
Adaptive Fourier Decomposition-Guided Neural Operator Design for Solving Inverse PDE Problems

Zeyuan Song^{†1,3}

Xiaocong Zhen^{†2}

Zheyu Jiang^{†3}

¹Department of Mathematics, Lehigh University, Bethlehem, Pennsylvania, USA

²School of Industrial Engineering and Management, Oklahoma State University, Stillwater, Oklahoma, USA

³School of Chemical Engineering, Oklahoma State University, Stillwater, Oklahoma, USA

Abstract

Inverse problems, which are generally ill-posed, aim to identify the unknown parameters of a physical system from the observations of its output. A large class of inverse problems for partial differential equations (PDEs) are only well-defined as mappings from operators to functions. However, existing operator learning frameworks either do not explicitly account for the underlying operator space or solve the inverse problems in a Hilbert space. Meanwhile, it has been shown that a Banach space setting for the parameter space would be closer to reality for a wide range of problems. Driven by this, we introduce **AFDONet-inv**, a novel neural operator solver whose design is rigorously guided by adaptive Fourier decomposition (AFD) theory, to solve inverse problems for PDEs in a Banach space. Each component of **AFDONet-inv**'s architecture, including primal and dual nets, latent-to-RKBS (reproducing kernel Banach space) network, and dynamic convolutional kernel network (CKN), has a corresponding component in the AFD operation in Banach space. This way, **AFDONet-inv** is mathematically explainable and grounded in the AFD theory and possesses several desirable properties. Extensive experiments demonstrate that **AFDONet-inv** outperforms state-of-the-art inverse PDE solvers in terms of solution accuracy.

1 INTRODUCTION

A wide range of scientific and engineering systems and phenomena, including water transport in soil, heat transfer,

structural mechanics, and cell growth, can be characterized and modeled by partial differential equations (PDEs) [Song and Jiang, 2026c]. A fundamental task in understanding the dynamics of these systems and phenomena is to accurately infer unknown parameters α in the PDE from observed solution data, which might be noisy. Unlike many PDE forward problems, inverse problems are generally ill-posed, in the sense that their solutions either do not exist, are not unique, or are unstable to small perturbations in the data [Kirsch, 2021]. For example, the inverse heat equation, which attempts to infer a previous temperature profile based on the final temperature distribution, is ill-posed in that the solution is highly sensitive to changes in the final data.

Solving ill-posed PDE inverse problems is considerably harder than solving their forward counterparts. Traditionally, inverse PDE problems are solved via PDE-constrained optimization [Hinze et al., 2009] or Bayesian inference [Stuart, 2010]. For PDE-constrained optimization, the goal is to minimize the difference between the observed data and the PDE solution, and the PDE is enforced as a constraint. The resulting optimization problem can be solved using adjoint methods or Tikhonov regularization. Meanwhile, for Bayesian inference, the inverse problem is formulated as a statistical inference problem, whose goal is to estimate the posterior distribution of PDE parameters given the solution data. This usually requires sampling over the parameter space and solving the forward PDE multiple times. Both classes of conventional methods require repeated solutions of forward PDEs and thus often lead to high computational costs, especially for nonlinear or high-dimensional problems.

Data-driven solutions of PDEs have emerged as a powerful paradigm to address these challenges. Among them, two of the most popular methodological advancements are physics-informed neural network (PINN) and operator learning. PINN-based methods directly embed physical laws into the loss function or neural network architecture [Raissi et al., 2017, 2019]. By minimizing the total loss, PINN can effectively solve the PDE, fit the data, and infer the parameters

[†] This work was conducted while affiliated with Oklahoma State University and was supported by the U.S. National Science Foundation award No. 2442806.

simultaneously. PINN-based solvers have been applied to a wide range of inverse problems, including ocean engineering [Jagtap et al., 2022b], supersonic flow [Jagtap et al., 2022a], nano-optics and metamaterial design [Chen et al., 2020b], to name a few. However, in these methods, the PDE is enforced as a soft constraint and thus faces the intrinsic trade-off between fitting the data and solving the PDE accurately. Furthermore, many PINN-based methods focus on solving a single problem instance, which poses computational efficiency challenges when it comes to real-time inference to multiple instances [Cho and Son, 2025].

Meanwhile, operator learning, which aims to directly learn the mapping between infinite-dimensional function spaces (e.g., from input functions to solutions), can enable fast, mesh-independent approximation of PDE solutions across different input conditions. Existing operator learning approaches for solving forward PDE problems include the deep operator network (DeepONet) [Lu et al., 2019, 2021] and its variants, as well as neural operator [Kovachki et al., 2023] and its variants, such as Fourier neural operator (FNO) [Li et al., 2020a, 2023], wavelet neural operator (WNO) [Tripura and Chakraborty, 2023], multiwavelet neural operator (MWT) [Gupta et al., 2021], Adaptive Mamba Neural Operator (AMO) [Song and Jiang, 2026b], etc.

Following these breakthroughs, several operator learning methods have been developed to solve inverse PDE problems. For instance, Wang and Wang [2024] presented a latent neural operator (LNO) method to solve forward and inverse PDE problems in their latent space. Molinaro et al. [2023] proposed neural inverse operator (NIO), which integrates DeepONet and FNO, to solve inverse PDE problems. More recently, Cho and Son [2025] developed a physics-informed operator learning framework called PI-DION for inverse problems without the need for labeled training data. Yu et al. [2024] introduced a new neural operator architecture called nonlocal attention operator (NAO) based on the attention mechanism and showed that the attention mechanism is equivalent to a double integral operator that enables nonlocal interactions among spatial tokens. This allows NAO to address ill-posedness and rank deficiency in inverse PDE problems. Building upon the NAO framework, Liu and Yu [2025] developed a scalable attention-based neural operator architecture called neural interpretable PDEs (NIPS). Using linear attention reformulation and Fourier convolution, NIPS achieved enhanced predictive accuracy and computational efficiency compared to NAO.

Despite these advances, existing operator learning frameworks for inverse PDE problems face two critical drawbacks. First, existing frameworks either do not explicitly account for the underlying operator space, or solve the inverse problems in a Hilbert space. Meanwhile, it has been shown that a Banach space setting for the parameter space would be closer to reality for a wide range of inverse PDE problems. This important aspect has been overlooked. Second, design-

ing effective neural operator architectures has been “more of an art than a science” [Sanderse et al., 2025], requiring significant intuition, expert experience, and trial-and-error experimentation. Often, neural operator design does not have a rigorous mathematical basis and thus lacks explainability. To address both challenges, here we introduce AFDONet-inv, a novel neural operator for solving inverse PDE problems in Banach space, whose design is systematically guided by the adaptive Fourier decomposition (AFD) theory. Each component in the neural architecture, including primal and dual nets, latent-to-RKBS (reproducing kernel Banach space) network, and dynamic convolutional kernel network (CKN), has a corresponding component in the AFD operation. This way, AFDONet-inv is mathematically explainable and grounded in the AFD theory, thereby providing rigorous theoretical justifications and performance guarantee. Through extensive experiments, we demonstrate that AFDONet-inv outperforms state-of-the-art inverse PDE problem solvers in terms of solution accuracy.

We summarize our **key contributions** as follows:

1. For the first time, we generalize classic AFD theory (traditionally in RKHS with orthonormal bases) to RKBS using dual pairing and a duality map, enabling greedy-style pole selection without relying on Hilbert-space orthogonality.
2. AFDONet-inv is designed so that each major module corresponds to an AFD component in Banach space. This way, AFDONet-inv is mathematically explainable and grounded in the AFD theory. Along with a set of theoretical proofs, we provide rigorous theoretical justifications and performance guarantee to our AFDONet-inv framework.
3. We demonstrate that, by explicitly modeling inverse problems in a Banach setting (suited to sparsity/irregularity) and building the operator learner around the RKBS structure, AFDONet-inv can handle cases where Hilbert-space assumptions are limiting, and the experiments report state-of-the-art accuracy improvements on benchmark inverse PDE tasks.

2 PRELIMINARIES

2.1 INVERSE PROBLEM IN HILBERT VS. BANACH SPACES

A Hilbert space is a complete inner product space (i.e., a vector space equipped with an inner product that induces a norm), and every Cauchy sequence in the space converges with respect to this norm. The interpretability given by the inner product has enabled rigorous convergence analysis and comprehensive application regularization techniques to be applied for solving inverse problems in Hilbert spaces over the last decades. However, for numerous inverse prob-

lems in PDEs, the reasons for using a Hilbert space setting seem to be based on conventions rather than an appropriate and realistic model choice. In fact, it has been shown that the nature of Hilbert spaces cannot accurately capture the structures of parameter space for many PDEs, and often a Banach space setting would be closer to reality [Schuster et al., 2012]. As a generalization of the Hilbert space, a Banach space is a complete normed vector space (i.e., a vector space equipped with a norm such that every Cauchy sequence in the space converges with respect to this norm), and the main difference between Hilbert and Banach spaces is the existence of an inner product and thus orthogonality. *Banach spaces are more suitable for solving inverse problems involving sparsity, discontinuities, or measure-valued representations.*

2.2 ADAPTIVE FOURIER DECOMPOSITION (AFD)

Conventional neural operators typically rely on fixed spectral bases (e.g., Fourier series e^{inx}) or learn continuous basis functions implicitly. However, non-smooth signals and dynamics (e.g., solutions to PDEs with boundary layers and singularities) are often better represented by rational functions. AFD is a novel signal decomposition technique that leverages the Takenaka-Malmquist system and adaptive orthogonal bases [Qian, 2010, Qian et al., 2012]. It is established as a new approximation theorem in a reproducing kernel Hilbert space (RKHS) sparsely in a given domain Ω as $s = \sum_{i=1}^{\infty} \langle s, \mathcal{B}_i \rangle \mathcal{B}_i$ for the chosen orthonormal bases $\mathcal{B}_i$ [Saitoh et al., 2016]. An RKHS is a Hilbert space of functions where evaluation at any point is continuous with respect to the inner product $\langle \cdot, \cdot \rangle$, and each point on the domain corresponds to a unique kernel function. For AFD in RKHS, the sparse bases $\{\mathcal{B}_i\}_i$ are made orthonormal to each other by applying Gram-Schmidt orthogonalization to the normalized reproducing kernels associated with a set of adaptively selected *poles* $\{a_i\}_i$, which are complex numbers used to parameterize the sparse bases. Specifically, the orthonormal basis functions $\mathcal{B}_i$ are Blaschke-type functions defined as:

$$\mathcal{B}_i(z) = \frac{\sqrt{1 - |a_i|^2}}{1 - \bar{a}_i z} \prod_{j=1}^{i-1} \frac{z - a_j}{1 - \bar{a}_j z}, \quad a_i \in \mathbb{D}, \quad (1)$$

where the unit disk $\mathbb{D} = \{z \in \mathbb{C} : |z| < 1\}$. Unlike standard Fourier bases, the poles in AFD are not fixed. To adaptively select the sequence of poles such that convergence of AFD approximation is ensured, one shall follow the so-called “*maximal selection principle*”, such that the resulting $|\langle s, \mathcal{B}_i \rangle|$ is as large as possible. That is, to select the next pole a_i given $i - 1$ already selected poles, $a_1, \dots, a_{i-1}$ (hence bases $\mathcal{B}_1, \dots, \mathcal{B}_{i-1}$), the corresponding orthonor-

mal basis $\mathcal{B}_i$ needs to satisfy:

$$|\langle s, \mathcal{B}_i \rangle| \geq \rho_i \sup \{|\langle s, \mathcal{B}'_i \rangle| | b_i \in \Omega \setminus \{a_1, \dots, a_{i-1}\}\}, \quad (2)$$

where $0 < \rho_0 \leq \rho_i < 1$, $\mathcal{B}'_1 = \frac{k_{b_1}}{\|k_{b_1}\|_{H(\Omega)}}$ and $\mathcal{B}'_i = \frac{k_{b_i} - \sum_{j=1}^{i-1} \langle k_{b_i}, \mathcal{B}_j \rangle \mathcal{B}_j}{\|k_{b_i} - \sum_{j=1}^{i-1} \langle k_{b_i}, \mathcal{B}_j \rangle \mathcal{B}_j\|_{H(\Omega)}}$. Here, k_{b_i} is the reproducing kernel (e.g., Gaussian or Bergman kernel) at b_i . Under the maximal selection principle, the convergence of AFD approximation can be established [Song and Sun, 2022]. In actual implementation, however, we often want to strengthen Equation (2) by introducing an extra *bias term* denoted as $\gamma_i > 0$ to enhance convergence. Essentially, this ensures that $|\langle s, \mathcal{B}_i \rangle|$ is always greater than the RHS of Equation (2) by at least γ_i . And the resulting updated maximal selection principle formulation becomes [Song and Jiang, 2026a]:

$$\gamma_i \leq |\langle s, \mathcal{B}_i \rangle| - \rho_i \sup \{|\langle s, \mathcal{B}'_i \rangle| | b_i \in \Omega \setminus \{a_1, \dots, a_{i-1}\}\}. \quad (3)$$

3 AFD IN REPRODUCING KERNEL BANACH SPACE (RKBS)

The classic AFD, which operates on RKHS, leverages orthonormal bases. On the other hand, one cannot properly define orthogonality and inner product in a Banach space. Instead, we extend the inner product definition by adopting the concept of “**dual pairing**”, denoted as $\langle \cdot, \cdot \rangle_{\mathcal{B}, \mathcal{B}^*}$ for the primal RKBS $\mathcal{B}$ and its dual $\mathcal{B}^*$. Essentially, a dual pairing is a non-degenerate bilinear map between two vector spaces that produces a scalar [Brezis and Brézis, 2011]. With this, we will adaptively identify poles following a similar maximal selection principle, such that $|\langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}|$ is as large as possible. Here, $r_{i-1} = s - s_{i-1}$ is the **residual** between the true signal s and its $(i - 1)$ -th decomposed component, s_{i-1} . And J is called **duality map**, which satisfies $J(\mathcal{B}_i) \in \mathcal{B}^*$ and $\langle \mathcal{B}_i, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} = \|\mathcal{B}_i\|_{\mathcal{B}}^2$. Specifically, to select the next pole a_i , the corresponding basis $\mathcal{B}_i$ needs to satisfy:

$$\gamma_i \leq |\langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}| - \rho_i \sup_{\mathcal{B}_i \in \mathcal{D}} \{|\langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}|\}, \quad (4)$$

which is analogous to Equation (3). In actual implementation, we find that setting γ_i to a fixed value of 0.5 works well for most problem settings. Here, we define set $\mathcal{D} = \{\mathcal{B}_i | a_i \in \mathcal{B}\}$ (note that we no longer need to exclude already selected poles as the concept of orthogonality does not hold in RKBS anymore), γ_i is the bias term, and $0 < \rho_0 \leq \rho_i < 1$. With this, the AFD operations in RKBS give $s = \sum_{i=1}^{\infty} \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i$. We remark that, to the best of our knowledge, such generalization of the AFD theory to Banach space has not been proposed before. The technical details and mathematical properties of AFD in RKBS are discussed in Appendix A.

