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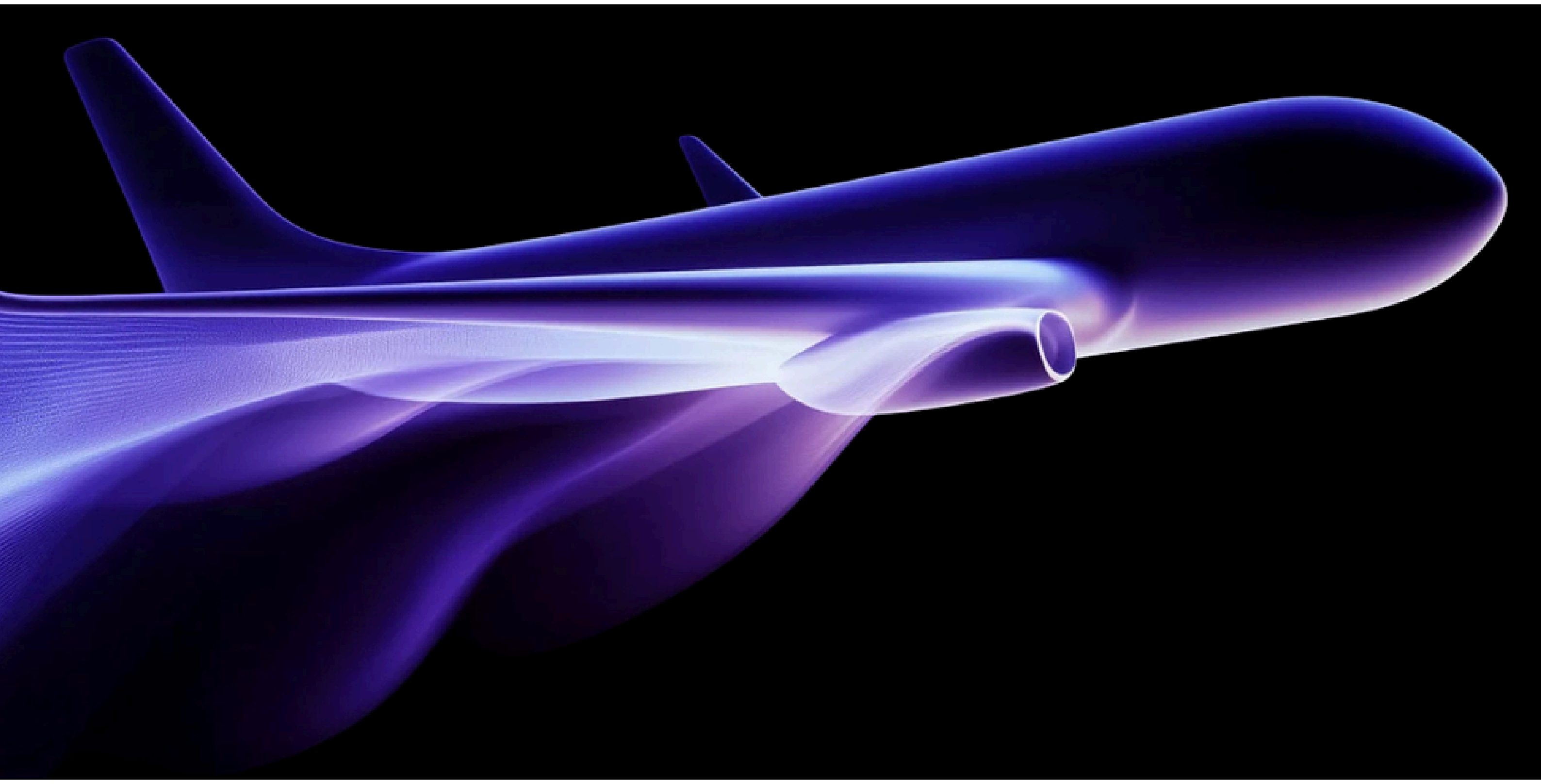

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Quantum computational fluid dynamics on real quantum hardware

A study of nonlinear fluid flow simulation around a solid object.

Contents

Quantum CFD on real quantum hardware

For the first time, nonlinear fluid flow around a solid object has been successfully simulated on Haiqu middleware, establishing an end-to-end quantum CFD workflow ready for current devices.

