BosonQ Psi

Enabling Simulations with Quantum Algorithms

Case Study :

AIRFOIL TOPOLOGY OPTIMIZATION

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Airfoil topology optimization using Quantum-Inspired Design Optimization (QIDO)

Executive Summary :

Quantum-Inspired Design Optimization (QIDO) is an innovative technique to solve design optimization problems where conventional gradient-based optimization methods often fall short in handling complex design domains.

Key Topics in this white paper:

- **Challenges in Airfoil Design:** Airfoil design optimization is a multidimensional problem that involves balancing the trade-off between performance, compliance, and volume. Traditional methods struggle to find an optimal solution within a reasonable timeframe.

- **Quantum-Inspired Design Optimization:** QIDO is a novel approach that leverages quantum computing principles to address complex optimization problems efficiently. By exploiting quantum-inspired algorithms, this methodology offers the potential for superior results in airfoil design.

- **Efficiency and Speed:** QIDO demonstrates the ability to significantly reduce the computational time required for airfoil optimization. This is especially critical in industries where time-to-market and performance gains are paramount.

- **Improved Performance:** The application of QIDO in airfoil design has the potential to yield airfoils with enhanced aerodynamic performance and structural integrity. This improvement is attributed to the optimal design of the components in a quantum-inspired framework.

- **Interdisciplinary Applications:** The QIDO methodology has broader applications beyond airfoil design. Its ability to address complex optimization challenges efficiently makes it a valuable tool for various engineering and scientific domains.

- **Cost-Effective Solutions:** Implementing QIDO may lead to significant cost savings in research and development, as it reduces the need for extensive computational resources and lengthy design iterations.

QIDO promises to revolutionize the way engineers approach complex design problems. This innovation is poised to impact various industries, offering a new avenue for cost-effective, efficient, and high-performance airfoil solutions.

Introduction :

This article talks about Quantum Inspired Design Optimization (QIDO), and specifically topology optimization, that harnesses the computational prowess of quantum-inspired algorithms to revolutionize the way we approach design challenges.

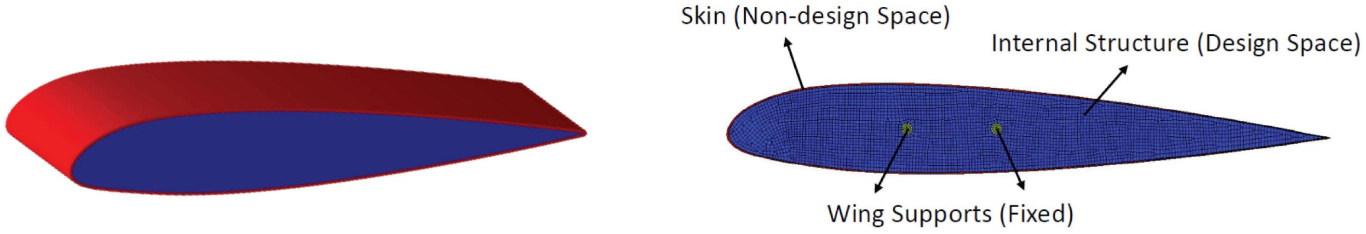

Figure 1: Schematic Airfoil section internal domain as design space, the outer skin as non-design space, and the wing supports are fixed.

It mainly focuses on volume minimization and compliance minimization of an airfoil cross-section. Volume minimization of an airfoil involves decreasing its physical size or space occupied while retaining its required aerodynamic properties, which can lead to more efficient and compact airfoil designs. On the other hand, compliance minimization of an airfoil refers to the reduction of its structural flexibility or deformation under load, ensuring it maintains its intended strength and shape during operation [1].

Optimization of critical components and systems is a resource-intensive endeavor, demanding extensive computational resources and expertise. However, by blending quantum-inspired algorithms with topology optimization techniques, we open the door to new possibilities. These algorithms, inspired by principles of quantum mechanics, offer a unique approach for solving complex optimization problems efficiently and effectively. It has the potential to outperform the conventional techniques in terms of speed and accuracy.

Section 1 : Challenges in Airfoil Optimization

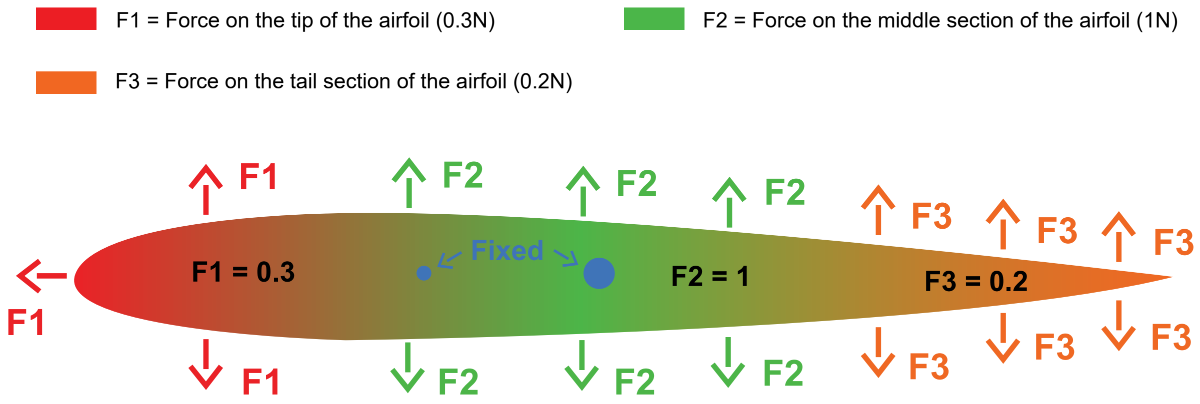

Figure 2: Differential loading scenarios in an airfoil

Challenges in traditional airfoil optimization :