4 AFD-GUIDED NEURAL OPERATOR DESIGN

Once we establish the theoretical framework for AFD in Banach space, we design a tailored neural operator architecture, which we name as **AFDONet-inv**, that reproduces and realizes this theoretical framework. AFDONet-inv is an AFD-based VAE architecture (see Figure 1) to solve inverse PDE problems in Banach space. After the encoder, AFDONet-inv identifies the closest RKBS where the latent variables reside using a latent-to-RKBS network. Subsequently, AFDONet-inv reconstructs the PDE parameters by adaptively selecting the poles in a specially designed decoder network, thereby resembling the AFD operation.

4.1 AFDONET-INV ARCHITECTURE

The encoder network. The encoder network maps the input $x \in \mathbb{R}^d$ (e.g., PDE solutions in training dataset during training or test dataset during inference stage) to latent variables in both the primal and dual latent spaces, which correspond to a Banach space B and its dual space B^* , respectively. Note that during training, since the PDE parameters α_{true} only appear in the loss function, they are part of training dataset but not part of the input x to the encoder. Each encoding branch follows the standard VAE framework. That is, for the primal branch:

$$(\mu_p(x), \log \sigma_p^2(x)) = W_{p,2} (\phi(W_{p,1}x)), \quad (5)$$

$$z_p = \mu_p(x) + \sigma_p(x) \odot \varepsilon, \quad \varepsilon \sim \mathcal{N}(0, I), \quad (6)$$

where $W_{p,1} \in \mathbb{R}^{w \times d}$, $W_{p,2} \in \mathbb{R}^{2r \times w}$ are the weight matrices, $\phi(\cdot)$ is the activation function, and $z_p \in \mathbb{R}^r$ is the latent variable in the primal space.

Similarly, for the dual branch:

$$(\mu_d(x), \log \sigma_d^2(x)) = W_{d,2} (\phi(W_{d,1}x)), \quad (7)$$

$$z_d = \mu_d(x) + \sigma_d(x) \odot \varepsilon, \quad \varepsilon \sim \mathcal{N}(0, I), \quad (8)$$

where $W_{d,1} \in \mathbb{R}^{W_e \times d}$ and $W_{d,2} \in \mathbb{R}^{2r \times W_e}$ are the dual encoder weight matrices, and $z_d \in \mathbb{R}^r$ is the dual latent variable in B^* .

The latent-to-RKBS network. Given the latent variables z_p and z_d , our goal is to determine their values in the parameter space, which lies in a RKBS. To do this, we extend the latent-to-kernel idea from Lu et al. [2020] and design a latent-to-RKBS network to project the latent variable z_p to its nearest RKBS where the kernel is constructed. And then, its dual space in which the latent variable z_d lie is obtained via the duality map $J(v) = \|v\|_p^{p-2} \cdot |v|^{p-2} \cdot v$ in the form of L^p norm. First, z_p and z_d are respectively mapped to the parameter space $\tilde{\alpha} \in B$ and $\tilde{\alpha}^* \in B^*$ through two identical multilayer perceptron networks (MLPs). Then, feature maps $\text{FM}(\cdot)$ will project $\tilde{\alpha}$ and $\tilde{\alpha}^*$ onto their corresponding

RKBS $\mathcal{B}$ and its dual $\mathcal{B}^*$, respectively. In other words, the feature map network is designed to map the latent vector $z_p \in \mathbb{R}^r$ to N scalar coefficients in $\mathbb{R}$ needed for the kernel decomposition (i.e., $\text{FM} : \mathbb{R}^r \rightarrow \mathbb{R}^N$). The latent-to-RKBS network learns the feature maps from a Banach space B to its nearest RKBS $\mathcal{B}$, where the reproducing kernel K_z for any pair of encoder inputs (i.e., PDE solutions in training or test dataset) is given by:

$$K_z(x_1, x_2) = \sum_{i=1}^N \text{FM}_i(z_p) \cdot k_i(x_1, x_2). \quad (9)$$

In Equation 9, N is the total number of basis kernels, $\text{FM}_i(z_p)$ is the i -th feature map coefficient for latent variable z_p , and $\{k_i(x_1, x_2)\}_i$ are the learned basis kernels are based on a Fourier spectral kernel formulation. Here, $k_i(x_1, x_2)$ contains a series of learned parameters in the spectral domain. Since these basis kernels are in RKBS, which is closed under finite linear combinations, K_z lies in the RKBS as well.

Primal-dual propagation. The concept of dual pairing is realized in a primal-dual propagation network. Consisting of a primal net and a dual net, it propagates and refines the feature representations $\text{FM}(\tilde{\alpha}) \in \mathcal{B}$ and $J(\text{FM}(\tilde{\alpha})) \in \mathcal{B}^*$, which correspond to the latent variables z_p and z_d , respectively. Here, the primal net performs the spectral convolution $\mathcal{S}(f)(x)$, which transforms a given function f into the frequency domain via a 2D Fourier transform [Li et al., 2020a]:

$$\mathcal{S}(f)(x) = \mathcal{F}^{-1}[\chi(\xi) \cdot \mathcal{F}(f)(\xi) \cdot W(\xi)](x), \quad (10)$$

where $\mathcal{F}[\cdot](\xi)$ is the Fourier transform at ξ , $\mathcal{F}^{-1}[\cdot](x)$ is its inverse Fourier transform at x , $\chi(\xi)$ denotes the mode selector, and $W(\xi)$ refers to the learnable weights in the frequency domain. From an RKBS perspective, the spectral convolution $\mathcal{S}(f)(x)$ is equivalent to a nonlocal kernel operator $\sum_{\xi} w_{\xi} \cdot \langle f, \varphi_{\xi} \rangle \cdot \psi_{\xi}(x)$, where w_{ξ} are learnable weights in the frequency domain, $\varphi_{\xi} \in \mathcal{B}^*$ is the basis in the dual space, and $\psi_{\xi} \in \mathcal{B}$ is the biorthogonal primal basis which satisfies $\langle \psi_{\xi}, \varphi_{\eta} \rangle = \delta_{\xi\eta} = 1$ if $\xi = \eta$ and $= 0$ otherwise [Zhang et al., 2009]. On the other hand, the dual net performs a point-wise convolution $\mathcal{C}(f)(x)$ as [Hua et al., 2018]:

$$\mathcal{C}(f)(x) = \sum_{c'=1}^C W_{cc'} f^{(c')}(x), \quad (11)$$

where C is the number of input channels of f , $f^{(c')}(x)$ refers to the value of f at x and channel c' , and $W_{cc'}$ denotes the learned map from channel c' to channel c . This point-wise convolution resembles a Dirac-type kernel integral on its domain Ω as:

$$\mathcal{C}(f)(x) = \int_{\Omega} \delta(x - y) \cdot W \cdot f(y) dy. \quad (12)$$

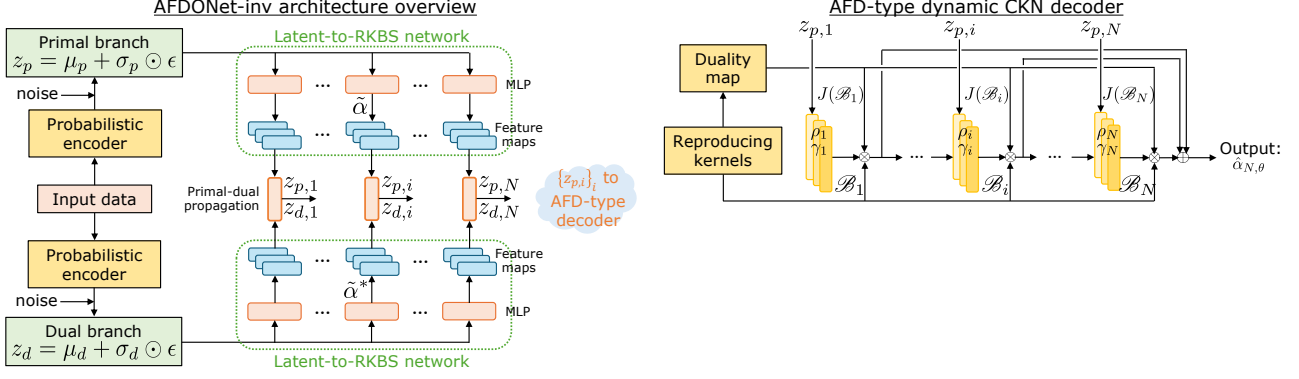


Figure 1: Our proposed AFDONet-inv framework, whose design is guided by the AFD theory and operation, for solving inverse PDE problems in Banach space. Note that the elements in the figure are static representations of the corresponding theoretical component, whereas *the actual computation follows the dynamic, recursive update defined by Equation (13)*.

Finally, the residuals in the primal space and its dual space after each layer are updated and propagated to the corresponding latent variables as:

$$\begin{aligned} z_{p,i} &= \text{GELU} \circ \text{BN} (z_{p,i-1} + \mathcal{S}(z_{p,i-1}) + \mathcal{C}(z_{p,i-1})), \\ z_{d,i} &= z_{d,i-1} + \mathcal{S}(z_{d,i-1}) + \mathcal{C}(z_{d,i-1}), \end{aligned} \quad (13)$$

where $z_{p,i}, z_{d,i}$ are the residuals of i -th layer in the primal space and its dual space with $z_{p,0} = \text{FM}(\hat{\alpha})$ and $z_{d,0} = J(\text{FM}(\hat{\alpha}))$, respectively. The initial latent vector, z_p , is used to define $\hat{\alpha}$, and $\hat{\alpha}$ then defines the initial decoder input, $z_{p,0}$. Here, GELU denotes the GELU activation function and BN is the batch normalizing transform [Ioffe and Szegedy, 2015].

It can be shown that z_p and z_d in Equation (13) actually correspond to the residual r_i and its dual $J(r_i)$ defined in the AFD theory as:

Theorem 4.1. *Let $\mathcal{B}$ be a uniformly smooth and uniformly convex Banach space, $r_i \in \mathcal{B}$ be the residual at step i in the AFD process, z_p and z_d are defined in Equation (13). Then, for any $\varepsilon > 0$, there exists a choice of parameters $W(\xi)$, $W_{cc'}$, and BN scalars such that:*

$$\|z_{p,i} - r_i\|_{\mathcal{B}} < \varepsilon, \text{ and } \|z_{d,i} - J(r_i)\|_{\mathcal{B}^*} < \varepsilon.$$

Proof. See Appendix B. $\square$

Note that, even though the variables $z_{p,i}$ are computationally represented as tensors, Theorem 4.1 shows that the learned network outputs behave as if they were the true theoretical Banach space residuals r_i .

The AFD-type decoder network. Once the RKBS and its reproducing kernel K_z are constructed, we design a decoder network based on the AFD operation to reconstruct parameters α from $z_{p,i}$. First, we normalize the reproducing kernel K_z in Equation (9) as $\mathcal{B}_i(\cdot) = \frac{K_z(\cdot, a_i)}{\|K_z(\cdot, a_i)\|_{\mathcal{B}}}$, each

associated with a pole a_i . The set of these normalized reproducing kernels is denoted as $\mathcal{D} = \{\mathcal{B}_i | a_i \in \mathcal{B}\}$. The decoder then adopts a dynamic convolutional kernel network (CKN) [Mairal et al., 2014, Chen et al., 2020a], in which, for each convolutional layer i , (i) performs dual pairing between $z_{p,i}$ and the normalized reproducing kernel $\mathcal{B}_i$, (ii) assigns a multiplier $0 < \rho_0 \leq \rho_i < 1$ to the output of each convolutional layer, and (iii) incorporates skip connections for each convolutional layer. Finally, the output of the dynamic CKN containing N convolutional layers is:

$$\hat{\alpha}_{N,\theta} = \sum_{i=1}^N \langle z_{p,i}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i. \quad (14)$$

Guided by the AFD theory, the selection of poles and their reproducing kernels follows a similar maximal selection principle as in the AFD theory. Here, starting from Equation (4), we can write an analogous condition for selecting poles as:

$$\gamma_i \leq |\langle z_{p,i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}| - \rho_i \sup_{\mathcal{B}_i \in \mathcal{D}} \{|\langle z_{p,i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}|\}. \quad (15)$$

In the actual implementation, the dynamic CKN acts like a differentiable weak-greedy approximation to the exact maximal selection principle. With this, and leveraging the convergence behavior of AFD, we can show that our decoder in AFDONet-inv converges as $N \rightarrow \infty$ by the following theorem:

Theorem 4.2. *Let $\mathcal{B}$ be a uniformly smooth and uniformly convex Banach space, and let $\hat{\alpha}_{N,\theta}$ be the output of the dynamic CKN decoder with N layers. By selecting poles and bias terms following the modified maximal selection principle of Equation (15), as $N \rightarrow \infty$:*

$$\|\hat{\alpha}_{N,\theta} - \alpha_{\text{true}}\|_{\mathcal{B}} \leq \hat{C} \prod_{i=1}^N \rho_i \cdot \|r_0\|_{\mathcal{B}},$$

where $\hat{C} > 0$ is a constant and r_0 is the initial residual.

Proof. See Appendix D. $\square$

4.2 TRAINING

Overall, our AFDONet-inv model is trained end-to-end by minimizing the following loss function:

$$\mathcal{L}(\theta) = \underbrace{\|\hat{\alpha}_{N,\theta} - \alpha_{\text{true}}\|_{\mathbf{p}'}^{\mathbf{p}'}}_{\text{reconstruction loss in } L^{\mathbf{p}'}} + \underbrace{\omega_p \mathcal{D}_{\text{KL}}(\mathcal{N}(\mu_p, \sigma_p^2) \| \mathcal{N}(0, I))}_{\text{latent regularization loss in primal space}} + \underbrace{\omega_d \mathcal{D}_{\text{KL}}(\mathcal{N}(\mu_d, \sigma_d^2) \| \mathcal{N}(0, I))}_{\text{latent regularization loss in dual space}}. \quad (16)$$

The training dataset consists of various sets of PDE parameters and their corresponding PDE solutions. The Adam optimizer with a learning rate of 5×10^{-4} is used to train our AFDONet-inv model. In actual implementation of the model, we use $\mathbf{p}' = 1$ (corresponding to L^1 loss) and $\omega_p = \omega_d = 1 \times 10^{-3}$ in the loss function of Equation (16).

