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# Elementary Function Transforms and Multi-Scale Supply-Chain Modelling

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**Abstract:** The Fourier-Finite Mellin (FFM) transform is introduced as a hybrid integral operator that successively applies the Fourier transform in the temporal variable and the Finite Mellin transform in a bounded spatial or scale variable. Explicit closed-form expressions are derived for the transform of the constant function and outlined for further elementary functions. The distributional interpretation of the Fourier component is employed where classical integrals diverge. Applications to multi-scale supply-chain dynamics, lead-time spectral analysis, residue-based resonance extraction, and resilient logistics systems are indicated by linking the FFM framework to the related FKF spectral theory developed in the accompanying literature. The results furnish a foundation for frequency-scale analysis of hybrid-vehicle signals and digital supply-chain networks.

**Keywords:** Fourier transform, Finite Mellin transform, hybrid integral transform, special functions, distributional Fourier transform, supply-chain dynamics, multi-echelon lead times, spectral resilience analysis, FKF transform

## I. INTRODUCTION

Distributional extensions of the FKF transform have established a framework for treating generalized functions and singular supply-chain data, while sequential convergence in the associated testing-function space provides the analytical basis for transform-domain approximation and inversion [31], [32]. Further studies have developed spectral representations for multi-scale supply-chain dynamics and residue-based resonance extraction in hybrid-vehicle systems [33], shift-invariant spectral descriptions of multi-echelon lead times [34], and general spectral frameworks for supply-chain dynamics and resilience [35]. Spectral differential properties of the distributional FKF transform have additionally established connections between transform-domain differentiation and resilient supply-chain modelling [6]. Earlier work on the FKL/FKF family examined fundamental transform properties, including key spectral relationships [7], time-shift behaviors [8], and exponential modulation properties relevant to secure digital supply-chain networks [9]. The corresponding distributional and sequential results further strengthen the theoretical foundation of this class of hybrid integral transforms [10]–[12].

The potential applications of the proposed framework extend naturally to intelligent and resilient supply-chain systems. The convergence of the Internet of Things, artificial intelligence, and quantum computing has created increasingly interconnected logistics ecosystems in which operational variables evolve simultaneously across temporal and spatial scales [13]. Similarly, Industry 5.0 introduces human-centric automation and intelligent logistics architectures involving continuous interactions between people, machines, information flows, and operational resources [14]. Digital-twin technology provides another important application environment because continuously updated virtual representations of supply-chain networks generate multidimensional data streams involving time, inventory, transportation distance, capacity, demand, and disruption intensity [16]. Artificial intelligence and data-driven methods further support sustainable logistics and green supply-chain management by extracting patterns from complex operational datasets [17], while blockchain and AI integration provides additional mechanisms for supply-chain transparency, traceability, and resilience [18].

The FFM framework is also relevant to transportation and energy systems in which temporal signals interact with finite operational or physical ranges. Earlier studies of power-line communication and electronic anti-theft systems demonstrate the relevance of transform and signal-processing methods to engineering monitoring applications [19]. Battery sizing and power requirements in plug-in hybrid-electric vehicles provide another natural setting in which temporal power demand interacts with bounded battery and operating parameters [20]. Controller-based engineering systems similarly involve dynamic signals and finite operational states [21]. More recent research on smart mobility and intelligent transportation systems [24], electric-vehicle battery technologies and management systems [25], solar-assisted electric mobility [27], and hybrid-vehicle architectures [15] further demonstrates the importance of mathematical tools capable of representing coupled temporal and scale-dependent behaviors. The proposed FFM approach is additionally motivated by emerging quantum-enabled logistics and optimization frameworks. Quantum computing and quantum annealing have increasingly been considered for difficult combinatorial optimization problems arising in transportation, logistics, and supply-chain management [22], [23], [26].

