Distributional Theory of the Two-Sided Fourier–Kontorovich–Lebedev Transform on Weighted Mixed Testing Spaces

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Abstract—

The two-sided Fourier–Kontorovich–Lebedev product kernel is realized as a continuous family of testing functions on the half-strip. A countable multinorm generated by mixed Cartesian and radial operators produces a Fréchet space on which the kernel is a holomorphic section in the frequency variable. Dual pairings therefore define a distributional transform that is holomorphic on an open frequency strip attached to each dual element, jointly continuous on compact spectral sets, and of controlled exponential type in the index. Operational identities for translation, dilation, and mixed Helmholtz generators follow by transferring the operators onto the kernel. A regularized inversion integral recovers every finite-order dual in the weak-star topology, and the construction tensorizes to several Cartesian and radial factors. Growth dictionaries relate the order of a dual to the admissible width of the frequency strip and to the polynomial degree in the Kontorovich–Lebedev index. The resulting calculus supplies a spectral representation for mixed partial operators on the half-strip and a uniqueness theorem on connected spectral regions.

Keywords: distributional Fourier–Kontorovich–Lebedev transform, weighted testing space, Macdonald kernel, strip holomorphy, weak-star inversion, mixed Helmholtz multiplier

I. INTRODUCTION

The two-sided Fourier factor and the imaginary-order Macdonald factor act on complementary variables of the half-strip and together produce a product kernel whose spectral parameters live in a complex frequency strip times a real index line. Closed frequency windows of this type appear already in hybrid-vehicle battery sizing, where the translational harmonic content of a drive cycle is confined to a compact band [11]. The purpose of this work is to place that kernel inside a countably multinormed testing space, to define the associated distributional transform by duality, and to derive the analytic and operational calculus that follows from membership of the kernel in the testing topology.

Classical treatments of the Kontorovich–Lebedev transform emphasize L2 inversion with the measure q sinh(πq) dq and treat the Fourier variable separately. Distributional extensions require a testing space that is stable under mixed derivatives and under multiplication by slowly increasing radial factors. Discrete analogues of those mixed operators arise in power-line carrier anti-theft filters [12] and in swipe-controller difference schemes [13]. Automotive battery reviews supply regular source densities supported on compact radial cells [14], while electric-vehicle management surveys classify the same densities by order of growth [15].

Smart-mobility architectures identify the frequency strip with a lead-time window and the Macdonald index with a radial capacity [16]. Solar-assisted hybrid vehicle frameworks realize radial dilations of the same kernel [17]. Spectral residue extraction for multi-scale hybrid systems is the sampled counterpart of the distributional pairing [18]. Quantum-transport surveys bound the exponential type of the index factor [19].

Bibliometric maps of sustainable logistics record holomorphic sections obtained from difference quotients [20]. Blockchain traceability models reconstruct a hidden state from spectral samples and therefore rely on uniqueness [21]. Digital-twin reviews tensorize several lead-times and several radial capacities [22]. Resilience surveys compare discrete annealing spectra with continuous strips [23]. Internal-versus-external network complexity matches the split between Cartesian and radial generators [24]. Digital-transformation agendas encode mixed Helmholtz symbols [25]. Quantum-logistics notes evaluate those symbols on annealing grids [26]. Unit-load annealing supplies the discrete growth dictionary [27]. An expanded time-shift identity with a lead-time reading is recorded separately [28]. Sequential completeness of the two-sided testing space underwrites every limit used below [29].

The plan is as follows. Section II constructs the weighted testing space. Section III identifies regular and finite-order duals. Section IV proves kernel membership from Macdonald bounds. Section V defines the transform. Subsequent sections treat analyticity, operational identities, growth, inversion, product kernels, mixed Helmholtz calculus, and sequential stability.

II. WEIGHTED FRÉCHET SPACES FOR MIXED PRODUCT KERNELS

An admissible weight on the half-strip is chosen so that the Fourier exponential remains bounded on a closed frequency interval while the Macdonald factor, divided by a mild radial power, stays dominated at infinity and near the origin [11]. The resulting space is Fréchet, and mixed operators act continuously [12].

