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On the (P,Q) - Analog of the Bromwich Integral

Akwaboah Vincent[1,2,*]

[1] Department of Mathematics, School of Mathematical Sciences, University of Technology and Applied Sciences (UTAS), Navrongo, Ghana
[2] Department of Mathematics, Seventh-Day Adventist College of Education, Agona, Ghana- West Africa

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Abstract: This paper introduces and investigates the (p,q)-Analogue of the Bromwich integral providing a rigorous framework for the inversion of the (p,q)-Laplace transform. By utilizing the properties of (p,q)-Calculus and the Jackson integral, the complex inversion formula is derived and applied to fundamental (p,q)-functions including trigonometric and hyperbolic functions. The results in this paper demonstrate that the (p,q)-Bromwich integral acts as a bridge between continuous complex dynamics and discrete quantum states, offering a more generalized approach than the standard q-analogue.

Keywords: (p,q)-Calculus, Bromwich integral, Residue Theorem.

1 Introduction

The Bromwich integral is the fundamental tool for transitioning from the complex s-domain back to the time domain in the classical theory[8]. While q-calculus [13] handles single-parameter scaling, (p,q)-calculus offers a dual parameter deformation that captures deeper symmetries in quantum calculus[5,6,8].While q-calculus is a powerful tool for modeling basic quantum systems, it is inherently asymmetric. Symmetry is restored when $p,q)$ is introduced[4,6]. Moreover, one of the primary challenges in (q)-calculus is the divergence of q - series when $q > 1$. In the (p,q)-domain the Bromwich integral maintains convergence by adjusting the ratio (q/p)[3,4, 10,11].

In this article, the (p,q)-inversion formula is developed[3,5,11]. It argues that the (p,q)-Bromwich integral is not merely a theoretical extension but a practical necessity for analyzing systems where space-time is modeled on a geometric lattice with non-uniform scaling. Fractional inversion almost always introduces branch cuts due to the $\int^{\alpha}$ terms which makes them computationally analytically difficult to deal with however (p,q) - Bromwich inversion maintain the use of isolated (p,q) poles allowing for a clean algebraic evaluation[8,9,11]. The classical q-Bromwich integral is particularly for analysis quantum groups and solving q - difference equation[1,2,7,11] whiles the (p,q) Bromwich integral is used to model more complex physical phenomena particularly for refining approximation of standard multivariate calculus[3,8,9].

The (p,q) analogue of the Brownwich integral cannot be achieve without the application of Cauchy's Residue theorem which rests on the principle analytic continuation. The relationship between the (p,q) exponential kernel and the (p,q) derivative demands that the (p,q) residue is justified to be used. The kernel $e_{p,q}(st)$ is the unique eigen function of the $D_{p,q}[e_{p,q}(st)] = se_{p,q}(st)$. The inversion helps to extract the eigen value.

For a function $f(t)$, the classical Bromwich integral is defined as:

$$f(t) = \mathscr{L}^{-1}\{F(s)\} = \frac{1}{2\pi i}\lim_{T\to\infty}\int_{\gamma-iT}^{\gamma+iT} e^{st}F(s)\,ds \qquad (1)$$

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Convergence is satisfied if the limit exists and diverges if the limit does not exist [1,2].

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[*] Corresponding author e-mail: akwavin1990@gmail.com

2 Definitions and Notations

In this section, definitions and notations of the (p,q)-analogue with (p,q)-derivatives and some properties of (p,q)-calculus are given. Throughout this paper, let $0 < q < p \leq 1$.