Abstract

A breakthrough end-to-end quantum CFD workflow, combining novel algorithms, hardware-aware circuits, and hybrid execution, proves quantum simulation is no longer theoretical.

This study presents a milestone in quantum computational fluid dynamics (CFD): the successful simulation of nonlinear fluid flow around a solid object on Haiqu middleware. The work establishes an end-to-end quantum CFD workflow that combines a novel algorithmic framework, hardware-aware circuit design, hybrid quantum-classical execution, and advanced middleware optimization. The result demonstrates that quantum CFD is no longer restricted to theoretical formulations alone, but can now be implemented as a functioning computational pipeline on current quantum devices.

The objective is to realize, in one end-to-end workflow, all the essential structural ingredients required for future practical quantum CFD: nonlinear fluid behavior, repeated time stepping, an embedded solid obstacle, physically meaningful boundary conditions, and execution on noisy real quantum hardware.

Background and motivation

Modern engineering increasingly depends on simulation, but CFD remains one of the most computationally constrained disciplines. As the scale, fidelity, and nonlinearity of modeled systems increase, classical solver architectures become restrictive.

'For example, a direct numerical simulation of a full aircraft under cruising conditions may involve Reynolds numbers on the order of 10^8, requiring a spatio-temporal computational problem approaching 10^{24} operations, far beyond the practical reach of classical high-performance computing.

Furthermore, the speed of running simulations directly impacts AI workflows, since they rely on generating large volumes of training data. To break through the classical ceiling, a multi-technology approach is required, combining cloud computing, AI, and quantum computing. Quantum computing is uniquely attractive because it offers an exponential growth in representable lattice size: a quantum state with 50 qubits can, in principle, encode a computational lattice with roughly 10^{15} grid points.

Quantum CFD on real quantum hardware

> **The One-Step Simplified Lattice Boltzmann Method (OSSLBM) merges collision and propagation into a single quantum step, dramatically cutting circuit complexity and making real-hardware execution feasible.**

The algorithmic framework: One-step simplified lattice Boltzmann method

The lattice Boltzmann method's mesoscopic structure maps naturally onto qubits; OSSLBM streamlines it into a single hardware-efficient step.

The method studied is based on the lattice Boltzmann method (LBM), which operates at a mesoscopic level rather than solving macroscopic Navier–Stokes equations directly. It tracks probability densities of fictitious particles on a discrete lattice, an architecture that maps naturally onto qubits.

The central algorithmic innovation of this study is the quantum adaptation of the one-step simplified lattice Boltzmann method (OSSLBM). In standard formulations, collision and propagation are separate computational stages. In OSSLBM, these are combined into a single streamlined one-step process. By consolidating the evolution, the framework reduces circuit complexity, lowers resource requirements, and becomes significantly more compatible with the limited depth and noise tolerance of near-term hardware.

Methodology and hybrid execution

The implemented method utilizes a hybrid quantum-classical execution loop. Classical fluid quantities are encoded into a quantum state, evolved on the quantum processor, measured, and then classically post-processed to reconstruct macroscopic fields and compute nonlinear quantities for the next time step.

The proof-of-concept was applied to a two-dimensional 8 x 8 grid flow problem with an embedded solid obstacle and Dirichlet zero boundaries. The implementation was run on IBM Heron R3-class quantum hardware, utilizing a total of 14 qubits (6 qubits encoding the 64 spatial lattice sites, and 8 auxiliary qubits).

To load classical data efficiently without dominating the computational cost, the study uses tensor-network-based state preparation. By expressing input distributions in tensor-network form, it synthesizes shallow quantum circuits that prepare the states efficiently, solving the critical input bottleneck.

Quantum CFD on real quantum hardware

> **Advanced middleware, circuit compression, diagonal obstacle offloading, and efficient error mitigation, reduced gate count from ~1,800 to ~540, enabling meaningful physics to survive hardware noise.**

Circuit compression and error mitigation

Executing complex fluid dynamics on noisy hardware required a suite of advanced middleware optimizations and error mitigation strategies:

> **Circuit resynthesis and compression:** The collision process, which does not act on the spatial lattice qubits, was absorbed into the state preparation stage. Alongside optimized multi-qubit gate decomposition and hardware-aware routing, the total circuit size was reduced from approximately 1,800 gates to approximately 540 gates (a roughly threefold reduction).