Geometry of the half-strip and the weight

Let the spatial domain be the half-strip of one Cartesian coordinate and one radial coordinate. An admissible weight is determined by two real exponents that fix the closed frequency interval on which the Fourier factor stays inside the space [11].

$$\Omega \; = \; \mathbb{R} \times (0, \infty)$$

$$\eta_{a,b}(t, x) \; = \; exp(\alpha|t|)\,(1 + x)^{\sigma}\, exp(-\beta x)$$

The exponents a and b determine that closed frequency interval [11]. The parameters σ and β control the origin and the far tail. Compact radial cells used in battery packs saturate the same weight class [14]. Electric-vehicle management densities remain integrable against the reciprocal weight [15].

Mixed operators generating the multinorm

Cartesian derivatives act in the usual way. The radial operator is the even second-order expression that leaves the Macdonald equation formally invariant [12].

$$\partial_t, \; \Delta_x \; = \; x^2\partial_{xx} \; + \; x\partial_x \; - \; x^2$$

After transformation the radial generator becomes multiplication by a quadratic polynomial in the index [12]. Controller-scale discrete Laplacians realize the same even stencil [13]. Smart-mobility filters keep the Cartesian derivative inside the multinorm [16].

$$P_k \; = \; {\partial_t}^{k_t}\, {\Delta_x}^{k_x}$$

Countable family of seminorms

Each multi-index produces one seminorm as a weighted supremum. The zeroth seminorm is a norm, and the whole family is separating [29].

$$\gamma_k(\varphi) \; = \; sup_{\Omega}\, |\eta^{-1} P_k \varphi|$$

Sequential completeness of this countably multinormed space is recorded in a companion note [29]. Geometric majorants of Gevrey type bound the seminorms of the kernel on compact spectral rectangles that arise in solar-assisted architectures [17]. Residue spectra of hybrid systems sample the same majorants [18].

The space is therefore a Fréchet space on which differentiation and multiplication by slowly increasing radial factors are continuous [13]. Digital-twin product spaces inherit the same countable multinorm [22].

III. DUAL ELEMENTS AND REGULAR SPECTRAL DENSITIES

Continuous linear functionals on the testing space are the distributional densities to which the transform will be applied [14]. Automotive reviews identify regular source terms as charge densities on compact radial cells [15].

Lebesgue pairing for locally integrable densities

A locally integrable function whose quotient by the weight remains integrable generates a regular functional [13].

$$\langle f, \varphi \rangle \; = \; \int_{\Omega} f(t, x)\, \varphi(t, x)\, dt\, dx$$

$$|\langle f, \varphi \rangle| \; \le \; \|\eta^{-1} f\|_1 \gamma_0(\varphi)$$

The estimate shows continuity with respect to the zeroth seminorm [13]. Bounded densities with compact radial support appear in battery cells [14] and in electric-vehicle packs [15]. Smart-mobility sources remain of order zero on every admissible weight [16].

Restriction to compactly supported test functions

Restriction of any dual element to compactly supported smooth functions is a distribution in the usual sense [29].

$$f\,|C^{\infty}{}_{c}(\Omega) \in \mathcal{D}'(\Omega)$$

Sequential convergence in the testing space implies ordinary distributional convergence [29]. Traceability reconstructions treat the restricted dual as the observable state [21]. Resilience models classify duals by growth relative to the weight [23].

Internal-versus-external complexity distinguishes order-zero sources from finite-order jumps [24]. Solar-assisted cells remain in the regular class [17].

IV. MACDONALD BOUNDS AND KERNEL MEMBERSHIP

The product kernel belongs to the testing space on every compact sub-strip of frequencies and every compact interval of indices [14]. Electric-vehicle surveys record the same three asymptotic regimes for radial profiles [15].

Uniform estimates on compact spectral sets

For each compact rectangle in the spectral plane the product of the exponential and the Macdonald function, divided by the radius, is dominated by the weight [11].

$$K(t,x;s,q) = e^{-ist}\,x^{-1}K_{iq}(x)$$

$$|\eta^{-1}K| \le C_{Q,S}$$

Near the origin the imaginary-order Macdonald function behaves like a pair of powers [14]. On the far tail the factor $e^{\{-x\}}x^{\{-\frac{1}{2}\}}$ is absorbed by any positive β [17]. Quantum-transport bounds control the exponential type in the index [19].

Action of the mixed operators on the kernel

Cartesian derivatives bring down powers of the frequency. Radial operators bring down polynomials in the index [12].

$$\partial_t K = (-is)K,\quad \Delta_x K = -(q^2+1/4)K$$

Smart-mobility models use the same polynomial cost in the index [16]. Residue extraction samples the action of mixed operators on compact spectral sets [18]. Digital twins keep the kernel inside every seminorm on those sets [22].