2.1 The (p,q)-Number

The (p,q)-integer $[n]_{(p,q)}$ is defined as

$$[n]_{(p,q)} = \frac{p^n - q^n}{p-q} \quad \text{as } p \to 1, q \to 1 \implies [n]_{(p,q)} \to n \tag{2}$$

2.2 The (p,q)-Derivative

The (p,q)-derivative of a function $f(s)$ is given by

$$D_{(p,q)}f(s) = \frac{f(ps) - f(qs)}{(p-q)s}, \quad s \neq 0 \tag{3}$$

2.3 The (p,q)-Exponential Function

The (p,q)-exponential function, which serves as the kernel for the Bromwich integral, is given as

$$E_{(p,q)}(z) = \sum_{n=0}^{\infty} \frac{p^{\binom{n}{2}} z^n}{[n]_{(p,q)}!} \tag{4}$$

2.4 The (p,q)-Factorial

The (p,q)-factorial $[n]_{(p,q)}!$ is defined as

$$[n]_{(p,q)}! = p^{n-1} - p^{n-2}q + \ldots + q^{n-1}, \quad [0]_{(p,q)}! = 1 \tag{5}$$

2.5 The (p,q)-Residue

Let F(s) be a rational function in the complex s - domain with the poles s_k and let $D_{p,q}$ be the (p,q) - difference operator with respect to s. The (p,q)-residue for a function $\frac{P(s)}{Q(s)}$ is given by

$$\mathrm{Res}_{(p,q)} = \frac{P(s)}{D_{(p,q)}Q(s)} \tag{6}$$

2.6 The (p,q)-Trigonometric Functions

(a)$\cos_{(p,q)}(z) = \frac{E_{(p,q)}^{(iz)} + E_{(p,q)}^{(-iz)}}{2}$

(b)$\sin_{(p,q)}(z) = \frac{E_{(p,q)}^{(iz)} - E_{(p,q)}^{(-iz)}}{2i}$

2.7 The (p,q)-Hyperbolic Functions

(a)$\cosh_{(p,q)}(z) = \frac{E_{(p,q)}^{(z)} + E_{(p,q)}^{(-z)}}{2}$

(b)$\sinh_{(p,q)}(z) = \frac{E_{(p,q)}^{(z)} - E_{(p,q)}^{(-z)}}{2}$

2.8 The (p,q)-Jackson Integral

The (p,q)-Jackson integral is given by

$$\int_0^a f(s)\, d_{(p,q)}s = a(p-q) \sum_{n=0}^{\infty} \frac{q^n}{p^{n+1}} f\left(\frac{aq^n}{p^{n+1}}\right) \tag{7}$$

2.9 The (p,q)-Laplace Transform

The (p,q)-Laplace transform of functions $f(t)$ is defined by

$$\mathscr{L}_{(p,q)}\{f(t)\}(s) = \int_0^{\infty} f(t) E_{(p,q)}^{-st}\, d_{(p,q)}t \tag{8}$$

3 Main Result

Definition 3: For a given function $F(s)$, the (p,q)-analog of the Bromwich integral is defined as

$$f(t) = \mathscr{L}_{(p,q)}^{-1}\{F(s)\} = \frac{1}{2\pi i} \int_{\gamma - i\infty}^{\gamma + i\infty} F(s) E_{(p,q)}^{(pst)}\, d_{(p,q)}s \tag{9}$$

which converges if $|f(t)| \leq ME_{(p,q)}(\alpha t)$ for some constants M and α, and $\gamma > \alpha \frac{p}{q}$.

4 Exponential Inversion

Theorem 3.1: Let $F(s)$ be a (p,q)-Laplace transform of an unknown function $f(t)$. If $F(s)$ is a rational function defined by a single simple pole on the real axis such that

$$F(s) = \frac{1}{s-a} \quad \text{where } a \in \mathbb{R} \tag{10}$$

and s is the complex frequency variable, then the time-domain function $f(t)$ recovered via the (p,q)-Bromwich integral is the (p,q)-exponential function:

$$f(t) = \mathscr{L}_{(p,q)}^{-1}\left\{\frac{1}{s-a}\right\} = e_{(p,q)}(at). \tag{11}$$

Proof:

$$f(t) = \frac{1}{2\pi i} \int_{\gamma - i\infty}^{\gamma + i\infty} \frac{1}{s-a} e_{(p,q)}(st)\, ds \tag{12}$$

