Application of New Integral Transform Bayawa Transform for Solving Linear Volterra Integral Equations of the First and the Second Kinds

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Abstract: *In this paper, we utilize new integral transform namely Bayawa transform for solving linear Volterra integral equations of the first and the second kinds and determined the analytical solution. Linearity property and convolution theorem for the Bayawa transform has been proved. Bayawa transform gives a effortless powerful tool for obtaining the exact solution without a need too much time absorbing and without massive calculation work.*

Keywords: Linear Volterra integral equation, Bayawa transform, Linear functions, Convolution theorem, Inverse Bayawa transform

I. INTRODUCTION

Linear Volterra integral equations that have enormous applications in applied problems including engineering, science, and technology (Wazwaz, 2015). The most standard form of Volterra integral equations are of the form

$$q(x)u(x) = g(x) + \lambda \int_0^x k(x-t)\, u(t)dt \tag{1}$$

The kernel $k(x,t)$, the function $g(x)$ are given real valued functions, x and 0 are limit of integration and λ is a parameter.

When $q(x) = 0$ in (1) become Volterra integral equation of the first kind

$$g(x) + \lambda \int_0^x k(x-t)\, u(t)dt = 0 \tag{2}$$

When $q(x) = 1$ in (1) become Volterra integral equation of the second kind

$$u(x) = g(x) + \lambda \int_0^x k(x-t)\, u(t)dt \tag{3}$$

In the recent years, scholars developed various new integral transformations, (Kamal, 2016), (Sawi, 2024), (Bayawa, 2024), (Mahgoub, 2023), (Shehu, 2019), (Sumudu, 1998), (Tarig, 2024), (Mohand, 2024), (Aboodh,, 2013). (Elzaki, 2011), (Rishi, 2024), (Emad Faith, 2021), (Iman, 2023), (ZZ, 2024). Numerous researchers were solved the first and second kind Volterra integral equations using various integral transformations. Rishi transform for solving second kind linear Volterra integral equations (Thakur and Thakur, 2022). Application of Aboodh transform solving linear volterra integral equations of first kind(Aggarwal et al., 2018). Application of Elzaki transform for solving linear volterra integral equation of first kind (Aggarwal et al., 2018). Used of Anuj transform for solving volterra integral equations of first kind(Patil et al., 2022). Application of general integral transform for solving linear volterra integral of second kind(Patil et al., 2023). Convolution theorem for kushare transform and application in convolution type volterra integral equations of first kind (Shide et al., 2024). Application of kamal transform for solving linear Volterra integral

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equations(Aggarwal et al., 2018). Solution of linear Volterra integral equations of second kind using Mohand Transform(Aggarwal et al., 2018). Primitive of second kind of linear Volterra integral equations (Aggarwal et al., 2018). Application of Mahgoub transform for solving linear Voltera integral equations(Aggarwal et al., 2018). Used of Sawi transform for solving Voltera integral equations and Voltera integro differential equations(Ahawel et al., 2024). Aboodh transform technique to solve linear Volterra integral equations of second kind. (Anuj., 2023). Develop a new integral transform Rishi transform with its fundamental properties and determine the solution of first kind Volterra integral equations with convolution type kernel using this transform(Kumar et al., 2022).The solution of linear volterra integral equations of first kind with ZZ transform(Ozdemirs et al., 2024). The solution of convolution types for linear volterra integral equations with formable transform(Gungor., 2022). Applied sawi transform for Bessels functions with application for evaluating definite integral(Aggarwal et al., 2020). Convolution for kamal and Mahgoupb transform to solve differential and integral equations(Fadhil., 2017).

The main goal of this work is to establish exact solution for solving linear Volterra integral equations of the first and the second kinds in a very short time and without computational work.

