m}T(v)-5\frac{1}{v^m}e^{-v}T(v)+\frac{1}{v^m}e^{-2v}T(v)=\frac{1}{V^{m+2}},$$

$$T(v)\left(\frac{6}{v^m}-5\frac{1}{v^m}e^{-v}+\frac{1}{v^m}e^{-2v}\right)=\frac{1}{v^{m+2}},$$

$$T(v)\frac{1}{v^m}(6-5e^{-v}+e^{-2v})=\frac{1}{v^{m+2}},$$

$$T(v)=\frac{1}{v^{m+2}\frac{1}{v^m}(6-5e^{-v}+e^{-2v})}=\frac{1}{v^{m+2}\frac{1}{v^m}(e^{-v}-2)(e^{-v}-3)},$$

$$T(v)=\frac{1}{v^{m+2}}\left[\frac{1}{\frac{1}{v^m}(2-e^{-v})}-\frac{1}{\frac{1}{v^m}(3-e^{-v})}\right],$$

$$T(v)=\frac{1}{v^{m+2}}\left[\frac{1}{\frac{2}{v^m}\left(1-\frac{e^{-v}}{2}\right)}-\frac{1}{\frac{3}{v^m}\left(1-\frac{e^{-v}}{3}\right)}\right],$$

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$$T(v)=\frac{1}{v^{m+2}}\left[\frac{1}{2v^{m}}\cdot\left(1+\frac{e^{-v}}{2}+\frac{e^{-2v}}{2^{2}}+\cdots\right)-\frac{1}{3v^{m}}\left(1+\frac{e^{-v}}{3}+\frac{e^{-2v}}{3^{2}}+\cdots\right)\right],$$

$$T(v)=\frac{1}{6v^{m+2}}+\sum_{w=1}^{\infty}\left(\frac{1}{2^{w+1}}-\frac{1}{3^{w+1}}\right)\frac{e^{-wv}}{v^{m+2}}\,. \tag{5}$$

The inverse of SEE integral transform of equation (5) is the exact solution of equation (4). Hence:

$$x(t)=\frac{1}{6}t+\sum_{w=1}^{[t]}\left(\frac{1}{2^{w+1}}-\frac{1}{3^{w+1}}\right)(t-\omega).$$

$[t]$ is the greatest integer, $[t]\leq t$.

Where, $v=s+dI, w=k+gI, t=a+bI.$

B. Solving the Differential-Difference Equation/neutrosophic differential difference equations Via the SEE Integral Transformation

Solve:

$$x'(t)+x(t-1)=t \text{ if } x(0)=0. \tag{6}$$

Applying the SEE integral transform to both sides of the above equation and applying the "derivative of original property" and the "time shifting property".

$$S\{x'(t)\}+S\{x(t-1)\}=S\{t\},$$

$$vT(v)-\frac{1}{v^{m}}x(0)+\frac{1}{v^{m}}e^{-v}T(v)=\frac{1}{v^{m+2}},$$

$$T(v)\left(v+\frac{1}{v^{m}}e^{-v}\right)=\frac{1}{v^{m+2}},$$

$$T(v)=\frac{1}{v^{m+2}\left(v+\frac{1}{v^{m}}e^{-v}\right)}=\frac{1}{v^{m+3}\left(1+\frac{1}{v^{m+1}}e^{-v}\right)},$$

$$=\frac{1}{v^{m+3}}\left(\frac{1}{v^{m}}\left(1-\frac{e^{-v}}{v}+\frac{e^{-2v}}{v^{2}}-\frac{e^{-3v}}{v^{3}}+\cdots\right)\right)$$

$$=\frac{1}{v^{m+3}}-\frac{e^{-v}}{v^{m+4}}+\frac{e^{-2v}}{v^{m+5}}-\frac{e^{-3v}}{v^{m+6}}+\cdots$$

$$=\sum_{w=0}^{\infty}\frac{-e^{wv}}{v^{m+w+3}}\,.,\tag{7}$$

The inverse of the SEE integral transform to equation (7) represents the exact solution of equation (6) as:

$$S^{-1}\left\{\sum_{w=0}^{\infty}\frac{e^{-wv}}{v^{m+w+3}}\right\}=\begin{cases}\frac{(t-w)^{\omega+3}}{(\omega+2)!} & t\geqslant\omega\\ 0\quad , & \text{otherwise}\end{cases}$$

Thus if $[t]$ denotes the greatest integer, $[t]\leq t$, then:

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$$x(t) = \sum_{w=0}^{[t]} \frac{(t-\omega)^{\omega+3}}{(w+2)!}.$$

Notes, [5]

1) $S\{t^n\} = \frac{n!}{v^{m+n+1}}$, $n \in \mathbb{N}$.
2) $S\{e^{at}\} = \frac{1}{v^m(v-a)}$, $a \in \mathbb{R}$.

Now, let us try to solve the neutrosophic version:

$$x'(t) + x(t-1) = t \text{ if } x(0) = 0. \ \ t = a + bI \tag{6}$$

Applying the SEE integral transform to both sides of the above equation and applying the "derivative of original property" and the "time shifting property".

$$S\{x'(t)\} + S\{x(t-1)\} = S\{t\},$$

$$vT(v) - \frac{1}{v^m}x(0) + \frac{1}{v^m}e^{-v}T(v) = \frac{1}{v^{m+2}},$$

$$T(v)\left(v + \frac{1}{v^m}e^{-v}\right) = \frac{1}{v^{m+2}},$$

$$T(v) = \frac{1}{v^{m+2}\left(v + \frac{1}{v^m}e^{-v}\right)} = \frac{1}{v^{m+3}\left(1 + \frac{1}{v^{m+1}}e^{-v}\right)},$$

$$= \frac{1}{v^{m+3}}\left(\frac{1}{v^m}\left(1 - \frac{e^{-v}}{v} + \frac{e^{-2v}}{v^2} - \frac{e^{-3v}}{v^3} + \cdots\right)\right)$$

$$= \frac{1}{v^{m+3}} - \frac{e^{-v}}{v^{m+4}} + \frac{e^{-2v}}{v^{m+5}} - \frac{e^{-3v}}{v^{m+6}} + \cdots$$

$$= \sum_{w=0}^{\infty} \frac{-e^{wv}}{v^{m+w+3}} \,. v = c + dI, w = g + kI \tag{7}$$

The inverse of the SEE integral transform to equation (7) represents the exact solution of equation (6) as:

$$S^{-1}\left\{\sum_{w=0}^{\infty} \frac{e^{-wv}}{v^{m+w+3}}\right\} = \begin{cases} \frac{(t-w)^{\omega+3}}{(\omega+2)!} & t \geqslant \omega \\ 0 \quad , & \text{otherwise} \end{cases}$$

Thus if $[t]$ denotes the greatest integer, $[t] \leq t$, then:

$$x(t) = \sum_{w=0}^{[t]} \frac{(t-\omega)^{\omega+3}}{(w+2)!}.$$

5. Conclusions

The integral transform is a straightforward and cost-effective approach that immediately addresses the resolution of several technical challenges encountered throughout their solution. By using the SEE integral transform, a precise analytical solution may be derived for solving both the difference equation/and its neutrosophic version and the differential difference equation with neutrosophic version of it. The findings presented in this paper enhance the practical advantages of using the SEE integral transform for solving difference equations, differential difference equations, neutrosophic difference equation, and differential difference equation.

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