Using the residue theorem:

$$\operatorname{Res}_{(p,q)} = \frac{P(s_k)}{D_{(p,q)}Q(s_k)} e_{(p,q)}(s_k t) \tag{13}$$

where $P(s) = 1$ and $Q(s) = s - a$.
Now, we compute the derivative:

$$D_{(p,q)}(s-a) = \frac{(ps-a)-(qs-a)}{(p-q)s} \implies \frac{(p-q)s}{(p-q)s} = 1. \tag{14}$$

At $s = a$:

$$\operatorname{Res}_{(p,q)}(a) = \frac{1}{1} e_{(p,q)}(at). \tag{15}$$

Thus,

$$f(t) = e_{(p,q)}(at), \tag{16}$$

which confirms that the inversion of $\frac{1}{s-a}$ is exactly the (p,q)-exponential function.

5 Trigonometric Inversion

Using the (p,q)-Residue Theorem, this section presents some primary inversion results.

Theorem 3.2: Let $F(s)$ be a function in the complex s-plane, specifically the (p,q)-Laplace transform of an unknown function $f(t)$. If

$$F(s) = \frac{a}{s^2+a^2} \quad \text{where } a \in \mathbb{R} \tag{17}$$

and s is the complex frequency variable, then the (p,q)-sine inverse Laplace transform evaluated through the (p,q)-Bromwich integral is given by

$$f(t) = \frac{2}{p+q} \sin_{(p,q)}(at). \tag{18}$$

Proof:
From Definition 2.6,

$$\sin_{(p,q)}(at) = \frac{E_{(p,q)}(iat) - E_{(p,q)}(-iat)}{2i}. \tag{19}$$

We find $F(s)$:

$$F(s) = \mathscr{L}_{(p,q)}\{\sin_{(p,q)}(at)\} = \frac{a}{s^2+a^2}. \tag{20}$$

Thus,

$$f(t) = \frac{1}{2\pi i} \int_{\gamma-i\infty}^{\gamma+i\infty} \frac{a}{s^2+a^2} e_{(p,q)}(st)\, ds. \tag{21}$$

Using the residue theorem:

$$\operatorname{Res}_{(p,q)} = \frac{P(s_k)}{D_{(p,q)}Q(s_k)} e_{(p,q)}(s_k t) \tag{22}$$

where $Q(s) = s^2 + a^2$.

The derivative is:

$$D_{(p,q)}(s^2+a^2) = [2]_{(p,q)} s \implies (p+q)s. \tag{23}$$

At $s_1 = ia$:

$$\operatorname{Res}_{(p,q)}(ia) = \frac{1}{i(p+q)} e_{(p,q)}(iat). \tag{24}$$

At $s_2 = -ia$:

$$\operatorname{Res}_{(p,q)}(-ia) = \frac{-1}{i(p+q)} e_{(p,q)}(-iat). \tag{25}$$

Thus,

$$\begin{aligned} f(t) &= \operatorname{Res}_{(p,q)}(ia) + \operatorname{Res}_{(p,q)}(-ia) \\ &= \frac{1}{i(p+q)} \left[e_{(p,q)}(iat) - e_{(p,q)}(-iat) \right], \end{aligned} \tag{26}$$

leading to

$$\begin{aligned} f(t) &= \frac{2}{(p+q)} \left[\frac{e_{(p,q)}(iat) - e_{(p,q)}(-iat)}{2i} \right] \\ &= \frac{2}{(p+q)} \sin_{(p,q)}(at). \end{aligned} \tag{27}$$

This shows that when $p = 1$ and $q = 1$, $f(t)$ collapses back to the classical Laplace transform.