II. METHODOLOGY

2.1 Definition of Bayawa transform(Bayawa and Haliru, 2024)

The Bayawa transform of the function $f(t), t \geq 0$ is given by

$$\beta\{f(t)\} = F(v) = v^2 \int_0^\infty f(t)\, e^{-\frac{t}{v^2}}\, dt, h_1 \leq v \leq h_2 \tag{4}$$

2.2 Bayawa transform of the derivatives of functions(Bayawa and Haliru, 2024)

$(i)\ \beta[f'(t)] = \frac{1}{v^2}F(v) - v^2 f(0)$

$(ii)\ \beta[f''(t)] = \frac{1}{v^4}F(v) - f(0) - v^2 f'(0)$

$(iii)\ \beta[f^n(t)] = \frac{1}{v^{2n}}F(v) - \sum_{k=0}^{n-1} v^{-2n+2k+4} f^{(k)}(0)$

2.3 Linearity Property theorem for Bayawa Transform.

Suppose $f_1(t)$ and $f_2(t)$ are Bayawa transform of functions $F_1(v)$ and $F_2(v)$, respectively, then Bayawa transform of $[df_1(t) + jf_2(t)]$ is given by $[dF_1(v) + jF_2(v)]$, where d and j are arbitrary constants.

Proof.

Using(1) above, we have

$$\beta\{f(t)\} = F(v) = v^2 \int_0^\infty f(t)\, e^{-\frac{t}{v^2}}\, dt$$

$$\beta\{df_1(t) + jf_2(t)\} \tag{5}$$

$$= v^2 \int_0^\infty [df_1(t) + jf_2(t)]\ e^{-\frac{t}{v^2}}\, dt$$

$$\beta\{df_1(t) + jf_2(t)\}$$

$$= d\left[v^2 \int_0^\infty f_1(t)\ e^{-\frac{t}{v^2}}\right] + j\left[v^2 \int_0^\infty f_2(t)\ e^{-\frac{t}{v^2}}\right] \quad (6)$$

$ß\{df_1(t) + jf_2(t)\}$

$= dß\{f_1(t)\} + jß\{f_2(t)\}$

$ß\{df_1(t) + jf_2(t)\}$

$$= dF_1(v) + jF_2(v) \quad (7)$$

2.4 Convolution of two Functions

The Convolution of two functions $f(t)$ and $r(t)$ is denoted by $f(t) * r(t)$ and it is defined by

$$f(t) * r(t) = f * r = \int_0^t f(x)\, r(t-x)dx$$

$$= \int_0^t r(x)\, f(t-x)dx$$

2.5 Convolution theorem for Bayawa transform

Suppose $ß\{f(t)\} = F(v)$ and $ß\{r(t)\} = R(v)$ then $ß\{f(t) * r(t)\} = ß\{f(t)\}ß\{r(t)\} = \frac{1}{v^2}F(v)R(v)$

Proof.

The key step is to interchange two integrals. Let we start the product of the Bayawa transforms, i.e $F(v)R(v)$

$$F(v) = v^2 \int_0^\infty f(w)\, e^{-\frac{w}{v^2}}\, dw \text{ and } R(v) = v^2 \int_0^\infty r(y)\, e^{-\frac{y}{v^2}}\, dy \quad (8)$$

$$F(v)R(v) = v^4 \int_0^\infty f(w)\, e^{-\frac{w}{v^2}} \int_0^\infty r(y)\, e^{-\frac{y}{v^2}}\, dwdy$$

$$= v^4 \int_0^\infty f(w) \int_0^\infty e^{-\frac{(w+y)}{v^2}} r(y)\ dwdy$$

$$= v^4 \int_0^\infty \int_0^\infty e^{-\frac{(w+y)}{v^2}} f(w)r(y)\, dwdy \quad (9)$$