4.3 CONNECTIONS TO THE AFD THEORY

In AFDONet-inv, the encoder network first maps the input to its latent space, followed by a latent-to-RKBS network which finds the corresponding nearest RKBS using a feature map FM. During training, when minimizing the loss function of Equation (16) over different sets of PDE solutions $\{x_j\}_{j=1}^m$, we find that the optimal feature map FM^* admits a finite representation $\text{FM}^*(\tilde{\alpha})(x) = \sum_{j=1}^m c_j K_z(x, x_j)$ with coefficients $c_j \in \mathbb{R}$ (see Appendix C for details). After that, the primal-dual propagation refines the value of latent variable in the Banach space and its dual, and produces the input to each layer of the dynamic CKN. This input is essentially the residual r_i of AFD operation at each step i , as illustrated in Theorem 4.1. In this regard, the AFD-type decoder basically replicates the AFD operations. Formally, let $P_N(\alpha) = \sum_{i=1}^N \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i$ be the N -term partial sum in the AFD decomposition. Then, the decoder approximation satisfies:

Theorem 4.3. *Let $\mathcal{B}$ be a uniformly smooth and uniformly convex Banach space, and let $\hat{\alpha}_{N,\theta}$ be the output of the AFD-type decoder after N layers. Then, for any $\varepsilon > 0$, there exists parameters in the primal net and dual net, such that:*

$$\|\hat{\alpha}_{N,\theta} - P_N(\alpha)\|_{\mathcal{B}} \leq \varepsilon + O\left(\frac{1}{\sqrt{N}}\right) \|\alpha\|_{\mathcal{B}}.$$

Proof. See Appendix E. $\square$

4.4 THEORETICAL ALIGNMENT AND PRACTICAL IMPLEMENTATION

A natural question arises regarding the alignment between the theoretical framework and practical implementation: how does the learned model align with AFD theory when the ideal pole selection principle (Equation (4)) is not explicitly enforced during training? We address this concern through a combination of architectural design and theoretical analysis, demonstrating that the practical implementation naturally encourages AFD-like behavior.

Implementation via Bias Term. The ideal pole selection principle requires computing $\sup_{a \in \mathbb{D}} |\langle r, J(\mathcal{B}_a) \rangle|$, which is not directly differentiable for gradient-based optimization. We implement this through the dynamic CKN with a bias term:

$$\hat{\alpha}_i = \text{CKN}(z_i, r_{i-1}) + b, \quad (17)$$

where $b \in \mathbb{R}$ is a hyperparameter that serves as a differentiable approximation to the ideal selection criterion. The bias term b is initialized based on the theoretical bound in Equation 4. For a given residual r and kernel dictionary $\{\mathcal{B}_{a_j}\}_{j=1}^K$, we initialize:

$$b_{\text{init}} = \frac{1}{K} \sum_{j=1}^K |\langle r, J(\mathcal{B}_{a_j}) \rangle|. \quad (18)$$

It provides a starting point that approximates the average selection strength, which the network refines during training to better align with the maximal selection principle.

5 ARCHITECTURE AND IMPLEMENTATION DETAILS

Our AFDONet-inv operates with a latent dimension of 128 and a width of 32 channels, utilizing a hybrid basis of Real Fast Fourier Transforms and cosine basis transformations with 12 Fourier modes across both dimensions. Its core consists of three consecutive propagation layers, incorporating dual polar spectral convolutions, 1×1 2D convolutions, Batch Normalization, GELU activations, and a DualityMap ($p = 1.5$), which feed into a decoder that pairs a standard 1×1 convolution with a dynamic 3×3 convolution generated by the dual latent vector. To optimize this architecture, the network is trained for 1000 epochs with a batch size of 32 using the Adam optimizer, applying a learning rate of 1×10^{-4} and a maximum gradient clipping norm of 1.0. The training objective incorporates a Kullback-Leibler divergence penalty weighted at 1×10^{-8} , with all random seeds left unconstrained.

6 EXPERIMENTS

In this section, we evaluate the performance of our AFDONet-inv on two commonly used benchmark inverse

problems by conducting extensive ablation studies and comparing the solution accuracy and run time with state-of-the-art neural solvers, including NAO [Yu et al., 2024], NIPS [Liu and Yu, 2025], LNO [Wang and Wang, 2024], and MWT [Gupta et al., 2021]. Each solver is trained for 1000 epochs for both benchmark problems. All experiments are performed on a B760M GAMING WIFI PLUS desktop equipped with an Intel Core i5-14600KF CPU and an NVIDIA GeForce RTX 4090 GPU (with 48GB GDDR6 memory).

6.1 PROBLEM SETTINGS AND DATASETS

2-D Darcy flow. The first inverse problem we consider is the 2-D Darcy flow problem introduced by Li et al. [2020b] and Yu et al. [2024]. It takes the following form:

$$\begin{aligned} \nabla \cdot (a(x) \nabla u(x)) &= f(x), \quad x \in [0, 1]^2, \\ u(x) &= 0, \quad x \in \partial[0, 1]^2, \end{aligned} \quad (19)$$

where $a(x)$ denotes the permeability field, and $f(x)$ is the source term. Given the solution $u(x)$ and the source term $f(x)$, here we aim to reconstruct the permeability field $a(x)$.

For Darcy flow dataset, the coefficients a are generated following a measure μ defined as $\mu = \psi(\mathcal{N}(0, (-\Delta + 9I)^{-2}))$, where the operator $(-\Delta + 9I)^{-2}$ utilizes a Neumann boundary condition. The field a is constructed to be piecewise constant with random geometry and a fixed contrast of 4, determined by the mapping $\psi(x) = 12$ for $x > 0$ and $\psi(x) = 3$ for $x \leq 0$. Solutions u are generated using a second-order finite difference scheme on a high-resolution grid (241×241).

Nonlinear magnetic Schrödinger equation. The second benchmark inverse problem involves solving the magnetic Schrödinger equation on a complex manifold $\mathcal{M}$:

$$\begin{aligned} (\Delta_A + q(|u(z)|^2)) u(z) &= 0, \quad z \in \mathcal{M}, \\ u(z) &= f, \quad z \in \partial\mathcal{M}, \end{aligned} \quad (20)$$

where $\mathcal{M} = \{z = (z_1, z_2) \in \mathbb{C}^2 : |z_1|^2 + |z_2|^2 \leq 1\}$ with boundary $\partial\mathcal{M} = S^3$, $\Delta_A = (d + iA)^*(d + iA)$ is the magnetic Laplacian (with d the exterior derivative and $*$ the Hodge star with respect to the Kähler metric), q is a nonlinear function, and f is the boundary term. In this problem, we aim to recover the potentials A and q from boundary conditions in the Dirichlet-to-Neumann (DN) map $\Lambda_{A,q} : f \mapsto \partial_\nu u|_{\partial\mathcal{M}}$, where ν is the outward normal vector, and u is the solution of Equation (20). For the nonlinear magnetic Schrödinger dataset, the DN map data will serve as the observations. That is, we only need to generate the DN map rather than the PDE solutions. The DN map is generated by numerically solving the highly nonlinear Schrödinger equation for various input boundary terms f and then calculating the resulting normal derivative $\partial_\nu u$ at the boundary. The

complete dataset consists of pairs of the unknown potentials (A, q) and their corresponding simulated DN maps.

Note that this inverse problem is more challenging to solve than the one directly given solution u , as the DN map only retains partial information of u . Note that we also consider the reduced case on a regular rectangular domain $[0, 1] \times [0, 1]$ in Appendix F.

Additional benchmark PDE problems, including inversion of reaction-diffusion [Cao et al., 2024], Navier-Stokes [Li et al., 2020a], as well as a real-world latex glove digital image correlation problem [You et al., 2022], are evaluated and discussed in Appendix F.

6.2 ABLATION STUDIES

We conduct the following set of ablation studies to illustrate the need for different components in AFDONet-inv. In Scenario 1, we remove the primal-dual propagation. In Scenario 2, we remove the dual branch in the encoder network and the duality map J . Finally, in Scenario 3, we remove both primal-dual propagation and the dual space. Results in Tables 1 and 2 indicate that incorporating primal-dual propagation and dual space is necessary for improving the overall accuracy of AFDONet-inv by reducing the MAE and relative L^2 error.

To explain this, we observe that, without the dual branch, the primal-dual propagation only gives $z_{p,i}$, which is the approximation of the residual r_i in the AFD theory according to Theorem 4.1. In this case, AFDONet-inv essentially approximates $\sum_{i=1}^N \langle r_i, \mathcal{B}_i \rangle \mathcal{B}_i$, which asymptotically converges under the pairing $\langle \cdot, \cdot \rangle$ with an error $O\left(\frac{1}{\sqrt{N}}\right)$. Meanwhile, when removing primal-dual propagation, the input to the AFD-type decoder is simply $\text{FM}(\tilde{\alpha})$. This way, AFDONet-inv essentially performs the operation $\sum_{i=1}^N \langle \text{FM}(\tilde{\alpha}), J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i$ in the Banach space, which converges with an error $O\left(\frac{1}{N^{k'}}\right)$ if the PDE parameters lie in $C^{k'}$. Finally, when both primal-dual propagation and the dual branch are removed, AFDONet-inv performs the operation $\sum_{i=1}^N \langle \text{FM}(\tilde{\alpha}), \mathcal{B}_i \rangle \mathcal{B}_i$, which may not even converge since the kernels $\{\mathcal{B}_i\}_i$ are not necessarily orthogonal to each other.

Specifically, we consider the 2-D Darcy flow problem, in which the permeability field $a(x)$ on a regular domain $[0, 1]^2$ is typically considered as a L^∞ (or $C^{s'}$ for $s' < 0.5$ [Teng et al., 2024]) function due to its irregularity. Thus, in Scenario 1, AFDONet-inv converges with an error $O\left(\frac{1}{N^{s'}}\right)$ while it converges with an error $O\left(\frac{1}{N^{0.5}}\right)$ in Scenario 2. This is consistent with the results shown in Table 1, in which the removal of primal-dual propagation has more significant impact on solution accuracy compared to the removal of the dual branch in the encoder. When both primal-dual propaga-

tion and dual branch are eliminated from the AFDONet-inv architecture (Scenario 3), we observe the highest MAE and relative L^2 error values.

Models	MAE	Relative L^2 error
Full	$1.82\text{E-}01 \pm 6.43\text{E-}02$	$6.64\text{E-}02 \pm 1.38\text{E-}03$
w/o prop.	$3.18\text{E-}01 \pm 1.06\text{E-}01$	$7.05\text{E-}01 \pm 2.19\text{E-}02$
w/o dual	$2.39\text{E-}01 \pm 5.32\text{E-}02$	$1.07\text{E-}01 \pm 4.45\text{E-}02$
w/o p.d.	$3.56\text{E-}01 \pm 7.01\text{E-}02$	$1.93\text{E-}01 \pm 3.74\text{E-}02$

Table 1: Comparison of MAE and relative L^2 error in permeability field $a(x)$ on Darcy flow equation. Here and hereinafter, “Full” stands for the full AFDONet-inv model, “w/o prop.” means “without primal-dual propagation” or Scenario 1 of the ablation studies, “w/o dual” means “without dual branch” or Scenario 2 of the ablation studies, and “w/o p.d.” means “without both primal-dual propagation and dual branch”.

For the magnetic Schrödinger equation problem on complex manifolds, the deterministic results of Krupchyk et al. [2024] indicate that both A and q can be relaxed to C^∞ . This implies a super-algebraic convergence behavior for AFDONet-inv when primal-dual propagation is removed, which explains why both MAE and relative L^2 error values are slightly lower for Scenario 1 compared to Scenario 2. Last but not least, removing both primal-dual propagation and dual branch leads to the highest MAE and relative L^2 error, as the resulting AFDONet-inv architecture exhibits the worst convergence behavior (or even divergence).

Models	MAE	Relative L^2 error
Full	$1.54\text{E-}02 \pm 2.78\text{E-}03$	$1.50\text{E-}05 \pm 6.23\text{E-}07$
w/o prop.	$7.39\text{E-}02 \pm 1.81\text{E-}02$	$3.06\text{E-}04 \pm 1.75\text{E-}04$
w/o dual	$7.83\text{E-}02 \pm 2.20\text{E-}05$	$3.47\text{E-}04 \pm 1.10\text{E-}05$
w/o p.d.	$8.01\text{E-}02 \pm 6.75\text{E-}03$	$3.58\text{E-}04 \pm 3.51\text{E-}05$

Table 2: Comparison of MAE and relative L^2 error in potentials A and q on magnetic Schrödinger equation.

6.3 COMPARISON WITH BENCHMARK SOLVERS

Nonlinear magnetic Schrödinger equation. The inverse problem associated with this nonlinear PDE is highly ill-posed. From Table 3, we observe that AFDONet-inv outperforms benchmark solvers by achieving up to one order of magnitude lower MAE and two to four orders of magnitude lower relative L^2 error. Meanwhile, in terms of computational efficiency, AFDONet-inv is competitive against these benchmark solvers. Note that in all experiments, the architecture size and training conditions are kept the same for all methods, whereas the number of parameters are different (due to the different structures associated with different solvers) but are in the same order of magnitude.

Due to the highly ill-posed nature of this inverse problem, non-smooth regularization such as L^1 penalty terms can greatly promote sparsity when reconstructing potentials A and q . Note that sparsity is naturally represented in an L^1 (Banach) space, not an L^2 (Hilbert) space. While the Hilbert space geometry often over-smoothens or distributes non-smooth PDE parameter features across many modes, the Banach space geometry can encode sparsity and jumps more effectively. In this regard, our proposed AFDONet-inv solver, grounded in a novel Banach space representer theorem [Parhi and Nowak, 2021], can better capture irregular, sparse features on complex manifolds when solving ill-posed inverse problems. On the other hand, existing state-of-the-art models, including NIPS, NAO, and LNO, are implicitly or explicitly grounded in the Hilbert space and thus perform poorly. This significant performance gap indicates how the Hilbert-space assumption in existing models limits their performance in practice.