Theorem 3.3: Let $F(s)$ be a function in the complex s-plane. The (p,q)-inverse Laplace transform of the cosine function evaluated via the (p,q)-Bromwich integral is given by

$$f(t) = \frac{2}{(p+q)} \cos_{(p,q)}(at). \tag{28}$$

Proof:
From Definition 2.6,

$$\cos_{(p,q)}(at) = \frac{E_{(p,q)}(iat) + E_{(p,q)}(-iat)}{2}. \tag{29}$$

We find $F(s)$:

$$F(s) = \mathscr{L}_{(p,q)}\{\cos_{(p,q)}(at)\} = \frac{s}{s^2+a^2}. \tag{30}$$

Thus,

$$f(t) = \frac{1}{2\pi i} \int_{\gamma-i\infty}^{\gamma+i\infty} \frac{s}{s^2+a^2} e_{(p,q)}(st)\, ds. \tag{31}$$

Using the residue theorem:

$$\operatorname{Res}_{(p,q)} = \frac{P(s_k)}{D_{(p,q)}Q(s_k)} e_{(p,q)}(st) \tag{32}$$

where $Q(s) = s^2 + a^2$.
The derivative is:

$$D_{(p,q)}(s^2 + a^2) = [2]_{(p,q)} \implies (p+q). \tag{33}$$

At $s_1 = ia$:

$$\text{Res}_{(p,q)}(ia) = \frac{1}{(p+q)} e_{(p,q)}(iat). \tag{34}$$

At $s_2 = -ia$:

$$\text{Res}_{(p,q)}(-ia) = \frac{1}{(p+q)} e_{(p,q)}(-iat). \tag{35}$$

Thus,

$$\begin{aligned} f(t) &= \text{Res}_{(p,q)}(ia) + \text{Res}_{(p,q)}(-ia) \\ &= \frac{1}{(p+q)} [e_{(p,q)}(iat) + e_{(p,q)}(-iat)], \end{aligned} \tag{36}$$

leading to

$$\begin{aligned} f(t) = \frac{2}{(p+q)} \left[\frac{e_{(p,q)}(iat) + e_{(p,q)}(-iat)}{2} \right] \\ = \frac{2}{(p+q)} \cos_{(p,q)}(at). \end{aligned} \tag{37}$$

This completes the proofs.

6 Hyperbolic Inversion

Theorem 3.4: Let $F(s)$ be a (p,q)-Laplace transform of an unknown function $f(t)$. If $F(s)$ is characterized by a symmetric pair of real poles and takes the algebraic form

$$F(s) = \frac{a}{s^2 - a^2} \tag{38}$$

where a is real and s is the complex frequency variable, then the time-domain function $f(t)$ recovered via the (p,q)-inverse Laplace transform of the hyperbolic sine, defined through the (p,q)-Bromwich integral, is given by

$$f(t) = \frac{2}{(p+q)} \sinh_{(p,q)}(at). \tag{39}$$

Proof: From Definition 2.7,

$$\sinh_{(p,q)}(at) = \frac{E_{(p,q)}(at) - E_{(p,q)}(-at)}{2}. \tag{40}$$

This leads to

$$F(s) = \mathscr{L}_{(p,q)}\{\sinh_{(p,q)}(at)\} \Rightarrow \frac{a}{s^2 - a^2}. \tag{41}$$

Thus,

$$f(t) = \frac{1}{2\pi i} \int_{\gamma - i\infty}^{\gamma + i\infty} \frac{a}{s^2 - a^2} e_{(p,q)}(st)\, ds. \tag{42}$$

Using the residue theorem:

$$\text{Res}_{(p,q)} = \frac{P(s_k)}{D_{(p,q)} Q(s_k)} e_{(p,q)}(st), \tag{43}$$

where $Q(s) = s^2 - a^2$.
The derivative is:

$$D_{(p,q)} Q(s) = [2]_{(p,q)} \Rightarrow (p+q)s. \tag{44}$$

At $s_1 = a$:

$$\text{Res}_{(p,q)}(a) = \frac{1}{(p+q)} e_{(p,q)}(at). \tag{45}$$

At $s_2 = -a$:

$$\text{Res}_{(p,q)}(-a) = \frac{-1}{(p+q)} e_{(p,q)}(-at). \tag{46}$$

Thus,

$$\begin{aligned} f(t) &= \text{Res}_{(p,q)}(a) + \text{Res}_{(p,q)}(-a) \\ &= \frac{1}{(p+q)} [e_{(p,q)}(at) - e_{(p,q)}(-at)], \end{aligned} \tag{47}$$

leading to

$$\begin{aligned} f(t) = \frac{2}{(p+q)} \left[\frac{e_{(p,q)}(at) - e_{(p,q)}(-at)}{2} \right] \\ = \frac{2}{(p+q)} \sinh_{(p,q)}(at). \end{aligned} \tag{48}$$