Let putting $w + y = t,\ y = t - w,\ dy = dt$ and changing order integration

$$= v^4 \int_0^\infty \int_0^t e^{-\frac{t}{v^2}} f(w)r(t-w)\, dwdt$$

$$= v^2\left\{v^2 \int_0^\infty e^{-\frac{t}{v^2}} \int_0^t f(w)r(t-w)\, dwdt\right\}$$

$$= v^2\left\{v^2 \int_0^\infty e^{-\frac{t}{v^2}} (f * r)dt\right\}$$

$$F(v)R(v) = v^2\{ß(f(t) * r(t))\} \quad (10)$$

Therefore $ß\{(f(t) * r(t))\} = \frac{1}{v^2}F(v)R(v)$

2.6 Bayawa transform of some useful functions(Bayawa and Haliru, 2024)

Table 1

S/N.	$f(t)$	$ß\{f(t)\} = F(t)$
1.	1	v^4
2.	t	v^6

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3.	t^2	$2!\,v^8$
4.	t^3	$3!\,v^{10}$
5.	$t^n, n \in N$	$v^{2n+4}.n!$
6.	e^{at}	$\frac{v^4}{1 - av^2}$
7.	$sinat$	$\frac{av^6}{1 + a^2v^4}$
8.	$cosat$	$\frac{v^4}{1 + a^2v^4}$
9.	$sinhat$	$\frac{av^6}{1 - a^2v^4}$
10.	$coshat$	$\frac{v^4}{1 - a^2v^4}$

2.7 Inverse Bayawa transform (Rashdi, 2024)

If $\beta\{f(t)\} = F(t)$ then $F(t)$ is called the inverse Bayawa transform of $F(t)$ and mathematically it is define as $f(t) = \beta^{-1}\{F(t)\}$ where the operator $\beta^{-1}$is called the inverse Bayawa transform operator

2.8 Inverse Bayawa transform of some useful functions (Rashdi, 2024)

Table 2

S/N.	$F(t)$	$f(t) = \beta^{-1}\{F(t)\}$
1.	v^4	1
2.	v^6	t
3.	v^8	$\frac{t^2}{2!}$
4.	v^{10}	$\frac{t^3}{3!}$
5.	v^{2n+4},$n \in N$	$\frac{t^n}{n!}$
6.	$\frac{v^4}{1 - av^2}$	e^{at}
7.	$\frac{av^6}{1 + a^2v^4}$	$sinat$
8.	$\frac{v^4}{1 + a^2v^4}$	$cosat$
9.	$\frac{av^6}{1 - a^2v^4}$	$sinhat$
10.	$\frac{v^4}{1 - a^2v^4}$	$coshat$

III. RESULT AND DISCUSSION

We use Bayawa transform for solving linear Volterra integral equations of the first and the second kinds given by (1). In this research, we assume that the kernel of (1) is difference kernel that can be expressed by difference $(x-t)$. The linear Volterra integral equations of the first and the second kinds of (1) can be expressed as

(i) Linear Volterra integral equation of the first kind:

$$g(x) = \lambda \int_0^x k(x-t)\, u(t) dt \quad (11)`$$

Applying the Bayawa transform from both sides of (11)

$$\beta\{g(x)\} = \lambda\beta\{\int_0^x k(x-t)\, u(t) dt\} \quad (12)$$

Using convolution theorem of Bayawa transform on (12), we have

$$\beta\{g(x)\} = \frac{1}{v^2}\, \lambda\beta\{k(x)\}\beta\{u(x)\}$$

$$u(x) = \frac{v^2\beta\{g(x)\}}{\lambda\beta\{k(x)\}} \quad (13)$$

Taking inverse Bayawa transform from both sides of (13), we have

$$u(x) = \beta^{-1}\left\{\frac{v^2\beta\{g(x)\}}{\lambda\beta\{k(x)\}}\right\} \quad (14)$$

(ii) Linear Volterra integral equation of the second kind:

$$u(x) = g(x) + \lambda \int_0^x k(x-t)\, u(t) dt \quad (15)$$

Applying the Bayawa transform from both sides of (15)

$$\beta\{u(x)\} = \beta\{g(x)\} + \lambda\beta\{\int_0^x k(x-t)\, u(t) dt\} \quad (16)$$

Using convolution theorem of Bayawa transform on (16) , we have

$$\beta\{u(x)\} = \beta\{g(x)\} + \frac{\lambda}{v^2}\beta\{k(x)\}\beta\{u(x)\} \quad (17)$$

Taking inverse Bayawa transform from both sides of(17), we have

$$u(x) = g(x) + \lambda\beta^{-1}\left\{\frac{1}{v^2}\beta\{k(x)\}\beta\{u(x)\}\right\} \quad (18)$$

IV. APPLICATIONS

Some applications are given in dictate to show the validity of Bayawa transform of linear Volterra integral equations of the first and the second kind kinds.