Models	MAE	Relative L^2 error	Training time
AFDONet-inv (ours)	$1.54\text{E-}02 \pm 2.78\text{E-}03$	$1.50\text{E-}05 \pm 6.23\text{E-}07$	0.52
NAO [Yu et al., 2024]	$4.65\text{E-}01 \pm 5.32\text{E-}02$	$6.29\text{E-}01 \pm 1.96\text{E-}01$	2.54
NIPS [Liu and Yu, 2025]	$2.19\text{E-}01 \pm 9.73\text{E-}02$	$1.32\text{E-}01 \pm 8.40\text{E-}02$	0.30
LNO [Wang and Wang, 2024]	$1.86\text{E-}01 \pm 6.15\text{E-}02$	$2.89\text{E-}03 \pm 3.71\text{E-}04$	0.90
MWT [Gupta et al., 2021]	$3.18\text{E-}01 \pm 1.56\text{E-}01$	$7.05\text{E-}01 \pm 2.46\text{E-}02$	1.86

Table 3: Comparison of MAE, relative L^2 error, and training time (seconds per epoch) among different models on magnetic Schrödinger equation.

2-D Darcy flow. Table 4 shows the MAE, relative L^2 error, and training time of AFDONet-inv compared to other benchmark solvers for the 2-D Darcy flow problem. We observe that AFDONet-inv is the second best performing solver in terms of MAE and outperforms all benchmark solvers in terms of relative L^2 error. Since the Darcy flow equation typically lies in L^∞ space, which is a Banach space, our AFDONet-inv incorporating RKBS outperforms most benchmark solvers. Meanwhile, we remark that for this problem, the Hilbert-space assumption is also reasonable because the permeability field $a(x)$ is often modeled with smoother priors, where the sparsity from Banach space may not be significant. This explains why the NIPS solver performs better on Darcy’s problem in terms of MAE.

Of course, it is worth mentioning that, using appropriate regularization, sparsity and non-smoothness can also be possibly handled within the Hilbert space inverse problem frameworks. We will conduct a more systematic comparison between Banach-space implementations and Hilbertized variants across different baselines in our future work.

7 CONCLUSION

In this work, we introduce AFDONet-inv to solve inverse problems in a Banach space. To the best of our knowledge, AFDONet-inv is the first neural inverse PDE solver whose

Models	MAE	Relative L^2 error	Training time
AFDONet-inv (ours)	$1.82\text{E-}01 \pm 6.43\text{E-}02$	$6.64\text{E-}02 \pm 1.38\text{E-}03$	2.69
NAO [Yu et al., 2024]	$1.11 \pm 2.10\text{E-}01$	$7.71\text{E-}02 \pm 2.09\text{E-}03$	3.40
NIPS [Liu and Yu, 2025]	$1.05\text{E-}01 \pm 4.71\text{E-}02$	$1.56\text{E-}01 \pm 1.03\text{E-}01$	0.96
LNO [Wang and Wang, 2024]	$2.78\text{E-}01 \pm 3.07\text{E-}02$	$1.00 \pm 3.48\text{E-}05$	2.92
MWT [Gupta et al., 2021]	45.95 ± 2.48	$9.73\text{E-}01 \pm 6.72\text{E-}02$	1.65

Table 4: Comparison of MAE, relative L^2 error, training time (seconds per epoch) among different models on Darcy flow equation.

design rigorously follows an established mathematical theory in every step. Each component of the neural architecture, including primal and dual nets, latent-to-RKBS network, and dynamic CKN, has a corresponding component in the AFD operation in Banach space. This way, AFDONet-inv is mathematically explainable and grounded in the AFD theory and possesses several theoretical justifications and performance guarantees. Thanks to the tailored design, our AFDONet-inv solver outperforms several state-of-the-art neural operator solvers by a significant margin in terms of accuracy on inverse problems with complex manifolds and parameter space. In particular, AFDONet-inv is most useful when the inverse problem is ill-posed and/or the parameter is sparse, localized, discontinuous, or Out-of-Distribution (OOD)-irregular. Overall, the performance of AFDONet-inv sheds light on the systematic design of explainable neural operator frameworks.

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Adaptive Fourier Decomposition-guided Neural Operator Design for Inverse PDE Problems

(Supplementary Material)

Zeyuan Song^{†1,3}

Xiaocong Zhen^{†2}

Zheyu Jiang^{†3}

¹Department of Mathematics, Lehigh University, Bethlehem, Pennsylvania, USA

²School of Industrial Engineering and Management, Oklahoma State University, Stillwater, Oklahoma, USA

³School of Chemical Engineering, Oklahoma State University, Stillwater, Oklahoma, USA

A AFD IN RKBS

The AFD operations in RKBS are conceptually illustrated in Algorithm 1. Note that here, we do not yet consider the bias term γ_i .

Algorithm 1 AFD in RKBS

Require: Target function α_{true} , dictionary $\mathcal{D}$, duality map J , parameter ρ_i , tolerance ε , maximum levels of decomposition N

```

1: Initialize:  $\alpha_0 \leftarrow 0, r_0 \leftarrow \alpha_{\text{true}}$ 
2: for  $i = 1$  to  $N$  do
3:   Kernel selection:
4:   Choose  $\mathcal{B}_i \in \mathcal{D}$  such that
      
$$|\langle r_{i-1}, \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}| \geq \rho_i \sup_{\mathcal{B} \in \mathcal{D}} |\langle r_{i-1}, \mathcal{B} \rangle_{\mathcal{B}, \mathcal{B}^*}|$$

5:   Coefficient selection:
6:   Compute  $a_i \leftarrow \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}$ 
7:   Update:
8:    $\alpha_i \leftarrow \alpha_{i-1} + a_i \mathcal{B}_i$ 
9:    $r_i \leftarrow \alpha_{\text{true}} - \alpha_i$ 
10:  if  $\|r_i\| < \varepsilon$  then
11:    break
12:  end if
13: end for
```

Here, we assume the following assumption holds. Especially, Assumption 3 is the property (Γ) from Ganichev and Kalton [2009].

1. $\mathcal{B}$ is a uniformly smooth and uniformly convex Banach space of functions on a domain Ω , with dual space $\mathcal{B}^*$.
2. $\mathcal{D}$ is defined as $\{\mathcal{B}_{a_i} | a_i \in \mathcal{B}\}$, where $\mathcal{B}_{a_i}(\cdot) = \frac{K_z(\cdot, a_i)}{\|K_z(\cdot, a_i)\|_{\mathcal{B}}}$ with poles a_i . The linear span of $\mathcal{D}$ is dense in $\mathcal{B}$.
3. There exists $\tilde{C} > 0$ such that for all $x \in \mathcal{B}$ with $\|x\|_{\mathcal{B}} = 1$ and $y \in \mathcal{B}$ with $\langle y, J(x) \rangle_{\mathcal{B}, \mathcal{B}^*} = 0$, we have $\langle y, J(x + y) \rangle_{\mathcal{B}, \mathcal{B}^*} \leq \tilde{C}(\|x + y\|_{\mathcal{B}} - 1)$.

With these assumptions, we first show that the residual r_i is decreasing with respect to i :

Theorem A.1. *At each iteration $i \geq 1$, it holds that:*

$$\|r_i\|_{\mathcal{B}} < \|r_{i-1}\|_{\mathcal{B}},$$

unless $\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^} = 0$.*

Proof. Define $\tilde{\phi}(a) = \|r_{i-1} - a\mathcal{B}_i\|_{\mathcal{B}}$. From Assumption 1, the uniform convexity of $\mathcal{B}$ ensures $\tilde{\phi}$ is strictly convex with a unique minimizer. Moreover, $\tilde{\phi}$ is Gâteaux differentiable in terms of its norm due to the uniform smoothness of $\mathcal{B}$. Its directional derivative is $\left. \frac{d}{dt} \|r_{i-1} + th\|_{\mathcal{B}} \right|_{t=0} = \frac{\Re\langle J(r_{i-1}), h \rangle_{\mathcal{B}, \mathcal{B}^*}}{\|r_{i-1}\|_{\mathcal{B}}}$. Now, we aim to find a direction h based on $\mathcal{B}_i$ that decreases the norm, i.e., $\Re\langle J(r_{i-1}), h \rangle_{\mathcal{B}, \mathcal{B}^*} < 0$. From , we choose $h = -\frac{\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}}{|\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}|}$, then

$$\begin{aligned} \Re\langle J(r_{i-1}), h \rangle_{\mathcal{B}, \mathcal{B}^*} &= \Re\langle J(r_{i-1}), -\frac{\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}}{|\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}|} \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*} \\ &= -\Re\left(\frac{\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}}{|\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}|} \langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}\right) \\ &= -|\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}|. \end{aligned} \quad (21)$$

If $\langle J(r_{i-1}), \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*} \neq 0$, the results of Equation (21) is negative. So, $\tilde{\phi}(t) < \tilde{\phi}(0)$ for $t > 0$. Strict convexity then implies $\tilde{\phi}(a_i) < \tilde{\phi}(0)$ if $a_i \neq 0$, hence $\|r_i\|_{\mathcal{B}} < \|r_{i-1}\|_{\mathcal{B}}$. $\square$

Then, the convergence of AFD in RKBS can be shown as:

Theorem A.2. *The sequence $\{\alpha_i\}_{i=1}^N$ generated by Algorithm 1 satisfies:*

$$\lim_{i \rightarrow \infty} \|\alpha_{true} - \alpha_i\|_{\mathcal{B}} = 0.$$

Proof. From Theorem A.1, the sequence $\{\|r_i\|_{\mathcal{B}}\}$ is nonincreasing and its lower bound is 0. Thus, the sequence $\{\|r_i\|_{\mathcal{B}}\}$ converges. Assume its limit $l > 0$ for contradiction. Uniform convexity from Assumption 1 implies the bounded $\{r_i\}$ has weak limit points r' with $\|r'\|_{\mathcal{B}} \leq l$ by weak lower semicontinuity. By properties of the duality map J , we have:

$$\sup_{\mathcal{B} \in \mathcal{D}} |\langle r_{i-1}, J(\mathcal{B}) \rangle_{\mathcal{B}, \mathcal{B}^*}| = \|r_{i-1}\|_{\mathcal{B}}. \quad (22)$$

Combining Equation (22) and $|\langle r_{i-1}, \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}| \geq \rho_i \sup_{\mathcal{B} \in \mathcal{D}} |\langle r_{i-1}, \mathcal{B} \rangle_{\mathcal{B}, \mathcal{B}^*}|$ leads to:

$$|\langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}| \geq \rho_i \|r_{i-1}\|_{\mathcal{B}}. \quad (23)$$

From Xu and Roach [1991], we have the following inequality by setting $p = 2$:

$$\|x + y\|_{\mathcal{B}}^2 \leq \|x\|_{\mathcal{B}}^2 + 2\langle J(x), y \rangle_{\mathcal{B}, \mathcal{B}^*} + 2\|x\|_{\mathcal{B}}^2 \rho \left(\frac{\|y\|_{\mathcal{B}}}{\|x\|_{\mathcal{B}}} \right), \quad (24)$$

where ρ is the modulus of smoothness. By setting $x = r_{i-1}$ and $y = -a_i \mathcal{B}_i$ and assuming that a_i is chosen such that $\langle J(r_{i-1}), a_i \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*} > 0$, the term $2\langle J(x), y \rangle_{\mathcal{B}, \mathcal{B}^*} = -2\langle J(r_{i-1}), a_i \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*} = -2|\langle J(r_{i-1}), a_i \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}|$. Then, the Equation (24) becomes:

$$\begin{aligned} \|r_i\|_{\mathcal{B}}^2 &\leq \|r_{i-1}\|_{\mathcal{B}}^2 - 2|\langle J(r_{i-1}), a_i \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}| \\ &\quad + 2\rho \left(\frac{|a_i|}{\|r_{i-1}\|_{\mathcal{B}}} \right) \|r_{i-1}\|_{\mathcal{B}}^2. \end{aligned} \quad (25)$$

Assume, for contradiction, that $\sup_{\mathcal{B} \in \mathcal{D}} |\langle r_i, J(\mathcal{B}) \rangle_{\mathcal{B}, \mathcal{B}^*}| \not\rightarrow 0$. Then there exists $\delta > 0$ such that for infinitely many i , $\sup_{\mathcal{B} \in \mathcal{D}} |\langle r_i, J(\mathcal{B}) \rangle_{\mathcal{B}, \mathcal{B}^*}| \geq \delta$. For such i , the Equation (23) yields $|\langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}| \geq \rho_i \delta$. Then, we normalize $u = \frac{r_{i-1}}{\|r_{i-1}\|_{\mathcal{B}}}$ and $b_i = \frac{a_i}{\|r_{i-1}\|_{\mathcal{B}}}$, so $\frac{r_i}{\|r_{i-1}\|_{\mathcal{B}}} = u - b_i \mathcal{B}_i$. Then, the normalized version of Equation (23) is $|\langle u, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}| \geq \frac{\rho_i \delta}{\|r_{i-1}\|_{\mathcal{B}}} \geq \frac{\rho_i \delta}{l}$. Next, we utilize the decomposition technique as $y = -b_i \mathcal{B}_i = \alpha J(u) + z$, where $\alpha \in \mathbb{C}$ and $\langle z, J(u) \rangle_{\mathcal{B}, \mathcal{B}^*} = 0$. Since $\langle y, J(u) \rangle_{\mathcal{B}, \mathcal{B}^*} = \alpha$, we have $|\langle u, J(y) \rangle_{\mathcal{B}, \mathcal{B}^*}| = |\alpha|$. And $|\alpha| \geq \rho_i \delta' b_i$ with $\delta' \geq \delta/l$. The optimality condition is $\langle J(u+y), y \rangle_{\mathcal{B}, \mathcal{B}^*} = 0$, leading to $\alpha \langle J(u+y), J(u) \rangle_{\mathcal{B}, \mathcal{B}^*} = -\langle J(u+y), z \rangle_{\mathcal{B}, \mathcal{B}^*}$. If $b_i < k\rho_i$ for a small $k > 0$, then y small implies that for $\varepsilon > 0$, $\|J(u+y) - J(u)\|_{\mathcal{B}} < \varepsilon$. Therefore, we also have $\|\alpha - \langle J(u+y), z \rangle_{\mathcal{B}, \mathcal{B}^*}\|_{\mathcal{B}} < \varepsilon$. From Assumption 3, since $\langle z, J(u) \rangle_{\mathcal{B}, \mathcal{B}^*} = 0$, $|\langle z, J(u+y) \rangle_{\mathcal{B}, \mathcal{B}^*}| \leq \tilde{C}(\|u+y\|_{\mathcal{B}} - 1)$. With $b_i \rightarrow 0$, by smoothness, we obtain $\|u+y\|_{\mathcal{B}} - 1 = O(b_i)$, so $|\alpha| \rightarrow 0$, contradicting $|\alpha| \geq \rho_i \delta' b_i$. Thus, it holds that $b_i \geq k\rho_i$ for $k > 0$ depending on $\tilde{C}$ and the smoothness modulus. Substitute them into Equation (24) leads to the term $-2|\langle J(r_{i-1}), a_i \mathcal{B}_i \rangle_{\mathcal{B}, \mathcal{B}^*}|$ is at least $c'\rho_i^2 \|r_{i-1}\|_{\mathcal{B}}^2$ for the constant c' , and the term $2\|r_{i-1}\|_{\mathcal{B}}^2 \rho(b_i)$ is $o(\rho_i^2 \|r_{i-1}\|_{\mathcal{B}}^2)$ since $\rho(\cdot) = o(\cdot)$, yielding