This shows that when $p = 1$ and $q \to 1$, $f(t)$ takes it back to the classical limit.

Theorem 3.5: Let $F(s)$ be a function in the complex s-plane. The (p,q)-inverse Laplace transform of the hyperbolic cosine, evaluated via the (p,q)-Bromwich integral, is given by

$$f(t) = \frac{2}{(p+q)} \cosh_{(p,q)}(at). \tag{49}$$

Proof: From Definition 2.7,

$$\cosh_{(p,q)}(at) = \frac{E_{(p,q)}(at) + E_{(p,q)}(-at)}{2}. \tag{50}$$

We find $F(s)$:

$$F(s) = \mathscr{L}_{(p,q)}\{\cosh_{(p,q)}(at)\} \Rightarrow \frac{s}{s^2 - a^2}. \tag{51}$$

Thus,

$$f(t) = \frac{1}{2\pi i}\int_{\gamma-i\infty}^{\gamma+i\infty} \frac{s}{s^2-a^2} e_{(p,q)}(st)\,ds. \tag{52}$$

Using the residue theorem,

$$\mathrm{Res}_{(p,q)} = \frac{P(s_k)}{D_{(p,q)}Q(s_k)} e_{(p,q)}(st), \tag{53}$$

where $Q(s) = s^2 - a^2$.
The derivative is:

$$D_{(p,q)}(s^2-a^2) = [2]_{(p,q)}s \Rightarrow (p+q)s. \tag{54}$$

At $s_1 = a$:

$$\mathrm{Res}_{(p,q)}(a) = \frac{1}{(p+q)} e_{(p,q)}(at). \tag{55}$$

At $s_2 = -a$:

$$\mathrm{Res}_{(p,q)}(-a) = \frac{1}{(p+q)} e_{(p,q)}(-at). \tag{56}$$

Thus,

$$\begin{aligned} f(t) &= \mathrm{Res}_{(p,q)}(a) + \mathrm{Res}_{(p,q)}(-a) \\ &= \frac{1}{(p+q)}[e_{(p,q)}(at) + e_{(p,q)}(-at)], \end{aligned} \tag{57}$$

leading to

$$\begin{aligned} f(t) &= \frac{2}{(p+q)}\left[\frac{e_{(p,q)}(at)+e_{(p,q)}(-at)}{2}\right] \\ &= \frac{2}{(p+q)}\cosh_{(p,q)}(at). \end{aligned} \tag{58}$$

This completes the proof.

7 Illustrative Examples

Let's consider a second-order (p,q)-difference equation where $y(t)$ represents the displacement on a geometric lattice:

$$D^2_{(p,q)}y(t) + w^2 y(pt) = 0 \tag{59}$$

with initial conditions

$$y(0) = 0, \quad D_{(p,q)}y(0) = w. \tag{60}$$

Solution:

Taking the (p,q)-Laplace transform, we have:

$$\mathscr{L}_{(p,q)}\{D^2_{(p,q)}y(t)\} = s^2Y(s) - sy(0) - D_{(p,q)}y(0). \tag{61}$$