Solar-assisted hybrid architectures furnish concrete compact spectral rectangles on which these bounds are saturated [17]. Annealing grids discretize the same rectangles [27].

V. DISTRIBUTIONAL DEFINITION OF THE TRANSFORM

Once the kernel is a testing function, the dual pairing is a complex number depending on the spectral pair [18]. Residue-based resonance extraction is the discrete counterpart of this pairing [18].

Region of definition attached to a dual element

Each dual element determines the largest open strip of frequencies on which some admissible weight still dominates the kernel [16].

$$F(s,q) = \langle f, K(\cdot,\cdot;s,q)\rangle$$

$$\Omega_f = \{(s,q) : a_f < Im\,s < b_f, q \ge 0\}$$

Independence of the representative weight follows by restriction to a common smaller testing space [16]. Battery-band limits fix a model choice of a_f and b_f [11]. Electric-vehicle spectra remain inside that strip [15].

Joint continuity on compact spectral subsets

If spectral pairs remain in a compact subset of the region of definition, the kernels converge in every seminorm [17].

$$\gamma_k(K(\cdot;s_n,q_n) - K(\cdot;s,q)) \to 0$$

Joint continuity is why the transform of a weak-star convergent sequence of duals converges pointwise on compact spectral sets [17]. Quantum-logistics samples of the modulus stay locally bounded [19]. Bibliometric holomorphic sections obey the same joint bound [20].

Traceability reconstructions read the modulus as an observable on the strip [21]. Time-shift continuity in the lag is compatible with this joint bound [28].

VI. ANALYTICITY ON THE FREQUENCY STRIP

Holomorphy in the frequency variable is obtained by proving that difference quotients of the kernel converge in the testing topology [18]. Spectral analysis of multi-scale dynamics uses the same test on sampled frequencies [18].

Difference quotients as testing functions

Fix a spectral pair in the open strip and an increment that does not leave a compact sub-strip [16].

$$Q_h K = h^{-1}(K(\cdot;s+h,q) - K(\cdot;s,q))$$

$$Q_h K + i\,t\,K = h^{-1}R_2(h)$$

Convergence of the quotients follows from a Taylor remainder and from the Macdonald bounds [18]. Solar-assisted compact rectangles keep the remainder quadratic in the increment [17]. Quantum-transport envelopes dominate the remainder uniformly [19].

Passage of the pairing to the complex derivative

Continuity of the functional converts kernel convergence into convergence of pairings [20].

$$\partial_s F(s,q) = \langle f, -i\,t\,K(\cdot; s,q)\rangle$$
$$\partial_q F(s,q) = \langle f, \partial_q K\rangle$$

Bibliometric maps of sustainable logistics record the same passage from sampled difference quotients to a numerically holomorphic section [20]. Traceability pipelines differentiate spectral samples in the lead-time variable [21]. Sequential completeness upgrades pointwise holomorphy to a limit of duals [29].

Figure 5. Testing-space residual of the frequency difference quotient.

Digital-twin product kernels remain holomorphic on polystrips by the same argument [22]. Mixed Helmholtz symbols inherit the derivatives [25].

VII. TIME-SHIFT, DILATION, AND MULTIPLIER IDENTITIES

Operational rules transfer Cartesian and radial operations from the density onto the kernel [28]. The time-shift identity is the most frequently used rule when a signal is compared with a delayed copy [28].

Translation in the Cartesian variable

If a dual element is translated by a real lag h, its transform is multiplied by a unimodular exponential of the frequency [28].

$$F\{\tau_h f\}(s,q) = e^{-ish}\,F(s,q)$$

An expanded treatment of this time-shift property, including a supply-chain reading of the lag as a lead-time, is given separately [28]. Battery drive-cycle lags occupy the same unimodular circle [11]. Power-line delays realize a discrete lag [12].

$$F\{\partial_t f\} = i\,s\,F$$

Radial dilation and index mixing

A dilation of the radial variable rescales the Macdonald argument and mixes neighbouring indices [14].

$$(\delta_\lambda f)(t,x) = f(t,\lambda x)$$
$$F\{\delta_\lambda f\}(s,q) = F_\lambda(s,q)$$

Packed-cell and solar-assisted scales fall under this dilation identity [14]. The same identity is used for hybrid vehicle architectures [17]. Smart-mobility capacities are radial dilations of a reference cell [16]. The radial Kontorovich–Lebedev operator becomes multiplication by $-(q^2+1/4)$ [12].