$$\|r_i\|_{\mathcal{B}}^2 \leq \|r_{i-1}\|_{\mathcal{B}}^2 - c\rho_i^2 \|r_{i-1}\|_{\mathcal{B}}^2, \quad (26)$$

for $c > 0$. Assume that there exists $\delta > 0$ such that for infinitely many indices i_k (with $\|r_{i_k}\|_{\mathcal{B}}^2 \rightarrow l^2$), the decrease satisfies

$$\|r_{i_k}\|_{\mathcal{B}}^2 - \|r_{i_k+1}\|_{\mathcal{B}}^2 \geq c\rho_{i_k}^2 \|r_{i_k}\|_{\mathcal{B}}^2 \geq c\rho^2 l^2/2 =: d > 0, \quad (27)$$

where the last inequality holds for sufficiently large k since $\|r_{i_k}\|_{\mathcal{B}}^2 \rightarrow l^2$ and $\rho_{i_k} \geq \rho > 0$. Let $S = \sum_{k=1}^{\infty} (\|r_{i_k}\|_{\mathcal{B}}^2 - \|r_{i_k+1}\|_{\mathcal{B}}^2) \geq \sum_{k=1}^{\infty} d = \infty$. Since the overall sequence decreases by at most $\|r_1\|_{\mathcal{B}}^2 - l^2 < \infty$, but includes $S = \infty$, which leads to a contradiction. Therefore, for large M , the remaining decrease after i_M is at least $\sum_{k>M} d = \infty$, but it is upper bounded by $\|r_{i_M}\|_{\mathcal{B}}^2 - l^2 < \infty$. Between i_k and i_{k+1} , the decrease is nonnegative. Thus, after m such steps,

$$\|r_{i_k+m}\|_{\mathcal{B}}^2 \leq \|r_{i_k}\|_{\mathcal{B}}^2 - md \rightarrow -\infty \quad (m \rightarrow \infty), \quad (28)$$

which is impossible for norms. The exponential form follows recursively. If decrease $\geq c\rho^2 \|r_i\|_{\mathcal{B}}^2$ at each of m steps, finally it leads to

$$\|r_{i+m}\|_{\mathcal{B}}^2 \leq (1 - c\rho^2)^m \|r_i\|_{\mathcal{B}}^2 \rightarrow 0, \quad (29)$$

contradicting convergence to $l^2 > 0$.

Thus, $\sup_{\mathcal{B} \in \mathcal{D}} |\langle r_i, J(\mathcal{B}) \rangle_{\mathcal{B}, \mathcal{B}^*}| \rightarrow 0$. For weak limit r' of $\{r_{i_k}\}$, $\langle r_{i_k}, J(\mathcal{B}) \rangle \rightarrow \langle r', J(\mathcal{B}) \rangle = 0$ for all $\mathcal{B} \in \mathcal{D}$. Bijectivity of J and density of span $\mathcal{D}$ imply $\{J(\mathcal{B})\}$ generates dense functionals, forcing $r' = 0$. All weak limits are 0, but $\|r_i\|_{\mathcal{B}} \rightarrow l > 0 = \|0\|_{\mathcal{B}}$, contradicting weak lower semicontinuity unless $l = 0$. Hence, $\lim_{i \rightarrow \infty} \|r_i\|_{\mathcal{B}} = 0$, so $\lim_{i \rightarrow \infty} \|\alpha_{\text{true}} - \alpha_i\|_{\mathcal{B}} = 0$. $\square$

B PROOF OF THEOREM 4.1

Without loss of generality, we consider the case $\mathcal{B} = L^p([0, L]^d)$ for $1 < p < \infty$. Before giving the complete proof of Theorem 4.1, we introduce some lemmas as follows.

Lemma B.1. *Let $\mathcal{B} = L^p([0, L]^d)$ for $1 < p < \infty$, a uniformly smooth Banach space admitting a Fourier transform $\mathcal{F}$. Let $(\psi_{\xi})_{\xi \in \mathbb{Z}^d}$ be the normalized Fourier basis $\psi_{\xi}(x) = e^{2\pi i \xi \cdot x/L}$, with Fourier coefficients $\hat{f}(\xi) = \mathcal{F}(f)(\xi)$. Define the partial sum operators $S_n : \mathcal{B} \rightarrow \mathcal{B}$ by $S_n f = \sum_{|\xi|_{\infty} \leq n} \hat{f}(\xi) \psi_{\xi}$, where $|\xi|_{\infty} = \max_j |\xi_j|$. Then, there exists $C'_p > 0$ (depending on p and d , but independent of n) such that $\|S_n f\|_{\mathcal{B}} \leq (C'_p)^d \|f\|_{\mathcal{B}}$ for all $f \in \mathcal{B}$ and all $n \in \mathbb{N}$.*

Proof. First, we prove this lemma for $d = 1$ (torus $\mathbb{T} \cong [0, L]$) and then extend it to higher dimensions. For $d = 1$, we have:

$$\begin{aligned} S_n f(x) &= \sum_{|k| \leq n} \hat{f}(k) e^{2\pi i k x/L} \\ &= f * D_n \\ &:= f * \left(\sum_{|k| \leq n} e^{2\pi i k x/L} \right). \end{aligned} \quad (30)$$

Define $\tilde{f}(x) = -i \sum_{k \in \mathbb{Z}} \text{sgn}(k) \hat{f}(k) e^{2\pi i k x/L}$, $\|\tilde{f}\|_{\mathcal{B}} \leq C_p \|f\|_{\mathcal{B}}$ indicates $\sup_n \|S_n\|_{\mathcal{B}} < \infty$ holds. Consider the Riesz projection $P_+(f) = \sum_{k \geq 0} \hat{f}(k) e^{2\pi i k x/L}$. Then, $P_+(f) = \frac{1}{2}(f + i\tilde{f}) + \frac{1}{2}\hat{f}(0)$, so boundedness of P_+ on L^p is equivalent to the boundedness of $\tilde{\cdot}$. Since

$$\begin{aligned} S_n f &= \hat{f}(0) + \sum_{k=1}^n \left(\hat{f}(k) e^{2\pi i k x/L} + \hat{f}(-k) e^{-2\pi i k x/L} \right) \\ &= 2 \text{Re}(P_+^{(n)}) - \hat{f}(0), \end{aligned} \quad (31)$$

where $P_+^{(n)}(f) = \sum_{k=0}^n \hat{f}(k) e^{i k x}$ and

$$\|P_+^{(n)}(f) - f\|_{\mathcal{B}} \leq (M + 1)\varepsilon \quad (32)$$

for a constant $M > 0$ and any $\varepsilon > 0$ from Miao [2014]. From the generalized M. Riesz Theorem [Berkson and Gillespie, 1985], it follows $\|\tilde{f}\|_{\mathcal{B}} \leq C_p \|f\|_{\mathcal{B}}$, which by the identity $P_+(f) = \frac{1}{2}(f + i\tilde{f}) + \frac{1}{2}\hat{f}(0)$, implies that the Riesz projection P_+ is also bounded on $\mathcal{B}$, with

$$\|P_+ f\|_{\mathcal{B}} \leq C'_p \|f\|_{\mathcal{B}}. \quad (33)$$

Since $P_+^{(n)}f \rightarrow P_+f$ in $\mathcal{B}$ norm as $n \rightarrow \infty$, it follows that $\{P_+^{(n)}\}_{n \in \mathbb{N}}$ is uniformly bounded on $\mathcal{B}$, i.e.,

$$\sup_n \|P_+^{(n)}\|_{\mathcal{B}} < \infty. \quad (34)$$

Therefore, one can obtain

$$\begin{aligned} \|S_n f\|_{\mathcal{B}} &\leq 2\|P_+^{(n)}f\|_{\mathcal{B}} + |\hat{f}(0)| \cdot \|1\|_{\mathcal{B}} \\ &\leq 2C_p\|f\|_{\mathcal{B}} + C\|f\|_{\mathcal{B}} = C'_p\|f\|_{\mathcal{B}} \end{aligned} \quad (35)$$

for a constant $C > 0$ using the triangle inequality.

For d -dimensional case, we define the d -dimensional kernel $D_n^d(\mathbf{x}) = \prod_{j=1}^d D_n(x_j)$ and the d -dimensional operator $S_n^d = S_n \otimes \cdots \otimes S_n$. From Equation (35), we have:

$$\|S_n^d f\|_{\mathcal{B}} \leq (C'_p)^d \|f\|_{\mathcal{B}}. \quad (36)$$

□

Lemma B.2. *Let $\mathcal{P}$ denote the space of trigonometric polynomials, i.e., finite linear combinations of plane waves $\psi_{\xi}(x) = e^{2\pi i \xi \cdot x/L}$ for $\xi \in \mathbb{Z}^d$. Then, $\mathcal{P}$ is dense in $\mathcal{B}$, meaning for any $f \in \mathcal{B}$ and $\epsilon > 0$, there exists $p \in \mathcal{P}$ such that $\|f - p\|_{\mathcal{B}} < \epsilon$. For any $g \in \mathcal{P}$ of degree at most n , it holds that $S_n g = g$, where $S_n g = \sum_{|\xi| \leq n} \hat{g}(\xi) \psi_{\xi}$.*

Proof. Since $\mathbb{T}^d$ is compact with finite measure, continuous functions $C(\mathbb{T}^d)$ are dense in $\mathcal{B}(\mathbb{T}^d)$ for any $1 \leq p < \infty$. For $f \in \mathcal{B}$, by Lusin's theorem (every measurable function is nearly continuous), for any $\epsilon > 0$, there exists a compact $K \subset \mathbb{T}^d$ with $\mu(\mathbb{T}^d \setminus K) < \epsilon$ and $f|_K$ continuous, hence can be approximated by continuous g with $\|f - g\|_{\mathcal{B}} < \epsilon$.

Next, we prove that $\mathcal{P}$ is dense in $C(\mathbb{T}^d)$. The Stone-Weierstrass theorem states that if $\mathcal{A}$ is a subalgebra of $C(X)$ that separates points (for any distinct $x, y \in X$, there exists $f \in \mathcal{A}$ with $f(x) \neq f(y)$) and contains constants, then $\mathcal{A}$ is dense in $C(X)$ under the sup-norm. Following this, considering the algebra $\mathcal{A} = \mathcal{P}_{\mathbb{R}}$ of real parts of $\mathcal{P}$, $\mathcal{A}$ contains constants and separates points: for distinct $x, y \in \mathbb{T}^d$, choose $\xi \in \mathbb{Z}^d$ such that $\xi \cdot (x - y) \not\equiv 0 \pmod{1}$, then $\cos(2\pi \xi \cdot x/L) \neq \cos(2\pi \xi \cdot y/L)$. Moreover, $\mathcal{A}$ is closed under multiplication. Thus, $\mathcal{A}$ is dense in $C(\mathbb{T}^d; \mathbb{R})$. Next, for $C(\mathbb{T}^d; \mathbb{C})$, density follows by approximating real and imaginary parts separately, since $\mathcal{P}$ includes both cosines and sines. Therefore, given $\mathcal{P}$ dense in $C(\mathbb{T}^d)$ and $C(\mathbb{T}^d)$ dense in $\mathcal{B}$, implies $\mathcal{P}$ dense in $\mathcal{B}$ from transitivity of density.

Then, for ($g \in \mathcal{P}$ with degree at most n , we have $\hat{g}(\xi) = 0$ for all $|\xi| > n$. Therefore, it follows:

$$S_n g = \sum_{|\xi| \leq n} \hat{g}(\xi) \psi_{\xi} = \sum_{\xi \in \mathbb{Z}^d} \hat{g}(\xi) \psi_{\xi} = g, \quad (37)$$

the last equality follows

$$g = \sum_{\xi \in \mathbb{Z}^d} \langle g, \psi_{\xi} \rangle \psi_{\xi}, \quad (38)$$

where $\langle g, \psi_{\xi} \rangle = \hat{g}(\xi)$. □

Lemma B.3. *With the Assumption 1, by assuming that $\mathcal{B}$ admits a Fourier transform $\mathcal{F}$ that is well-defined and invertible on a periodic domain $[0, L]^d$, for the Fourier basis of plane waves $\psi_{\xi}(x) = e^{2\pi i \xi \cdot x/L}$ denoted as $(\psi_{\xi})_{\xi \in \mathbb{Z}^d}$, and the biorthogonal dual functionals $(\varphi_{\xi})_{\xi \in \mathbb{Z}^d} \subset \mathcal{B}^*$ satisfying $\hat{f}(\xi) = \mathcal{F}(f)(\xi) = \langle f, \varphi_{\xi} \rangle_{\mathcal{B}, \mathcal{B}^*}$ for any $f \in \mathcal{B}$, then the inverse Fourier transform satisfies $\mathcal{F}^{-1}(\hat{f}(\xi)) = \sum_{\xi \in \mathbb{Z}^d} \hat{f}(\xi) \psi_{\xi}(x)$ in the sense that the series converges to f in the $\mathcal{B}$ -norm, i.e., $\lim_{n \rightarrow \infty} \left\| f - \sum_{|\xi| \leq n} \hat{f}(\xi) \psi_{\xi} \right\|_{\mathcal{B}} = 0$.*

Proof. Following Lin et al. [2022], one can show that the plane waves $\psi_{\xi}(x) = e^{2\pi i \xi \cdot x/L}$ span a dense subspace of trigonometric polynomials in $\mathcal{B}$. The corresponding dual functionals $\varphi_{\xi} \in \mathcal{B}^*$ extract the Fourier coefficients via the pairing $\hat{f}(\xi) = \langle f, \varphi_{\xi} \rangle_{\mathcal{B}, \mathcal{B}^*}$. Biorthogonality, given by $\langle \psi_{\xi}, \varphi_{\eta} \rangle_{\mathcal{B}, \mathcal{B}^*} = \delta_{\xi\eta}$, is ensured by the RKBS structure and follows from the spectral theorem applied to the associated kernel integral operator. Then, we define the operator $S_n : \mathcal{B} \rightarrow \mathcal{B}$ via $S_n f = \sum_{|\xi| \leq n} \hat{f}(\xi) \psi_{\xi}$. From Lemma B.1, $\|S_n\|_{\mathcal{B} \rightarrow \mathcal{B}}$ is bounded by a constant $(C'_p)^d$ independent of n .