Example 1 Consider the linear volterra integral equation of the second kind

$$sinx = \int_0^x e^{(x-t)} u(t) dt \quad (19)$$

Applying the Bayawa transform from both sides of (19)

$$\frac{v^6}{1+v^4} = \beta\left\{\int_0^x e^{(x-t)} u(t)\right\} dt \quad (20)$$

Using convolution theorem of Bayawa transform on (20) and simplify, we have

$$\frac{v^6}{1+v^4} = \frac{1}{v^2}\beta(e^x) * \beta\{u(x)\}$$

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$\frac{v^6}{1+v^4} = \frac{1}{v^2}.\frac{v^4}{1-v^2}\beta\{u(x)\}$

$\beta\{u(x)\} = \frac{v^6(1-v^2)}{v^4(1+v^4)}$

$\beta\{u(x)\} = \frac{v^6 - v^8}{v^4(1+v^4)}$

$\beta\{u(x)\} = \frac{v^6}{v^2(1+v^4)} - \frac{v^8}{v^2(1+v^4)}$

$\beta\{u(x)\} = \frac{v^4}{(1+v^4)} - \frac{v^6}{(1+v^4)}$ (21)

Taking inverse Bayawa transform from both sides of(21) , we have

$\beta^{-1}\{\beta\{u(x)\}\} = \beta^{-1}\left\{\frac{v^4}{(1+v^4)} - \frac{v^6}{(1+v^4)}\right\}$

$u(x) = cosx - sinx$ (22)

Example 2 Consider the linear volterra integral equation of the second kind

$x = \int_0^x e^{(x-t)}u(t)dt$ (23)

Applying the Bayawa transform from both sides of (23), we have

$v^6 = \quad \beta\left\{\int_0^x e^{(x-t)}u(t)\right\}dt$ (24)

Using convolution theorem of Bayawa transform on (24) and simplify, we have

$v^6 = \frac{1}{v^2}\beta(e^x) * \beta\{u(x)\}$

$v^6 = \frac{1}{v^2}.\frac{v^4}{1-v^2}\beta\{u(x)\}$

$\beta\{u(x)\} = \frac{v^6 - v^8}{v^2}$

$\beta\{u(x)\} = v^4 - v^6$ (25)

Taking inverse Bayawa transform from both sides of (25) , we have

$\beta^{-1}\{\beta\{u(x)\}\} = \beta^{-1}\{v^4 - v^6\}$

$u(x) = 1 - x$ (26)

Example 3 Consider the linear Volterra integral equation of the second kind

$u(x) = x - \int_0^x (x-t)u(t)dt$ (27)

Applying the Bayawa transform from both sides of (27), we have

$\beta\{u(x)\} = v^6 - \beta\{\int_0^x (x-t)\,(u(t))\}dt$ (28)

Using convolution theorem of Bayawa transform on (28), we have

$\beta\{u(x)\} = v^6 - \frac{1}{v^2}\beta(x) * \beta\{u(x)\}$

$\beta\{u(x)\} = v^6 - \frac{1}{v^2}\,.v^6 * \beta\{u(x)\}$

$\beta\{u(x)\} = v^6 - v^4\beta\{u(x)\}$

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$\beta\{u(x)\}\,\{1+v^4\} = v^6$

$\beta\{u(x)\} = \frac{v^6}{1+v^4}$ (29)

Taking inverse Byawa transform from both sides of (29), we have

$\beta^{-1}\{\beta\{u(x)\}\} = \beta^{-1}\left\{\frac{v^6}{1+v^4}\right\}$

$u(x) = sinx$ (30)

Example 4 Consider the linear Volterra integral equation of the second kind

$u(x) = 1 - \int_0^x (x-t)u(t)dt$ (31)