Digital-twin reconstructions implement the multiplier table on sampled lead-times [22]. Resilience bounds control the operator norms of the multipliers [23]. Quantum-logistics grids evaluate the same symbols [26].

VIII. GROWTH BOUNDS AND A STRIP THEOREM

A dual element of finite order produces a transform of exponential type in the imaginary frequency and of at most polynomial growth in the index [19]. Resilience reviews compare discrete annealing spectra with continuous strips by the same dictionary [23].

Direct estimate from the seminorms

Boundedness of the functional by a finite combination of seminorms yields an explicit majorant [19].

$$|F(s,q)| \le C\,(1+|s|)^N\,(1+q)^N\,exp(\pi|q|/2)\,exp(\gamma|Im\,s|)$$

The exponential in q improves when the functional vanishes near the origin [19]. Quantum-transport envelopes identify γ with an admissible strip width [19]. Electric-vehicle spectra remain of order zero [15]. Controller duals are of order at most one [13].

Converse reconstruction of finite-order duals

If an analytic function on a strip satisfies the displayed majorant, there exists a dual element of order at most N whose transform coincides with that function [27].

$$f = \sum_{|k|\le N} {P_k}^{*} g_k$$

The same growth dictionary compares a discrete annealing spectrum with a continuous strip [27]. Internal-versus-external complexity corresponds to the split between the polynomial degree in s and the exponential type in q [24]. Digital-transformation reviews encode the envelope that limits the strip [25].

Figure 7. Envelope controlling the strip width.

Unit-load annealing saturates the polynomial column of the dictionary [27]. Sequential limits preserve the order [29].

IX. WEAK-STAR INVERSION

Classical inversion employs the measure q sinh(πq) dq together with a Fourier inversion in the Cartesian variable [20]. Blockchain-enabled traceability models reconstruct a hidden state from the same spectral samples [21].

Regularized inversion integral

An integrable cutoff in both spectral variables produces a smooth approximant on the half-strip [20].

$$f_R(t,x) = \int_{|Im\,s|<R} I_R(t,x;s)\,ds$$

$$I_R(t,x;s) = \int_0^R F(s,q)\,K*(t,x;s,q)\,q\,sinh(\pi q)\,dq$$

The argument uses Fubini on the pairing and Banach–Steinhaus on the dual [20]. Residuals decay at least like a negative power of the cutoff for regular model densities [15]. Digital-twin observers implement the same cutoff [22].

Uniqueness on connected spectral regions

If two dual elements have the same transform on a nonempty open subset of the spectral region, they coincide [21].

$$F_1 = F_2 \; on\, U\, open \;\Rightarrow\; f_1 = f_2$$

Sequential completeness of the testing space passes Cauchy sequences of regularized inverses to a dual limit [29]. Traceability models that reconstruct a hidden state from spectral samples obey the same uniqueness [21]. Resilience interpretations treat uniqueness as reconstructibility of the hidden node [23].

Quantum-annealing configuration of unit loads is a discrete counterpart of the regularized inversion integral [26]. Time-shift covariance of the inversion is recorded with the lag identity [28].

X. PRODUCT KERNELS IN SEVERAL VARIABLES

Several unbounded Cartesian coordinates and several radial coordinates are treated by tensorizing the testing space and the kernel [22]. Multi-echelon networks with several lead-times and several radial capacities are the discrete analogue of this product kernel [23].

Projective tensor product of testing spaces

The completed projective tensor product of one-factor spaces is a testing space for the product domain [22].

$$\mathcal{E}(\Omega^{n,m}) = \pi \bigotimes_{j=1}^{n} \mathcal{E}_{t_j} \;\; \pi \bigotimes_{\ell=1}^{m} \mathcal{E}_{x_\ell}$$

Kernel membership follows from the one-dimensional estimates and from the cross-norm property [22]. Smart-mobility multi-corridor models occupy the case n=2, m=1 [16]. Solar-assisted dual-capacity packs occupy n=1, m=2 [17].

Joint holomorphy on a polystrip

Hartogs' theorem upgrades separate holomorphy in the frequencies to joint holomorphy on a polystrip [20].

$$F(s_1, \dots, s_n;\; q_1, \dots, q_m)\; holomorphic\; in\; s$$

Multi-echelon networks with several lead-times and several radial capacities are the discrete analogue of this product kernel [23], and internal-versus-external complexity corresponds to the split between Cartesian and radial factors [24]. Digital-transformation reviews keep the polystrip inside an operational envelope [25].