From Lemma B.2 and uniform boundedness principle, $S_n f \rightarrow f$ in $\mathcal{B}$ -norm for all $f \in \mathcal{B}$. □

Remark B.1. An important consequence is the Hausdorff–Young inequality:

$$\left(\sum_{\xi} |\hat{f}(\xi)|^q \right)^{1/q} \leq C \|f\|_{\mathcal{B}}, \quad \text{where } \frac{1}{p} + \frac{1}{q} = 1, \quad (39)$$

which provides a bound on the Fourier coefficients in ℓ^q , which facilitates convergence of the Fourier series. For finite modes $\Lambda \subset \mathbb{Z}^d$, the sum is finite and exact, and the infinite case follows by taking limits as $|\Lambda| \rightarrow \infty$. Thus, the reconstruction defines the inverse Fourier transform $\mathcal{F}^{-1}(\hat{f}(\xi)) = \sum_{\xi} \hat{f}(\xi) \psi_{\xi}(x)$ in $\mathcal{B}$.

Lemma B.4. It holds that

$$\mathcal{S}(f)(x) = \sum_{\xi \in \Lambda} w_{\xi} \langle f, \varphi_{\xi} \rangle_{\mathcal{B}, \mathcal{B}^*} \psi_{\xi}(x),$$

where $w_{\xi} = W(\xi)$, $\varphi_{\xi} \in \mathcal{B}^*$ are dual bases, and $\psi_{\xi} \in \mathcal{B}$ are biorthogonal primal bases with $\langle \psi_{\xi}, \varphi_{\eta} \rangle_{\mathcal{B}, \mathcal{B}^*} = \delta_{\xi\eta}$.

Proof. In spectral methods for RKBS, one can show that the Fourier transform diagonalizes convolution operators [Kovachki et al., 2021]. Specifically, we assume a biorthogonal Fourier basis $(\psi_{\xi}, \varphi_{\xi})_{\xi \in \mathbb{Z}^d}$, where $\psi_{\xi}(x) = e^{2\pi i \xi \cdot x/L}$ for domain $[0, L]^d$, and φ_{ξ} are dual functionals satisfying the biorthogonality from the reproducing property: $\langle f, \varphi_{\xi} \rangle = \hat{f}(\xi) = \mathcal{F}(f)(\xi)$. Then, the spectral convolution applies pointwise multiplication in frequency space:

$$\widehat{\mathcal{S}(f)}(\xi) = \chi(\xi) W(\xi) \hat{f}(\xi). \quad (40)$$

Taking the inverse Fourier transform on Equation (40) leads to:

$$\mathcal{S}(f)(x) = \sum_{\xi \in \Lambda} W(\xi) \hat{f}(\xi) \psi_{\xi}(x), \quad (41)$$

where $\chi(\xi) = 1$ for $\xi \in \Lambda$ and 0 otherwise. Substituting $\hat{f}(\xi) = \langle f, \varphi_{\xi} \rangle_{\mathcal{B}, \mathcal{B}^*}$ into Equation (41) leads to

$$\mathcal{S}(f)(x) = \sum_{\xi \in \Lambda} W(\xi) \langle f, \varphi_{\xi} \rangle_{\mathcal{B}, \mathcal{B}^*} \psi_{\xi}(x). \quad (42)$$

Biorthogonality $\langle \psi_{\xi}, \varphi_{\eta} \rangle = \delta_{\xi\eta}$ follows from the Fourier basis orthogonality in the dual pairing, ensured by the RKBS structure [Li et al., 2022]. $\square$

Remark B.2. Equation (42) is nonlocal because the kernel involves global frequency modes rather than localized supports.

Lemma B.5. For any continuous operator $T : \mathcal{B} \rightarrow \mathcal{B}$ and $\delta > 0$, there exists a set of parameters of $W(\xi)$ in Equation (10) such that $\|\mathcal{S}(g) - T(g)\|_{\mathcal{B}} < \delta$ for all g in a bounded subset of $\mathcal{B}$.

Proof. First, we define integral operators $T(f)(x) = \int K_T(x, y) f(y) dy$, with kernel K_T continuous. Then, fixing a bounded set $G \subset \mathcal{B}$, we say G is weakly compact since $\mathcal{B}$ is uniformly smooth and reflexive. By Arzelà–Ascoli theorem, continuous kernels $K_T(x, y)$ and thus operator $T(f)$ can be approximated uniformly on G . We denote the Fourier operator $T_M(f) = \mathcal{F}^{-1}[\sum_{|\xi| \leq M} \hat{K}_T(\xi) \mathcal{F}(f)(\xi)]$, where $\hat{K}_T(\xi)$ is the Fourier transform of the kernel $K_T(x, y)$. From universal approximation theorem [Kovachki et al., 2021], we have:

$$\|T - T_M\|_{\mathcal{B}} \rightarrow 0, \quad \text{as } M \rightarrow \infty \quad (43)$$

Next, by setting $\Lambda = \{\xi : |\xi| \leq M\}$, $\chi(\xi) = 1_{\Lambda}(\xi)$, and $W(\xi) = \hat{K}_T(\xi)$, it follows

$$\|\mathcal{S} - T_M\|_{\mathcal{B}} \rightarrow 0, \quad \text{as } M \rightarrow \infty. \quad (44)$$

Finally, substituting Equation (43) to Equation (44) leads to:

$$\begin{aligned} \|\mathcal{S}(g) - T(g)\|_{\mathcal{B}} &\leq \|\mathcal{S}(g) - T_M(g) + T_M(g) - T(g)\|_{\mathcal{B}} \\ &\leq \|\mathcal{S}(g) - T_M(g)\|_{\mathcal{B}} + \|T(g) - T_M(g)\|_{\mathcal{B}} \\ &< \frac{\delta}{2} + \frac{\delta}{2} = \delta, \end{aligned} \quad (45)$$

which completes the proof. $\square$

Lemma B.6. Define $\mathcal{C}(f)(x) = \int_{\Omega} \delta(x-y) \cdot W \cdot f(y) dy$, where δ is the Dirac delta distribution. The integral is well-defined in the distributional sense.

Proof. First, we consider the single channel ($C = 1, W = 1$). In this case, we have $\mathcal{C}(f)(x) = f(x) = \int_{\Omega} \delta(x-y) f(y) dy$, where the integral is the pairing $\langle \delta_x, f \rangle_{\mathcal{B}, \mathcal{B}^*}$ in the dual space since $\delta_x \in \mathcal{B}^*$ for spaces admitting point evaluations. Next, for multi-channel $f = (f^{(1)}, \dots, f^{(C)})$, we extend $\mathcal{C}(f)^{(c)}(x)$ to $\sum_{c'=1}^C W_{cc'} f^{(c')}(x)$. Then, it follows

$$\begin{aligned} \mathcal{C}(f)^{(c)}(x) &= \sum_{c'=1}^C W_{cc'} f^{(c')}(x) \\ &= \sum_{c'=1}^C W_{cc'} \int_{\Omega} \delta(x-y) f^{(c')}(y) dy \\ &= \int_{\Omega} \delta(x-y) (W f(y))^{(c)} dy, \end{aligned} \tag{46}$$

where $W f(y)$ applies the matrix pointwise. Equation (46) becomes to

$$\mathcal{C}(f)(x) = \int_{\Omega} \delta(x-y) \cdot W \cdot f(y) dy, \tag{47}$$

for $f(y) \in \mathbb{R}^C$. □

Remark B.3. $\mathcal{C}(f)(x)$ is a local projection because the kernel $\delta(x-y)W$ has support only at $y = x$ which projects onto the span of channels without spatial smearing. In practice, for a discrete domain, it reduces to matrix multiplication at pixels. For a continuous domain, it is actually the distributional convolution with a point mass.

Lemma B.7. Finite-rank operators are dense in the space of compact operators.

Proof. It is equivalent to show for any $\delta > 0$, there exists a finite-rank operator K_m such that $\|T - K_m\|_{\mathcal{B}} < \delta$. Assume the operator T is compact, then its image on a unit ball B has compact closure. Therefore, for any $x \in \mathcal{B}_B$, there exists $v_i \in \mathcal{B}$, such that $\|T(x) - v_i\|_{\mathcal{B}} < \delta$ for any $\delta > 0$. Now, we define a projection $\pi_V : \text{range}(T) \rightarrow V$, which maps each $T(x)$ to its best approximation in V . It is well-defined because V is finite-dimensional and $\mathcal{B}$ is a Banach space. Then, one can also define $K_m := \pi_V \circ T$, which is a linear and bounded operator. And the range of K_m lies in the span of v_i , implying that K_m is finite-rank. This way, one can verify $\|T(f) - K_m(f)\|_{\mathcal{B}} = \|T(f) - \pi_V(T(f))\|_{\mathcal{B}} \leq \delta$ for any $\delta > 0$ and $f \in \mathcal{B}$. Since $K_m(f) \in \text{span}\{v_1, \dots, v_m\}$, one can formulate it as $K_m(f) = \sum_{i=1}^m a_i(f) v_i$, for linear functionals a_i . □

Lemma B.8. $\mathcal{C}$ is finite-rank. For any operator $T : \mathcal{B} \rightarrow \mathcal{B}$ following $T = I - P$, where P is a projection, and $\delta > 0$, there exists $W_{cc'}$ such that $\|\mathcal{C}(g) - T(g)\|_{\mathcal{B}} < \delta$ for all g in a bounded subset $G \subset \mathcal{B}$, with the error decaying as the matrix rank (channel dimension) C increases.

Proof. First, we show that $\mathcal{C}$ is finite-rank. Since $\mathcal{B}$ is an RKBS, the evaluation functional is continuous, for $f \in \mathcal{B}$, $f(x) = \langle f, K(\cdot, x) \rangle_{\mathcal{B}, \mathcal{B}^*}$ holds, and $K(\cdot, x) \in \mathcal{B}^*$ satisfies $\|K(\cdot, x)\|_{\mathcal{B}^*} < \infty$. Let $\mathcal{B}^C = \mathcal{B} \otimes \mathbb{R}^C$, $f = (f^{(1)}, \dots, f^{(C)})$ has evaluations $f(x) = (f^{(1)}(x), \dots, f^{(C)}(x)) \in \mathbb{R}^C$, with

$$f^{(c)}(x) = \langle f^{(c)}, K(\cdot, x) \rangle_{\mathcal{B}, \mathcal{B}^*}. \tag{48}$$

For each channel $c = 1, \dots, C$, we have

$$\mathcal{C}(f)^{(c)}(x) = \sum_{c'=1}^C W_{cc'} f^{(c')}(x). \tag{49}$$

The reproducing property follows

$$f^{(c')}(x) = \langle f^{(c')}, K(\cdot, x) \rangle_{\mathcal{B}, \mathcal{B}^*} = \langle f^{(c')}, \delta_x \rangle_{\mathcal{B}, \mathcal{B}^*} \tag{50}$$

in the distributional sense as long as $\mathcal{B}$ embeds into a space where δ_x is defined. Then, it holds that

$$\langle f^{(c')}, \delta_x \rangle_{\mathcal{B}, \mathcal{B}^*} = \int_{\Omega} \delta(x-y) f^{(c')}(y) dy \tag{51}$$

in the weak sense. Therefore, we have:

$$\begin{aligned}\mathcal{C}(f)^{(c)}(x) &= \sum_{c'=1}^C W_{cc'} \langle f^{(c')}, \delta_x \rangle_{\mathcal{B}, \mathcal{B}^*} \\ &= \sum_{c'=1}^C W_{cc'} \int_{\Omega} \delta(x-y) f^{(c')}(y) dy.\end{aligned}\tag{52}$$

Next, Equation (52) becomes:

$$\mathcal{C}(f) = \sum_{c=1}^C \sum_{c'=1}^C W_{cc'} \langle f, \mathcal{B}_{c'} \rangle_{\mathcal{B}^C} \mathcal{B}_c,\tag{53}$$

where $\langle f, \mathcal{B}_{c'} \rangle_{\mathcal{B}^C} = \langle f^{(c')}, \mathcal{B}_c \rangle_{\mathcal{B}, \mathcal{B}^*}$ for the basis $\mathcal{B}_c$ of $\mathcal{B}$. The rank of $\mathcal{C}(f)$ is at most $c \times c' \leq C^2$, so $\mathcal{C}(f)$ is finite-rank. We note that if an operator is finite-rank, it is bounded and compact in Banach space $\mathcal{B}$.

Moreover, we consider the operator $T = I - P$, where P is a projection operator. Assume that P is finite-rank and thus compact, and then the operator T is also compact. Since T is compact, for any $\delta > 0$, there exists finite-rank approximation $K_m = \sum_{i=1}^m \sigma_i \langle \cdot, u_i \rangle_{\mathcal{B}^C} v_i$, where $u_i, v_i \in \mathcal{B}^C$, such that

$$\|T(g) - K_m(g)\|_{\mathcal{B}} < \frac{\delta}{\sup_{g \in G} \|g\|_{\mathcal{B}^C}}\tag{54}$$

for $g \in G$ from Lemma B.7.

Then, by denoting $A = I - P$, from Equation (54), we have:

$$\begin{aligned}\|\mathcal{C}(g) - T(g)\|_{\mathcal{B}^C} &= \left\| \int_{\Omega} \delta(x-y) (W - A(y)) g(y) dy \right\|_{\mathcal{B}^C} \\ &= \left(\int_{\Omega} \|(W - A(y)) g(y)\|_{\mathbb{R}^C}^2 dy \right)^{1/2} \\ &\leq \sup_y \|W - A(y)\|_{\mathcal{B}^C} \left(\int_{\Omega} \|g(y)\|_{\mathbb{R}^C}^2 dy \right)^{1/2} \\ &\leq \epsilon \|g\|_{\mathcal{B}^C} < \delta,\end{aligned}\tag{55}$$

by choosing $\epsilon < \delta / (2 \sup \|g\|_{\mathcal{B}^C})$. □

Now, we give the full proof of Theorem 4.1 assuming GELU is globally Lipschitz with constant L_{GELU} .