> **Diagonal obstacle operation:** The operation implementing the obstacle is diagonal in the computational basis. Therefore, it was applied exactly in classical post-processing rather than on the quantum hardware, avoiding the injection of additional noise.

> **Error mitigation strategy:** Current quantum devices remain noisy. The study applied dynamical decoupling, twirling, and observable decoherence renormalization (ODR). ODR compares simplified, classically simulable circuits against hardware runs to compute a calibration factor that renormalizes the observables measured from the target circuit.

Quantum CFD on real quantum hardware

> **Despite hardware noise, the quantum simulation reproduced correct flow behavior around the obstacle, with error decreasing over iterations, proving the pipeline carries meaningful physical information.**

Output reconstruction

Function tomography using Chebyshev polynomials reconstructs macroscopic fluid fields from quantum measurements without the cost of full state tomography.

To avoid the prohibitive cost of full quantum state tomography, the study employs function tomography. The relevant output distributions are represented in a basis of fixed functions (specifically Chebyshev polynomials). By minimizing the Kullback–Leibler divergence, the algorithm fits a small number of basis coefficients (in this experiment three or four) to accurately reconstruct the evolved density and velocity components. This provides the classical fields required to continue the hybrid time-stepping loop efficiently.

Results and validation

Validation against ideal reference simulations confirmed both correct qualitative flow features and positive convergence behavior on real noisy hardware.

Validation was performed against an ideal reference simulation. The study successfully reproduced the expected qualitative behavior of the flow around the obstacle:

Physical flow features: The density field showed the anticipated compression ahead of the object and deficit behind it. The y-component of the velocity field reflected the expected diversion and characteristic spatial patterning of bypass flow around a solid inclusion.

Convergence behavior: Despite substantial device noise preventing full convergence to the ideal steady state, the error decreased over repeated iterations, proving that the hardware execution carries meaningful dynamical information forward through time.

Discussion and industrial outlook

> **This work is not a claim of numerical superiority over classical CFD, it is proof that quantum CFD has crossed from theory into experimentally realized, end-to-end workflow. The pipeline blueprints how quantum-enhanced simulation will be built.**

The study does not claim present-day industrial-scale numerical superiority over classical CFD. The claim is that the field has successfully moved from theory to an experimentally realized workflow.

The results establish that practical execution depends not just on the core algorithm, but heavily on middleware (data loading, compression, error mitigation, and function tomography). In the near term, hybrid workflows will dominate, potentially using quantum simulators to generate high-fidelity information about fine-scale physical features to train machine learning systems.

> The right time to develop these pipelines, tooling, and methodological habits is before perfectly fault-tolerant hardware exists. This study provides a concrete blueprint for how future quantum-enhanced simulation workflows may be built.

About the collaborators

Quanscient is a multiphysics simulation company developing next-generation simulation software built on cloud computing, artificial intelligence, and quantum computing. Founded in 2021 in Tampere, Finland, the company focuses on enabling massive simulation throughput, supporting AI-scale training data generation, and unlocking simulation regimes that are classically infeasible.

Haiqu is a quantum middleware company focused on bridging the gap between abstract quantum algorithms and real hardware execution. Haiqu develops the software infrastructure that connects quantum application design with implementation on noisy devices, providing optimized data-loading routines, circuit compression tools, and error mitigation essential for execution on real quantum hardware, and agentic frameworks to automate their deployment.

Key takeaways

- The study demonstrates one of the first end-to-end quantum CFD simulations of nonlinear fluid flow around a solid object on real quantum hardware.
- A simplified quantum lattice Boltzmann approach (OSSLBM) reduces circuit complexity by merging collision and propagation into a single step.
- The workflow uses a hybrid quantum-classical loop on IBM Heron hardware, with tensor-network-based state preparation to efficiently load data.
- Advanced optimization and error mitigation techniques reduced circuit size from roughly 1,800 gates to 540 gates, helping maintain meaningful physical behavior despite hardware noise.
- The results successfully reproduced expected flow behavior around a solid obstacle and demonstrated that quantum-enhanced CFD pipelines are already becoming experimentally viable, even before fault-tolerant quantum computers exist.

Get in touch

Learn more and request a demo at
quanscient.com/quantum ⟶

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