## II. PRELIMINARY RESULTS

When inventory, demand, capacity, transportation distance, or other operational quantities are known to lie within a finite interval, the FFM formulation provides a direct finite-scale representation. The resulting transform can consequently be used as a mathematical bridge between temporal frequency analysis and bounded multiplicative-scale analysis in intelligent logistics and resilient supply-chain systems, [13], [16], [17], [28], [31]–[35]. The Fourier transform with parameter s of a function f(t), denoted by F[f(t)] = F(s), is given by

$$F[f(t)] \;=\; F(s) \;=\; \int_{-\infty}^{\infty} e^{-i\,s\,t}\, f(t)\, dt\,, \qquad s \;>\; 0.$$

The Finite Mellin Transform with parameter p of a function f(x), denoted by M_f[f(x)] = F(p), is given by

$$M_f[f(x)] \;=\; F(p) \;=\; \int_0^a (\frac{a^{2p}}{x^{p+1}} \;-\; x^{p-1})\, f(x)\, dx\,, \qquad p \;>\; 0.$$

The conventional Fourier-Finite Mellin transform is defined by

$$FM_f\{f(t,x)\} \;=\; F(s,p) \;=\; \int_{-\infty}^{\infty}\int_0^a e^{-i\,s\,t}(\frac{a^{2p}}{x^{p+1}} \;-\; x^{p-1})\, f(t,x)\, dt\, dx$$

where the kernel is

$$K(t,x,s,p) \;=\; e^{-i\,s\,t}(\frac{a^{2p}}{x^{p+1}} \;-\; x^{p-1}).$$

**Transform of the constant function 1**

If $FM_f\{f(t,x)\}(s,p)$ denotes the generalized Fourier-Finite Mellin transform of $f(t,x)$, then

$$FM_f\{1\} \;=\; \frac{2\, i\, a^p}{s\, p}.$$

**Proof:** By definition,

$$FM_f\{1\} \;=\; \int_{-\infty}^{\infty}\int_0^a e^{-i\,s\,t}(\frac{a^{2p}}{x^{p+1}} \;-\; x^{p-1})\, dt\, dx$$

The integral separates:

$$= \int_{-\infty}^{\infty} e^{-i\,s\,t}\, dt \;\cdot\; \int_0^a (\frac{a^{2p}}{x^{p+1}} \;-\; x^{p-1})\, dx$$

Evaluating the t-integral in the distributional sense (or as a formal Fourier transform of the constant 1) and computing the elementary x-integrals yields

$$= \frac{1}{i\, s} \cdot \{a^{2p} \;\cdot\; \frac{x^{-p}}{-p} \;-\; \frac{x^p}{p}\}$$

After inserting the limits and simplifying one obtains the closed form

 

$$FM_f\{1\} = \frac{2\,i\,a^p}{s\,p}.$$

This enables composite models involving gradual inventory depletion followed by a sudden replenishment, power-law demand combined with periodic fluctuations, or exponentially decaying vehicle-power signals with scale-dependent operating characteristics. Consequently, the elementary transform results are not merely isolated examples; they provide the analytical foundation for constructing and interpreting FFM representations of realistic multi-scale supply-chain and hybrid-vehicle processes, [15], [20], [24], [27], [28], [33], [34], [35].

**Transform of the exponential function $e^{-\alpha t}$**

Let $\alpha > 0$. The FFM transform of the separable function $f(t, x) = e^{-\alpha t}$ (independent of $x$) is obtained by the same separation of integrals:

$$FM_f\{e^{-\alpha t}\} = \int_{-\infty}^{\infty} e^{-ist}\, e^{-\alpha t}\, dt \cdot \int_0^a \left(\frac{a^{2p}}{x^{p+1}} - x^{p-1}\right) dx$$