Proof. We start with the residual:

$$\begin{aligned}r_i &= \alpha_{\text{true}} - \alpha_i = (\alpha_{\text{true}} - \alpha_{i-1}) - (\alpha_i - \alpha_{i-1}) \\ &= r_{i-1} - \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i.\end{aligned}\tag{56}$$

Then, let $T(g) = \langle g, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i$, from Lemma B.5, one can obtain:

$$\|\mathcal{S}(z_{p,i-1}) - \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i\|_{\mathcal{B}} < \frac{\varepsilon}{4L_{\text{GELU}}}.\tag{57}$$

Next, from Lemma B.8, we can also get:

$$\begin{aligned}\|\mathcal{C}(z_{p,i-1}) - (r_{i-1} - z_{p,i-1}) - \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i\|_{\mathcal{B}} \\ < \frac{\varepsilon}{4L_{\text{GELU}}}.\end{aligned}\tag{58}$$

By adjusting the parameters in GELU (i.e., γ, β), one can show:

$$\begin{aligned}\|\text{BN}(z_{p,i-1} + \mathcal{S}(z_{p,i-1}) + \mathcal{C}(z_{p,i-1})) - (r_{i-1} \\ - \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i)\|_{\mathcal{B}} < \frac{\varepsilon}{2L_{\text{GELU}}}.\end{aligned}\tag{59}$$

By Lipschitz continuity of GELU, we have:

$$\|z_{p,i} - r_i\|_{\mathcal{B}} < L_{\text{GELU}} \cdot \left(\frac{\varepsilon}{4L_{\text{GELU}}} + \frac{\varepsilon}{4L_{\text{GELU}}} + \frac{\varepsilon}{2L_{\text{GELU}}} \right) < \varepsilon. \quad (60)$$

Since J is continuous, one can show $\|z_{d,i} - J(r_i)\|_{\mathcal{B}}$ at the same way. $\square$

C THE OPTIMAL FEATURE MAP FM^*

We denote the training data points here as (x_i, y_i) . The empirical risk minimization in the RKBS $\mathcal{B}$ is utilized in the form $\min_{f \in \mathcal{B}} \sum_{j=1}^m \ell(\text{FM}(x_j), y_j) + \lambda \|\text{FM}\|_{\mathcal{B}}$, where FM refers to the possible feature maps, ℓ is the loss function which is assumed to be convex, continuous, and Lipschitz, and $\lambda \geq 0$ is the regularization parameter. Since $\mathcal{B}$ is reflexive, we know that the optimal feature map FM^* as a minimizer exists. Then, we calculate it by solving $\partial(\sum \ell(\text{FM}(x_j), y_j)) + \lambda \partial \|\text{FM}\|_{\mathcal{B}} = 0$ following:

$$\begin{aligned} \partial(\sum \ell(\text{FM}(x_j), y_j)) &= \sum_j \partial_u \ell(u, y_j)|_{u=\text{FM}(x_j)} \cdot \partial \text{FM}(x_j) \\ &= \sum_j \partial_u \ell(u, y_j)|_{u=\text{FM}(x_j)} \cdot K_z^*(x_j, \cdot), \end{aligned} \quad (61)$$

where $\partial \text{FM}(x_j) = K_z^*(x_j, \cdot) \in \mathcal{B}^*$ from evaluation functional. Thus, $\partial \ell(\text{FM}) \subset \text{span}\{K_z^*(x_j, \cdot)\}_{j=1}^m$ in dual.

On the other hand, we have $\partial \|\text{FM}\|_{\mathcal{B}} = \frac{J(\text{FM})}{\|\text{FM}\|_{\mathcal{B}}}$ if $\text{FM} \neq 0$. We admit FM^* follows the form $\sum_{j=1}^m c_j K_z(x, x_j)$, where c_j needs to be determined. Substituting it into the gradient condition leads to:

$$\sum_k c_k K_z(x_k, x_j) + \lambda \langle J(\text{FM}^*), K_z(\cdot, x_j) \rangle_{\mathcal{B}, \mathcal{B}^*} = -\partial \ell(\text{FM}^*(x_j), y_j), \quad (62)$$

which is a linear system can be solved accordingly.

D PROOF OF THEOREM 4.2

Before providing the full proof of Theorem 4.2, we give several definitions and lemmas first.

Definition D.1. A Banach space $\mathcal{B}$ is uniformly convex if there exists a function $\delta : [0, 2] \rightarrow [0, 1]$, the modulus of convexity, such that for all $u, v \in \mathcal{B}$ with $\|u\|_{\mathcal{B}} = \|v\|_{\mathcal{B}} = 1$ and $\|u - v\|_{\mathcal{B}} \geq \tau$,

$$\left\| \frac{u + v}{2} \right\|_{\mathcal{B}} \leq 1 - \delta(\tau), \quad \delta(\tau) > 0 \text{ for } \tau > 0.$$

$\mathcal{B}$ is uniformly smooth if the modulus of smoothness $\rho(\tau) = \sup\{ \frac{\|u + \tau v\|_{\mathcal{B}} + \|u - \tau v\|_{\mathcal{B}}}{2} - 1 : \|u\|_{\mathcal{B}} = \|v\|_{\mathcal{B}} = 1 \}$ satisfies $\rho(\tau) = o(\tau)$ as $\tau \rightarrow 0$.

Lemma D.1. For any $\eta > 0$, there exist parameters in the primal-dual propagation such that $\|z_{p,i} - r_i\|_{\mathcal{B}} < \eta$ and $\|z_{d,i} - J(r_i)\|_{\mathcal{B}^*} < \eta$ for each i . Therefore, it holds that

$$|\langle z_{p,i}, J(\mathcal{B}_{i+1}) \rangle_{\mathcal{B}, \mathcal{B}^*} - \langle r_i, J(\mathcal{B}_{i+1}) \rangle_{\mathcal{B}, \mathcal{B}^*}| < \eta.$$

Proof. This lemma follows directly from Theorem 4.1. $\square$

Lemma D.2. In the AFD operations, the residuals satisfy

$$\|r_i\|_{\mathcal{B}}^2 \leq \rho_i^2 \|r_{i-1}\|_{\mathcal{B}}^2,$$

where $\rho_i^2 = 1 - \delta \left(2 \frac{|\langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}|}{\|r_{i-1}\|_{\mathcal{B}}} \right) < 1$, and $\mathcal{B}_i$ is chosen greedily as $\max_{\mathcal{B}_j \in \mathcal{D}} |\langle r_{i-1}, J(\mathcal{B}_j) \rangle_{\mathcal{B}, \mathcal{B}^*}|$.

Proof. For $u = \frac{r_{i-1}}{\|r_{i-1}\|_{\mathcal{B}}}$ and $v = \frac{\langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i}{\|r_{i-1}\|_{\mathcal{B}}}$, it follows

$$\left\| \frac{r_i}{\|r_{i-1}\|_{\mathcal{B}}} \right\|_{\mathcal{B}} = \left\| u - \frac{\langle u, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i}{\|r_{i-1}\|_{\mathcal{B}}} \right\|_{\mathcal{B}} = \|u - v\|_{\mathcal{B}}. \quad (63)$$

Since $\|u - v\|_{\mathcal{B}}^2 \leq 1 - \delta(2\|u\|_{\mathcal{B}}\|v\|_{\mathcal{B}})$, we have:

$$\begin{aligned} \|u - v\|_{\mathcal{B}}^2 &\leq 1 - \delta(2\|v\|_{\mathcal{B}}) \\ &\leq 1 - 2\delta \left(\frac{|\langle r_{i-1}, J(\mathcal{B}_{a_i}) \rangle_{\mathcal{B}, \mathcal{B}^*}|}{\|r_{i-1}\|_{\mathcal{B}}} \right) := 1 - \rho_i. \end{aligned} \quad (64)$$

Equation (64) becomes to:

$$\|r_i\|_{\mathcal{B}}^2 \leq \rho_i^2 \|r_{i-1}\|_{\mathcal{B}}^2. \quad (65)$$

Iterating Equation (65) leads to:

$$\|r_N\|_{\mathcal{B}} \leq \left(\prod_{i=1}^N \rho_i \right) \|r_0\|_{\mathcal{B}}. \quad (66)$$

□

Lemma D.3. *The bias terms satisfy*

$$\sum_{i=1}^N |\gamma_i| \leq \left(1 - \prod_{i=1}^N \rho_i \right) \|r_0\|_{\mathcal{B}} + N\varepsilon,$$

where the bias term satisfying $\gamma_i \leq |\langle z_{p,i-1}, J(\mathcal{B}_i) \rangle| - \rho_i \sup_{\mathcal{B}_j \in \mathcal{D}} |\langle z_{p,i-1}, J(\mathcal{B}_j) \rangle|$, and $\|z_{p,i-1} - r_{i-1}\|_{\mathcal{B}} < \varepsilon$.

Proof. Assume $\mathcal{D}$ is rich in $\mathcal{B}$, we have:

$$\begin{aligned} |\gamma_i| &= |\langle z_{p,i-1}, J(\mathcal{B}_i) \rangle| - \rho_i \sup_{\mathcal{B}_j} |\langle z_{p,i-1}, J(\mathcal{B}_j) \rangle| \\ &\leq (1 - \rho_i) \|z_{p,i-1}\|_{\mathcal{B}}. \end{aligned} \quad (67)$$

Now, from Theorem 4.1, one can have:

$$\|z_{p,i-1}\|_{\mathcal{B}} \leq \|r_{i-1}\|_{\mathcal{B}} + \|z_{p,i-1} - r_{i-1}\|_{\mathcal{B}} \leq \|r_{i-1}\|_{\mathcal{B}} + \varepsilon \quad (68)$$

for $\varepsilon > 0$.

From Lemma D.2, Equation (68) becomes to:

$$\|z_{p,i-1}\|_{\mathcal{B}} \leq \prod_{j=1}^{i-1} \rho_j \|r_0\|_{\mathcal{B}} + \varepsilon. \quad (69)$$

Substituting Equation (67) into Equation (69) leads to:

$$|\gamma_i| \leq (1 - \rho_i) \left(\prod_{j=1}^{i-1} \rho_j \|r_0\|_{\mathcal{B}} + \varepsilon \right). \quad (70)$$

Then, we sum both sides of Equation (67) over $i = 1$ to N and get:

$$\begin{aligned} \sum_{i=1}^N |\gamma_i| &\leq \sum_{i=1}^N (1 - \rho_i) \left(\prod_{j=1}^{i-1} \rho_j \|r_0\|_{\mathcal{B}} + \varepsilon \right) \\ &= \|r_0\|_{\mathcal{B}} \sum_{i=1}^N (1 - \rho_i) \prod_{j=1}^{i-1} \rho_j + \varepsilon \sum_{i=1}^N (1 - \rho_i) \\ &\leq \|r_0\|_{\mathcal{B}} \sum_{i=1}^N (1 - \rho_i) \prod_{j=1}^{i-1} \rho_j + \varepsilon N. \end{aligned} \quad (71)$$

For the first term in Equation (71), it follows

$$\begin{aligned}
\sum_{i=1}^N (1 - \rho_i) \prod_{j=1}^{i-1} \rho_j &= \sum_{i=1}^N \left(\prod_{j=1}^{i-1} \rho_j - \prod_{j=1}^i \rho_j \right) \\
&= (1 - \rho_1) + (\rho_1 - \rho_1 \rho_2) + (\rho_1 \rho_2 - \rho_1 \rho_2 \rho_3) \\
&\quad + \cdots + \left(\prod_{j=1}^{N-1} \rho_j - \prod_{j=1}^N \rho_j \right) \\
&= 1 - \prod_{j=1}^N \rho_j.
\end{aligned} \tag{72}$$

Putting everything together, we arrive:

$$\sum_{i=1}^N |\gamma_i| \leq \left(1 - \prod_{i=1}^N \rho_i \right) \|r_0\|_{\mathcal{B}} + N\varepsilon, \tag{73}$$

which completes the proof. $\square$

Now, we are safe to give the full proof of Theorem 4.2.

Proof. To start with, we consider

$$\begin{aligned}
\|\hat{\alpha}_{N,\theta} - \alpha_{\text{true}}\|_{\mathcal{B}} &= \left\| \sum_{i=1}^N \langle z_{p,i}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i + \sum_{i=1}^N \gamma_i - \right. \\
&\quad \left. \sum_{i=1}^{\infty} \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i \right\|_{\mathcal{B}} \\
&\leq \sum_{i=1}^N |\langle z_{p,i} - r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}| \cdot \|\mathcal{B}_i\|_{\mathcal{B}} \\
&\quad + \sum_{i=1}^N |\gamma_i| + \left\| \sum_{i=N+1}^{\infty} \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i \right\|_{\mathcal{B}}.
\end{aligned} \tag{74}$$

From Lemma D.1, one can have:

$$|\langle z_{p,i} - r_{i-1}, J(\mathcal{B}_i) \rangle| < \eta, \tag{75}$$

for any $\eta > 0$, which implies

$$\sum_{i=1}^N |\langle z_{p,i} - r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*}| < N\eta = \frac{\varepsilon}{2} \tag{76}$$

by setting $\eta = \frac{\varepsilon}{2N}$. By Theorem A.2, we have:

$$\alpha_{\text{true}} = \sum_{i=1}^{\infty} \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i, \tag{77}$$

so the tail is

$$\left\| \sum_{i=N+1}^{\infty} \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i \right\|_{\mathcal{B}} = \|r_N\|_{\mathcal{B}} \leq \prod_{i=1}^N \rho_i \|r_0\|_{\mathcal{B}} \tag{78}$$

from Lemma D.2. Next, from Lemma D.3, the bias term γ_i satisfying:

$$\begin{aligned}
\sum_{i=1}^N |\gamma_i| &\leq \left(1 - \prod_{i=1}^N \rho_i \right) \|r_0\|_{\mathcal{B}} + N\eta \\
&= \left(1 - \prod_{i=1}^N \rho_i \right) \|r_0\|_{\mathcal{B}} + \frac{\varepsilon}{2}.
\end{aligned} \tag{79}$$

By choosing $\gamma_i \leq (1 - \rho_i) \prod_{j=1}^{i-1} \rho_j \|r_0\|_{\mathcal{B}}$, we have:

$$\begin{aligned} \|\hat{\alpha}_{N,\theta} - \alpha_{\text{true}}\|_{\mathcal{B}} &\leq \frac{\varepsilon}{2} + \prod_{i=1}^N \rho_i \|r_0\|_{\mathcal{B}} + \frac{\varepsilon}{2} \\ &= \varepsilon + \prod_{i=1}^N \rho_i \|r_0\|_{\mathcal{B}}, \end{aligned} \tag{80}$$

which completes the proof. $\square$

E PROOF OF THEOREM 4.3

Before proving Theorem 4.3, we give a lemma first.

