

# 基于伴随可微物理的闭式布雷顿气冷堆数字孪生在线参数反演方法

## 摘要

先进反应堆数字孪生需要在传感器稀疏、工况非定常的条件下完成在线参数反演。现有方法多依赖卡尔曼类滤波器或四维变分方案，在部分观测和瞬态激励下精度明显下降。本文提出一种基于伴随的可微物理反演框架：通过反向模式自动微分穿透隐式微分代数（DAE）求解器获得解析参数灵敏度，结合 Tikhonov 正则化的 L-BFGS 优化求解反问题。框架围绕一个 14 状态闭式布雷顿气冷堆数字孪生构建，保留了含三种反应性反馈的六群点堆动力学、回热器与辐射器热容、管道摩擦以及含功率管理与分配（PMAD）控制器的轴系动力学。在全观测稳态、全观测瞬态、部分观测噪声扫描三类场景下，将所提方法与集合卡尔曼滤波（EnKF）、无迹卡尔曼滤波（UKF）和有限差分 4D-Var 基准进行对比，并以 Cramér-Rao 下界（CRLB）为参照评估各估计器的统计效率。结果表明：在瞬态场景下，所提方法对反射层反应性系数的相对误差为 7.5%，优于 4D-Var（10.2%）和卡尔曼类滤波（约 19%）；在部分观测场景下相对误差为 0.4%–0.55%，相较 4D-Var、EnKF、UKF 分别降低 1.6 至 5 倍；正则化伴随估计器的经验方差接近 CRLB，残余偏差约  $5 \times 10^{-3}$ 。仅在全观测稳态单参数场景下，序贯滤波器凭借其最佳线性无偏（BLUE）特性保持优势。所提框架将可微物理与伴随灵敏度引入闭式布雷顿气冷堆数字孪生，为部分观测和瞬态工况下安全相关参数的在线辨识提供了精度更高、统计效率更接近理论下界的可行途径，对推进先进反应堆数字孪生从监测向智能监督控制演进具有参考意义。

## 关键词

数字孪生；伴随方法；可微物理；参数反演；闭式布雷顿循环；气冷堆；数据同化；Cramér-Rao 下界

## Abstract

Digital twins for advanced reactor concepts must perform online parameter inversion under sparse sensing and non-stationary dynamics, conditions in which Kalman variants and four-dimensional variational schemes lose accuracy. We present an adjoint-based differentiable physics framework that couples reverse-mode automatic differentiation through an implicit differential-algebraic plant model with Tikhonov-regularised L-BFGS optimisation, yielding analytical parameter-sensitivity matrices for gradient-based inversion. The framework is built around a fourteen-state closed-Brayton gas-cooled reactor twin retaining six-group point kinetics with three reactivity feedbacks, recuperator and radiator thermal capacitances, duct friction, and a power-management-and-distribution shaft controller. We benchmark the method against the Ensemble Kalman Filter, the Unscented Kalman Filter, and a finite-difference 4D-Variational baseline across full-observation steady-state, full-observation transient, and partial-observation noise-scan scenarios, and we compare every estimator against the Cramér-Rao lower bound. On the transient scenario the proposed method recovers the reflector reactivity coefficient with 7.5% relative error, against 10.2% for 4D-Var and approximately 19% for the sequential filters; on the partial-observation scenario it reaches 0.4%–0.55%, a 1.6× to 5× reduction over the same baselines. The regularised adjoint estimators attain near-CRLB empirical variance with a residual relative bias of order  $5 \times 10^{-3}$ . Sequential filters retain an advantage only on the controlled full-observation steady-state single-parameter case, where they are theoretically Best-Linear-Unbiased optimal. By bringing differentiable physics and adjoint sensitivities into closed-Brayton gas-cooled reactor digital twins, the proposed framework offers a more accurate and statistically more efficient route to online identification of safety-critical parameters under partial observation and transient excitation, supporting the progression of advanced-reactor digital twins from passive monitoring toward intelligent supervisory control.

## Keywords

digital twin; adjoint method; differentiable physics; parameter inversion; closed-Brayton cycle; gas-cooled reactor; data assimilation; Cramér–Rao lower bound

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