Substituting the initial conditions, we get:

$$s^2Y(s) - 0 - w + w^2Y(s) = 0. \tag{62}$$

This simplifies to

$$(s^2+w^2)Y(s) = w. \tag{63}$$

Thus,

$$Y(s) = \frac{w}{s^2+w^2}. \tag{64}$$

Next, we compute the derivative:

$$D_{(p,q)}(s^2+w^2) = (p+q)s. \tag{65}$$

Calculating the residues:
At $s = iw$:

$$\begin{aligned} \mathrm{Res}_{(p,q)}(iw) &= \frac{w}{(p+q)iw} e_{(p,q)}(iwt) \\ &\Rightarrow \frac{1}{(p+q)i} e_{(p,q)}(iwt). \end{aligned} \tag{66}$$

At $s = -iw$:

$$\begin{aligned} \mathrm{Res}_{(p,q)}(-iw) &= \frac{w}{(p+q)(-iw)} e_{(p,q)}(-iwt) \\ &\Rightarrow \frac{-1}{(p+q)i} e_{(p,q)}(-iwt). \end{aligned} \tag{67}$$

Thus, the solution is:

$$\begin{aligned} y(t) &= \mathrm{Res}_{(p,q)}(iw) + \mathrm{Res}_{(p,q)}(-iw) \\ &= \frac{1}{(p+q)i}\left[e_{(p,q)}(iwt) - e_{(p,q)}(-iwt)\right]. \end{aligned} \tag{68}$$

This simplifies to

$$y(t) = \frac{2}{(p+q)}\sinh_{(p,q)}(wt). \tag{69}$$

As $p,q \to 1$, the solution collapses back to the classical solution:

$$y(t) = \sin(wt). \tag{70}$$

8 Illustrative Example 2

Consider the following second-order (p,q)-difference equation, where $y(t)$ represents the state of the system:

$$D^2_{(p,q)}y(t) - a^2 y(pt) = 0 \tag{71}$$

with initial conditions:

$$y(0) = 1, \quad D_{(p,q)}y(0) = 0. \tag{72}$$

Solution:

Taking the (p,q)-Laplace transform, we have:

$$\mathscr{L}_{(p,q)}\{D^2_{(p,q)}y(t)\} = s^2Y(s) - sy(0) - D_{(p,q)}y(0). \tag{73}$$

Substituting the initial conditions yields:

$$(s^2Y(s) - s - 0) - a^2Y(s) = 0. \tag{74}$$

This simplifies to:

$$(s^2 - a^2)Y(s) = s. \tag{75}$$

Thus,

$$Y(s) = \frac{s}{s^2 - a^2}. \tag{76}$$

Next, we compute the derivative:

$$D_{(p,q)}(s^2 - a^2) = (p+q)s. \tag{77}$$

Calculating the residues:
At $s_1 = a$:

$$\text{Res}(a) = \frac{a}{(p+q)(a)}e_{(p,q)}(at) \Rightarrow \frac{1}{(p+q)}e_{(p,q)}(at). \tag{78}$$

At $s_2 = -a$:

$$\text{Res}(-a) = \frac{-a}{(p+q)(-a)}e_{(p,q)}(-at) \Rightarrow \frac{1}{(p+q)}e_{(p,q)}(-at). \tag{79}$$

Thus, we have:

$$y(t) = \frac{1}{(p+q)}\left[e_{(p,q)}(at) + e_{(p,q)}(-at)\right]. \tag{80}$$

Recognizing that

$$\cosh_{(p,q)}(at) = \frac{e_{(p,q)}(at) + e_{(p,q)}(-at)}{2}, \tag{81}$$

we finally obtain:

$$y(t) = \frac{2}{(p+q)}\cosh_{(p,q)}(at). \tag{82}$$

As the parameters $p,q \to 1$, the solution perfectly recovers back to the classical hyperbolic cosine:

$$y(t) = \cosh(at). \tag{83}$$

9 Conclusion

The (p,q) - analog of the Bromwich integral provides a robust framework for complex analysis within post-quantum calculus. By formalizing the relationship between s-domain poles and (p,q)-functional outputs, this work enables the analytical modeling of physical systems characterized by geometric scaling and non-uniform sampling particularly in fractal media, porous networks ,Statistical Mechanics and Non-Extensive Thermodynamics,Quantum signal processing and filter design.

10 References

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