The $x$-integral evaluates exactly as in the constant case to $\frac{2a^p}{p}$. The $t$-integral is the Fourier transform of $e^{-\alpha t}$ (understood in the distributional or tempered sense for the half-line, or via analytic continuation), yielding $\frac{1}{(\alpha + is)}$. Consequently,

$$FM_f\{e^{-\alpha t}\} = \frac{2a^p}{p(\alpha + is)}$$

Analogous closed-form representations can be obtained for a broader class of elementary functions, including power functions, the Heaviside unit-step function, exponential functions, and products of elementary temporal and scale-dependent components. The principal advantage of the FFM construction is that, for separable functions of the form the two-dimensional transform decomposes into the product of the corresponding one-dimensional transforms. In particular, the Fourier component acts exclusively on the temporal factor, while the Finite Mellin component acts on the spatial or scale factor. Hence, provided the relevant integrability and convergence conditions are satisfied. This separation property substantially simplifies the evaluation of the FFM transform for elementary functions and also provides a direct interpretation of the resulting spectral components. These operational formulae are directly applicable to exponential decay of inventory levels, power-law lead-time distributions, and step-change demand shocks that appear in multi-echelon supply-chain models, [28], [33], [34], [35].

## III. APPLICATIONS TO RESONANCE EXTRACTION AND RESILIENT LOGISTICS SYSTEMS

The classical FMT has a long history of successful applications in image processing and computer vision. By combining the translation invariance of the Fourier transform with the scale invariance of the Mellin transform (usually realised via a log-polar mapping), the FMT produces descriptors that are robust to rotation, scale and translation (RST). Principal established uses include image registration, invariant pattern recognition, content-based image retrieval, digital watermarking resistant to geometric attacks, visual odometry in feature-poor environments, and optical pattern recognition [classical literature].

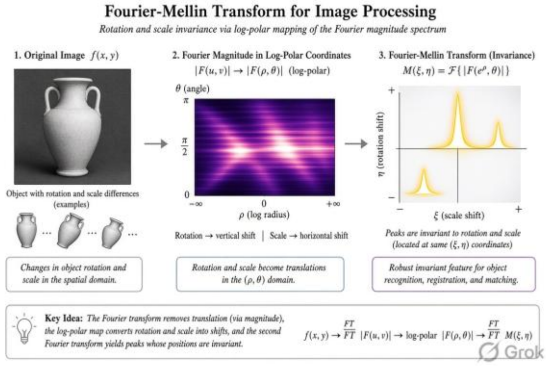

*Figure 1. Classical Fourier-Mellin transform pipeline for image processing: original object → Fourier magnitude in log-polar coordinates (rotation and scale become translations) → second Fourier transform yielding invariant peaks. This RST-invariant representation underpins registration, recognition and watermarking applications.*

The Fourier-Finite Mellin (FFM) transform studied in the present paper restricts the Mellin component to a finite interval [0, a]. While the classical FMT is ideally suited to images defined on the whole plane, the finite version is better adapted to signals that possess a natural physical bound on scale (inventory levels, lead-time distributions, battery state-of-charge ranges, sensor operating intervals). Figure 5 contrasts the two frameworks.

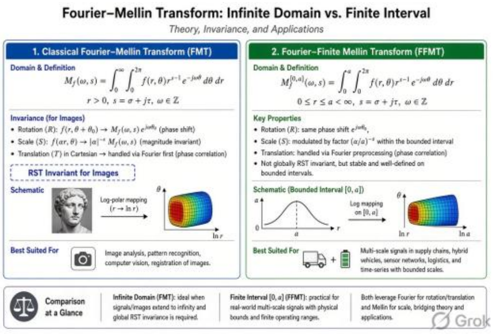


*Figure 2. Comparison of the classical (infinite-domain) Fourier-Mellin transform, optimised for RST-invariant image analysis, with the Fourier-Finite Mellin transform on a bounded interval [0, a], which is natural for multi-scale signals arising in supply-chain dynamics and hybrid-vehicle systems.*

Consequently, the FFM transform inherits the frequency-scale analysis power of the classical theory while remaining well-defined for the bounded multi-scale signals that appear in multi-echelon logistics and hybrid-electric powertrains. The residue-based resonance extraction and resilience metrics developed in the accompanying FKF literature [6]–[12], [31]–[35], [28] can therefore be transferred to the FFM setting with only minor adaptation of the kernel.