Lemma E.1. *Let ℓ be a convex and L -Lipschitz loss function on a compact convex subset $\mathcal{B}_0 \subseteq \mathcal{B}$, and let Φ be a μ -strongly convex mirror map on $\mathcal{B}_0$. Then, the mirror descent algorithm (MDA) with projected updates achieves a convergence rate of $O(1/\sqrt{N})$ for N iterations:*

$$\ell(f_N) - \ell(f^*) \leq O\left(\frac{1}{\sqrt{N}}\right),$$

where f^* is the minimizer, and the constant depends on L , μ , and the diameter of $\mathcal{B}_0$.

Proof. It follows from Kumar et al. [2024] by setting $g_N = g_{N-1} - \eta \partial_{f_{N-1}} \mathcal{L}$ and $f_N = \Pi_{\mathcal{B}_0}^{\Phi}((\partial\Phi)^{-1}(g_N))$, where Π is the Bregman projection. $\square$

Remark E.1. *We remark that, AFD can be interpreted as a greedy variant of mirror descent in RKBS, where each layer corresponds to a descent step with duality pairing approximating subgradients, and the normalized kernels $\mathcal{B}_i$ are utilized to select the directions. In AFD, the greedy selection maximizes the projection $|\langle r_{i-1}, J(\mathcal{B}_i) \rangle|$, which is equivalent to a subgradient descent step in the dual space, with the mirror map $\Phi(f) = \frac{1}{2} \|f\|_{\mathcal{B}}^2$. Furthermore, $r_i = r_{i-1} - \langle r_{i-1}, J \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i$ is a projected mirror descent step.*

With this, now we prove Theorem 4.3.

Proof. Define the loss function $\ell(f) = \|\alpha - f\|_{\mathcal{B}}$ on $\mathcal{B}_0 = \{f \in \text{span}(\mathcal{D}) : \|f\|_{\mathcal{B}} \leq \|\alpha\|_{\mathcal{B}}\}$. Since $\mathcal{B}$ is uniformly convex, $\mathcal{B}_0$ is compact. The function $\ell(f)$ is convex and Lipschitz:

$$|\ell(f) - \ell(g)| = \left| \|\alpha - f\|_{\mathcal{B}} - \|\alpha - g\|_{\mathcal{B}} \right| \leq \|f - g\|_{\mathcal{B}}. \tag{81}$$

One can know that the minimizer is $f^* = \alpha$ and $\ell(f^*) = 0$ holds in this case. In AFD, we have

$$r_i = r_{i-1} - \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i \tag{82}$$

and

$$P_i(\alpha) = P_{i-1}(\alpha) + \langle r_{i-1}, J(\mathcal{B}_i) \rangle_{\mathcal{B}, \mathcal{B}^*} \mathcal{B}_i, \tag{83}$$

where $\mathcal{B}_i$ maximizes $|\langle r_{i-1}, J(\mathcal{B}_j) \rangle_{\mathcal{B}, \mathcal{B}^*}|$. This way, AFD corresponds to a greedy mirror descent step, where the subgradient direction is approximated by $J(\mathcal{B}_i)$. Denote $f_i = P_i(\alpha)$, so $r_i = \alpha - f_i$. Furthermore, Equation (83) is equivalent to:

$$f_i = f_{i-1} + \eta_i J^*(\partial\ell(f_{i-1})), \tag{84}$$

where $\eta_i = \langle r_{i-1}, J(\mathcal{B}_i) \rangle$, and $J^* : \mathcal{B}^* \rightarrow \mathcal{B}$ is the inverse duality map since $\mathcal{B}$ is reflexive.

From Lemma E.1, considering $\ell(f) = \|\alpha - f\|_{\mathcal{B}}$ on $\mathcal{B}_0$, we have

$$\ell(f_N) - \ell(f^*) = \|\alpha - f_N\|_{\mathcal{B}_0} \leq O\left(\frac{1}{\sqrt{N}}\right), \tag{85}$$

where the diameter $\text{diam}(\mathcal{B}_0) \leq 2\|\alpha\|_{\mathcal{B}}$. Since $f_N = P_N(\alpha)$, and $\ell(f^*) = 0$,

$$\|P_N(\alpha) - \alpha\|_{\mathcal{B}_0} = \|\alpha - f_N\|_{\mathcal{B}_0} \leq O\left(\frac{1}{\sqrt{N}}\right). \quad (86)$$

Then, we generalize it to $\|\alpha\|_{\mathcal{B}}$ by scaling diameter:

$$\|P_N(\alpha) - \alpha\|_{\mathcal{B}} \leq O\left(\frac{1}{\sqrt{N}}\right) \|\alpha\|_{\mathcal{B}}. \quad (87)$$

Finally, from Theorem 4.2, we obtain:

$$\begin{aligned} \|\hat{\alpha}_{N,\theta} - P_N(\alpha)\|_{\mathcal{B}} &\leq \|\hat{\alpha}_{N,\theta} - \alpha\|_{\mathcal{B}} + \|\alpha - P_N(\alpha)\|_{\mathcal{B}} \\ &\leq \hat{C} \prod_{i=1}^N \rho_i \cdot \|r_0\|_{\mathcal{B}} + O\left(\frac{1}{\sqrt{N}}\right) \|\alpha\|_{\mathcal{B}} \\ &< \varepsilon + O\left(\frac{1}{\sqrt{N}}\right) \|\alpha\|_{\mathcal{B}}, \end{aligned} \quad (88)$$

which completes the proof. $\square$

F ADDITIONAL EXPERIMENTS

Here, we conduct an additional experiment considering the magnetic Schrödinger equation problem on a **regular rectangular domain** $[0, 1] \times [0, 1]$. The results are shown in Table 5.

Models	MAE	Relative L^2 error
AFDONet-inv (ours)	3.20E-02	5.30E-05
NAO [Yu et al., 2024]	8.09E-01	1.01
NIPS [Liu and Yu, 2025]	2.07E-01	8.05E-02
LNO [Wang and Wang, 2024]	4.64E-01	1.86E-01
MWT [Gupta et al., 2021]	2.82E-01	1.00

Table 5: Comparison of MAE and relative L^2 error among different models on magnetic Schrödinger equation on $[0, 1] \times [0, 1]$.

Furthermore, we also explore the effect of **data augmentation**. Given that the data augmentation process is achieved by random permutations. Here, we implement 100 random permutations on top of the training data containing 6000 solution samples. We compare our model to NAO and NIPS in Table 7, whose performance heavily relies on data augmentation.

Models	MAE	Relative L^2 error	Training time
AFDONet-inv (ours)	9.94E-03	1.20E-05	2.52
NAO [Yu et al., 2024]	5.98E-02	6.11E-03	2.54
NIPS [Liu and Yu, 2025]	4.81E-02	4.29E-03	3.26

Table 6: Comparison of MAE, relative L^2 error and training time (seconds per epoch) among different models on magnetic Schrödinger equation on $[0, 1] \times [0, 1]$ under 100 random permutations.

More benchmark problems are added, including inversion of reaction-diffusion, Navier-Stokes, as well as a real-world problem, to strength our manuscript. We use the public datasets of reaction-diffusion, Navier-Stokes, and a real-world problem from Cao et al. [2024], Li et al. [2020a], and You et al. [2022], respectively. The relative L^2 error values are reported as follows:

When it comes to the **real-world latex glove DIC (Digital Image Correlation) original dataset**, the relative L^2 error is reported compared to FNO and existing SOTA, namely the IFNO [You et al., 2022]. Here, we report the best results in terms of hidden layers for FNO and IFNO. The results of two traditional methods, GMR model fitting and GMR inverse analysis, are taken from You et al. [2022].

Equation	AFDONet-inv (ours)	NAO [Yu et al., 2024]	NIPS [Liu and Yu, 2025]	LNO [Wang and Wang, 2024]
reaction-diffusion	$6.51\text{E-}03 \pm 1.28\text{E-}04$	$8.02\text{E-}03 \pm 2.39\text{E-}04$	$7.98\text{E-}03 \pm 1.67\text{E-}04$	$1.12\text{E-}02 \pm 5.67\text{E-}04$
Navier-Stokes	$8.85\text{E-}04 \pm 1.27\text{E-}05$	$1.08\text{E-}03 \pm 2.93\text{E-}05$	$9.57\text{E-}04 \pm 1.08\text{E-}04$	$1.25\text{E-}03 \pm 1.28\text{E-}05$

Table 7: Comparison of relative L^2 error among different models on reaction-diffusion and Navier-Stokes equations.

AFDONet-inv (ours)	FNO [Li et al., 2020a]	IFNO [You et al., 2022]	GMR model fitting	GMR inverse analysis
$9.70\text{E-}03 \pm 2.08\text{E-}05$	$3.40\text{E-}02 \pm 4.09\text{E-}04$	$3.30\text{E-}02 \pm 4.63\text{E-}04$	$3.30\text{E-}01$	$2.91\text{E-}01$

Table 8: Comparison of relative L^2 error among different models on real-world latex glove DIC original dataset.

G DISTRIBUTION OF POLES

Our goal is to infer the parameters of PDE problems based on the solutions or Dirichlet-to-Neumann maps, while accounting for the fact that the space of parameters is sparse in nature. Unlike Hilbert space as a function space, the parameter space is not continuous or even a function space. Therefore, we generalize the AFD theory from reproducing kernel Hilbert space to reproducing kernel Banach space, and the key insights of AFD are as follows:

1. AFD serves as a kernel-based decomposition theory, which relies on the bases obtained by orthogonal kernels with adaptively selected poles.
2. Each pole can be viewed as a “tuning knob” that selects a particular spatial pattern in the solution, with its location in the complex plane controlling how localized that pattern is. Adaptive poles allow our model to survey more heavily in regions where the parameters change rapidly, while using fewer poles in smooth regions.
3. Across layers, the poles evolve from broad, coarse patterns in early layers to more refined, problem-specific patterns in deeper layers. This is analogous to how CNN filters specialize from edges to complex shapes.

As shown in Figure 2, the evolution of poles across network layers differs fundamentally between well-posed and ill-posed inverse problems, reflecting the adaptive nature of the AFD selection mechanism. For well-posed problems such as Darcy flow, where the parameter α is piecewise constant with relatively smooth structure, poles exhibit moderate evolution from the center of the unit disk (small $|a|$) toward moderate distances, as the uniform parameter structure can be adequately captured without aggressive refinement. In contrast, for ill-posed problems such as the nonlinear magnetic Schrödinger equation, where parameters exhibit sparse, non-smooth structures with rapid changes, poles evolve more aggressively toward the unit circle (large $|a|$), with strong clustering in regions corresponding to rapid parameter variations. This difference arises because the adaptive selection principle $\sup_{a \in \mathbb{D}} |\langle r, J(\mathcal{B}_a) \rangle|$ naturally concentrates poles where the residual r_{i-1} contains stronger signals, which occurs in regions of rapid parameter change for ill-posed problems. The mathematical foundation lies in the relationship between pole magnitude and basis function localization: small $|a|$ yields broad, low-frequency patterns suitable for smooth structures, while $|a| \rightarrow 1$ yields highly localized, high-frequency patterns necessary for capturing rapid changes. The Banach space setting enables this adaptive behavior by allowing norms that better capture sparsity and non-smoothness compared to Hilbert space methods.

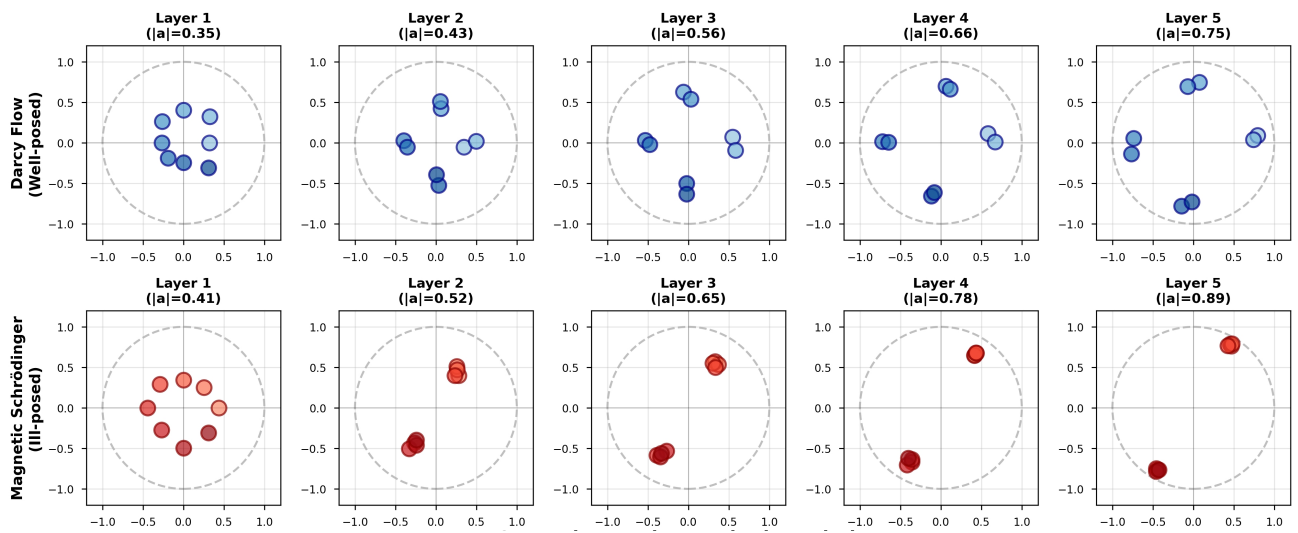


Figure 2: Pole distribution of AFDONet-inv on Darcy flow and magnetic Schrödinger equation across different layers.