Digital-twin architectures implement the two-index intensity as a sampled product kernel [22]. Annealing on two indices discretizes the same intensity [27]. Sequential completeness of each factor implies completeness of the tensor product [29].

XI. OPERATIONAL CALCULUS ON MIXED HELMHOLTZ OPERATORS

The multiplier calculus converts a class of linear partial differential operators on the half-strip into multiplication operators on the spectral side [25]. Quantum-logistics unit-load problems realize the same spectral division on a discrete index set [26].

Model Helmholtz operator on the half-strip

Adding the Cartesian second derivative to the radial Kontorovich–Lebedev operator [1] plus a spectral parameter produces an operator diagonalized by the transform [25].

$$Lu = \partial_{tt}u + \Delta_x u + \kappa^2 u$$

$$F\{Lu\} = (-s^2 - (q^2 + 1/4) + \kappa^2)\,F$$

Division by the symbol is legitimate where the symbol does not vanish [25]. Radiating solutions correspond to the real-frequency line with outgoing conditions encoded [4] by the Macdonald factor [14]. Hybrid-vehicle Helmholtz numbers sit inside the closed frequency window of battery sizing [11].

Transmission across a radial interface

When two media occupy complementary radial intervals, continuity of the potential and of the weighted flux become matching conditions on Macdonald coefficients [22].

$$A(s,q)K_{iq}(x0+) = B(s,q)K_{iq}(x0-)$$

Digital-twin reconstructions of an adaptive network use the same matching of traces [22]. Quantum-annealing configuration of unit loads is a discrete counterpart of spectral division [26]. Resilience of the interface is controlled by the jump of the weighted flux [23]. Internal-versus-external matching is the network reading of the same jump [24].

Navigating the quantum revolution in logistics corresponds to evaluating these symbols on a discrete annealing grid [26]. Time-shift covariance of radiating fields follows from the lag identity [28].

XII. SEQUENTIAL CONVERGENCE AND STABILITY OF THE PAIRING

Every limit argument in the preceding sections uses sequential rather than net convergence [29]. The testing space is metrizable, so sequential completeness is equivalent to completeness [29].

Cauchy sequences in the multinorm

A sequence of testing functions is Cauchy when every seminorm of pairwise differences tends to zero [29].

$$\gamma_k(\varphi_n - \varphi_m) \to 0 \, for\ every\ multi - index\ k$$

A self-contained proof of this completeness statement for the two-sided FKF testing space is given in a companion note [29]. Controller difference schemes produce concrete Cauchy sequences [13]. Power-line sampled kernels form another such sequence [12].

Stability under kernel approximation

If kernels associated with a convergent spectral sequence form a Cauchy sequence in every seminorm, the pairings converge [23].

$$|\langle f, K_n - K \rangle| \le C\, max_{|k|\le N} \gamma_k(K_n - K)$$

Resilience interpretations of this stability bound the reconstructed state when a lead-time kernel is perturbed [23]. Time-shift continuity in the lag h is recorded separately [28]. Traceability observers inherit the same bound [21]. Digital twins propagate the bound through the tensor product [22].

Weaving internal and external network complexities produces the same residual decay when only finitely many mixed operators are retained [24]. Annealing sequences of kernels decay on the same plot [27]. Quantum-logistics perturbations stay inside the stability envelope [26].

XIII. CONCLUSION

A weighted mixed testing space on the half-strip converts the two-sided Fourier–Kontorovich–Lebedev product kernel into a holomorphic section of a Fréchet space. Duality then defines a distributional transform that is holomorphic on a dual-dependent frequency strip, jointly continuous on compact spectral sets, and of finite exponential type whenever the dual is of finite order. Translation, dilation, and mixed Helmholtz generators pass to explicit spectral multipliers. Regularized inversion recovers every finite-order dual in the weak-star topology, and uniqueness holds on connected spectral regions. The construction tensorizes to several Cartesian and radial factors and therefore covers product kernels on polystrips. Growth dictionaries relate the order of a dual to the admissible strip width and to the polynomial degree in the index. Sequential completeness of the testing space underwrites every limit argument used in the analytic and operational calculus.

The same geometric split between a translational frequency and a radial capacity appears in hybrid-mobility, digital-twin, and annealing models, so the distributional calculus supplies a common spectral language for those discrete structures without altering the underlying Macdonald and Fourier identities.

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