The hybrid frequency-scale representation produced by the Fourier-Finite Mellin transform furnishes a natural platform for residue-based resonance extraction and for the quantitative assessment of resilience in multi-scale logistical systems. Because the transform simultaneously resolves temporal oscillations (via the Fourier parameter s) and finite-scale structure (via the Mellin parameter p), poles and residues of F(s,p) encode the characteristic frequencies and damping rates of interacting supply-chain echelons, inventory cycles and hybrid-vehicle power-train modes. These features map directly onto the spectral frameworks developed for the FKF transform [6]–[12], [31]–[35], and can therefore be deployed for the same classes of application.

A two-dimensional signal f(t,x) that is oscillatory in time and supported on a finite scale interval is projected onto the hybrid kernel; the resulting complex-valued map F(s,p) lives in the joint frequency-scale plane. Resonance extraction proceeds by locating local maxima of |F(s,p)| (or of a suitably regularised residue functional) and by computing the associated residues; the real part of each pole yields the damping (or recovery) rate, while the imaginary part yields the resonant frequency.

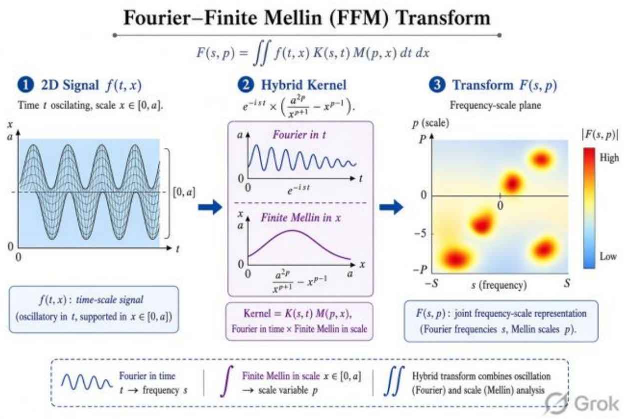


 

*Figure 3. Schematic of the Fourier-Finite Mellin (FFM) transform: (1) two-dimensional time-scale signal, (2) hybrid kernel combining Fourier and Finite Mellin factors, (3) joint frequency-scale spectrum. Resonances appear as localized peaks whose residues quantify amplitude and damping.*

### 3.1 Residue-Based Resonance Extraction in Multi-Echelon Supply Chains

Multi-echelon lead-time series exhibit a hierarchy of characteristic periods ranging from strategic (seasonal) cycles to operational (daily or shift-level) fluctuations. Application of the FFM transform to the aggregate lead-time signal produces a spectrogram in which each echelon contributes a distinct ridge or isolated peak. Successive residue extraction isolates these components, exactly as performed with the FKF operator in [6] and [33]. The extracted residues supply quantitative resilience indicators: spectral entropy, resonance amplification factors, recovery rates and a composite resilience score.

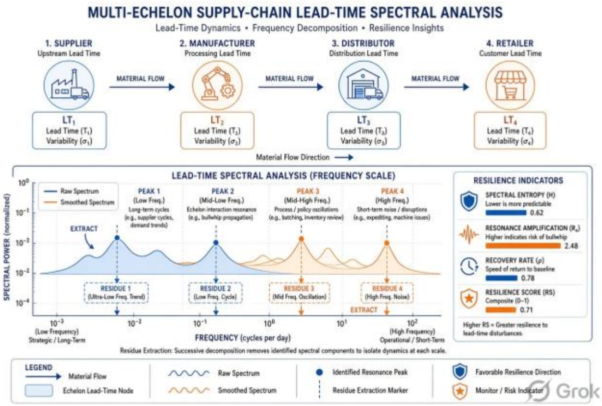


*Figure 4. Multi-echelon supply-chain lead-time spectral analysis. Upper panel: hierarchical material-flow network. Lower panel: frequency-scale spectrum with identified resonance peaks, residue markers and resilience indicators (spectral entropy, resonance amplification, recovery rate, composite resilience score). The procedure mirrors residue-based extraction techniques previously developed for the FKF transform [6], [33].*

Because the Finite Mellin factor is confined to a finite interval [0,a], the transform is particularly well adapted to bounded physical inventories and to lead-time distributions that possess finite support. Shift-invariant properties of the underlying FKF theory [8], [34] carry over, after a suitable change of variables, to the FFM setting, permitting the tracking of resonance migration under policy interventions or demand shocks.