Applying the Bayawa transform from both sides of (31)

$\beta\{u(x)\} = v^4 - \beta\{\int_0^x (x-t)\,(u(t))\}dt$ (32)

Using convolution theorem of Bayawa transform on (32) and simplify, we have

$\beta\{u(x)\} = v^4 - \frac{1}{v^2}\beta(x) * \beta\{u(x)\}$

$\beta\{u(x)\} = v^4 - \frac{1}{v^2}\,.\,v^6 * \beta\{u(x)\}$

$\beta\{u(x)\} = v^4 - v^4\beta\{u(x)\}$

$\beta\{u(x)\}\,\{1+v^4\} = v^4$

$\beta\{u(x)\} = \frac{v^4}{1+v^4}$ (33)

Taking inverse Bayawa transform from both sides of (33), we have

$\beta^{-1}\{\beta\{u(x)\}\} = \beta^{-1}\left\{\frac{v^4}{1+v^4}\right\}$

$u(x) = cosx$ (34)

Example 5 Consider the linear Volterra integral equation of the second kind

$u(x) = 1 - \frac{x^2}{2} + \int_0^x u(t)dt$ (35)

Applying the Bayawa transform from both sides of (35), we have

$\beta\{u(x)\} = v^4 - v^8 + \beta\{\int_0^x u(t)\}dt$ (36)

Using convolution theorem of Bayawa transform on (36), and simplify, we have

$\beta\{u(x)\} = v^4 - v^8 + \beta\{\int_0^x u(t)\}dt$

$\beta\{u(x)\} = v^4 - v^8 + \frac{1}{v^2}\beta(1) * \beta\{u(x)\}$

$\beta\{u(x)\} = v^4 - v^8 + \frac{1}{v^2}\,.\,v^4 * \beta\{u(x)\}$

$\beta\{u(x)\} = v^4 - v^8 + v^2\beta\{u(x)\}$

$\beta\{u(x)\}\,\{1-v^2\} = v^4 - v^8$

$\beta\{u(x)\} = \frac{v^4-v^8}{1-v^2}$ (37)

Simplifying and taking inverse Bayawa transform from both sides of (37), we have

$$ß\{u(x)\} = v^4\left\{\frac{1-v^4}{1-v^2}\right\} = \frac{v^4(1+v^2)(1-v^2)}{1-v^2}$$

$$ß^{-1}\{ß\{u(x)\}\} = ß^{-1}\{v^4 + v^6\}$$

$$u(x) = 1 + x \quad (38)$$

Example 6 Consider the linear Volterra integral equation of the second kind

$$u(x) = 1 + \int_0^x u(t)dt \quad (39)$$

Applying the Bayawa transform to both sides of (39), we have

$$ß\{u(x)\} = v^4 + ß\{\int_0^x u(t)\}dt \quad (40)$$

Using convolution theorem of Bayawa transform on (40) and simplify, we have

$$ß\{u(x)\} = v^4 + ß\{\int_0^x u(t)\}dt$$

$$ß\{u(x)\} = v^4 + \frac{1}{v^2}ß(1) * ß\{u(x)\}$$

$$ß\{u(x)\} = v^4 + \frac{1}{v^2}.v^4 * ß\{u(x)\}$$

$$ß\{u(x)\} = v^4 + v^2ß\{u(x)\}$$

$$ß\{u(x)\}\{1-v^2\} = v^4$$

$$ß\{u(x)\} = \frac{v^4}{1-v^2} \quad (41)$$

Taking inverse Bayawa transform from both sides of (41) , we have

$$ß^{-1}\{ß\{u(x)\}\} = ß^{-1}\left\{\frac{v^4}{1-v^2}\right\}$$

$$u(x) = 1 + x$$

$$(42)$$

V. CONCLUSION

We have successfully utilized the new Bayawa transform to obtain exact solution of both first and second kind of linear Volterra integral equations. The results show that new Bayawa transform is a very useful integral transform for solving these type equations for finding the exact solution without large computational work.

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