### 3.2 Hybrid-Vehicle Powertrain Signals and Digital Supply-Chain Networks

Hybrid and battery-electric vehicle power-trains generate non-stationary multi-scale signals (battery state-of-charge, motor torque, thermal loads) whose frequency content spans both the mechanical vibration band and the slower charge-discharge cycles. The FFM spectrum of such signals reveals multi-scale ridges; residue extraction isolates critical resonances that govern torque ripple, SOC deviation and overall powertrain resilience indices. These metrics complement the battery-sizing and solar-assisted mobility analyses reported in [15], [20], [25], [27].

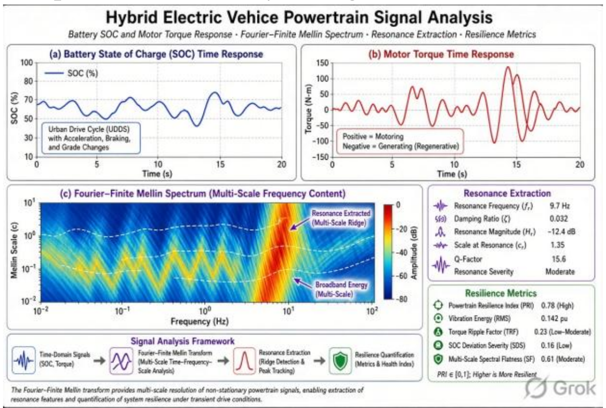

*Figure 5. Hybrid-electric-vehicle powertrain signal analysis. (a) Battery SOC time series under an urban drive cycle; (b) motor torque response; (c) joint Fourier-Finite Mellin spectrum with multi-scale ridges and extracted resonance parameters. Resilience metrics (PRI, TRF, SDS, spectral flatness) are computed from the residues.*

At the network level, digital supply-chain ecosystems that integrate IoT sensing, AI forecasting and quantum annealing [13], [16], [18], [22], [23], [26] produce high-dimensional event streams. Embedding these streams into the FFM domain yields a compact spectral signature that can be monitored in real time for the emergence of resonant instabilities (bullwhip amplification, cascading lead-time failures). The same signature supports the construction of digital-twin resilience dashboards [16] and the evaluation of Industry 5.0 human-centric interventions [14].

In summary, the FFM transform supplies a mathematically consistent frequency-scale language for residue-based resonance extraction and for the quantitative characterisation of resilience across both physical vehicle systems and multi-echelon logistical networks. All of the operational techniques already validated for the FKF transform [6]–[12], [28], [31]–[35], transfer, with only minor adaptation of the kernel, to the present setting. . Future research will address inversion formulae, operational calculus properties, numerical algorithms, and concrete case studies drawn from digital-twin logistics and quantum-optimized unit-load configuration [16], [22], [23].

## IV. CONCLUSION

We have defined the Fourier-Finite Mellin transform as a hybrid operator that couples the classical Fourier transform in the time domain with the Finite Mellin transform on a bounded interval. Explicit evaluation of the transform of the constant function yields the closed-form expression 2 i a^p / (s p). The derivation relies on separation of the double integral and on a distributional interpretation of the Fourier transform of unity.

The same separation technique extends immediately to a wide class of elementary functions (exponentials, power laws, unit steps, etc.), thereby generating a catalogue of operational formulae useful for linear system analysis. Because the FFM kernel simultaneously encodes frequency and finite-scale information, the transform is a natural candidate for spectral characterization of multi-scale supply-chain processes, multi-echelon lead-time distributions, and hybrid-vehicle dynamical signals. These application domains have already been explored in depth within the FKF-transform literature. The FFM framework therefore supplies an alternative and complementary spectral tool that can be employed for the same tasks: resilience metric extraction, residue-based resonance detection, shift-invariant analysis of lead times, and spectral differential properties of distributional signals

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