Initial drag discrepancy: One of the primary hurdles is the substantial difference between the initial drag of an airfoil and the prescribed constraint value. As shown in the above figure, different sections of an airfoil experience different forces which makes it challenging to achieve the most optimized designs. In practical terms, the initial airfoil often exhibits a drag that is more than eight times higher than the desired constraint level [1]. This significant gap between the starting point and the target adds complexity to the optimization process, demanding substantial improvements in the airfoil's design to meet the specified criteria.

Nonlinear drag constraints: The drag constraint in airfoil optimization is not a simple linear function of the design variables. Instead, it involves intricate nonlinear relationships, typically governed by the coefficients of the polynomial used to describe the airfoil's geometry [2]. These nonlinearities make it exceedingly challenging to construct a precise mathematical model of the airfoil design problem. Consequently, the optimization process becomes inherently complex, requiring a greater number of iterations and computational resources to converge to an efficient and optimized design.

Constrained design space: The constraint imposed on the drag coefficient further complicates the optimization landscape. It significantly restricts the pool of acceptable airfoil designs that can meet the stringent requirements [3]. Consequently, the search for feasible solutions becomes more intricate, as fewer airfoil configurations can satisfy the demanding criteria.

Structural constraints: In designing space exploration for aerospace structures, the dominant factors affecting the variations of aerodynamic and structural parameters are:

1. the airfoil camber, 2. radius of the leading edge and 3. the chord-wise position of the maximum thickness.

These parameters have a significant impact on the performance of the airfoil. Furthermore, it has been observed that the overall design space exhibits highly nonlinear aerodynamic responses due to the nonlinear effects of the airfoil's chord-wise position of the maximum camber and the radius of the leading edge [3, 4].

Intermediate density: Compliance minimization of an airfoil refers to the objective of optimizing the design of an airfoil to reduce its structural flexibility or deformation under external loads. Density-based topology optimization method is used for solving multi-physics problems. In that context, compliance is an ideal objective to optimize, along with volume minimization [1, 5]. Two popular interpolation schemes, SIMP (Solid Isotropic Material with Penalization), and RAMP (Relaxation Adaptive Memory Programming) are often used to find the optimum solid-void topology based on the local stiffness-to-weight ratio of the material. However, it's important to note that intermediate-density areas have lower stiffness-to-weight ratios than solid or void areas, making them undesirable in an optimally stiff structure. When considering aerodynamic objectives, additional care is needed to recover this property, and non-discreteness may need to be explicitly penalized.

It becomes essential to consider structural constraints such as stress limitations, however, it is essential to note that gradient information may not always be readily available. This lack of gradient information poses a challenge, particularly when optimizing high-dimensional constrained problems where function evaluations are costly.

All the above-mentioned challenges necessitate the development of more efficient and effective optimization methods for aerospace structures, focusing on reducing computational costs, improving accuracy, and accommodating structural constraints.

Section 2 : Quantum-Powered Optimization Techniques

BosonQ Psi's BQPhy is poised to usher in a new era of efficient product design through its quantum-powered optimization techniques. At the heart of BQPhy lie three core components that together form a comprehensive framework for airfoil optimization: parametrization, airfoil evaluation, and optimization. These components work in harmony to empower users in their pursuit of creating highly efficient airfoil designs.

- **Parametrization:** The process begins with the parametrization of airfoil geometries. By employing quantum-inspired algorithms, BQPhy allows users to define intricate design parameters, enabling efficient airfoil design exploration in ways that were previously unattainable. This innovative approach enables users to explore a vast design space efficiently, facilitating the creation of novel designs that can enhance performance and efficiency.

- **Structural evaluation:** BQPhy's quantum-powered simulation platform takes airfoil evaluation to unprecedented heights. Leveraging both classical and quantum computing resources, it conducts in-depth simulations of airfoil designs, accurately assessing their structural performance. This finite element (FE) evaluation provides valuable insights, enabling engineers to make informed decisions regarding design refinements.

- **Optimization:** The optimization phase represents the culmination of BQPhy's capabilities. Users are presented with a versatile toolkit that empowers them to fine-tune airfoil designs for maximum efficiency. BQPhy allows users to define 2D/3D geometries and mesh files, assign materials, specify relevant loads and boundary conditions, and select design domains and optimization parameters such as objectives and constraints. Design domain selection particularly plays a pivotal role in topology optimization, as it enables BQPhy to explore a wide search space, handle numerous design parameters, and maintain continuity in airfoil shape and performance.

Section 3 : Optimization methods

Generally, numerical optimization incorporates a large number of design variables and constraints. For instance, an optimization problem may be expressed as a set of equations that capture the essence of the design criteria and constraints:

$$\begin{aligned} &\min_{\alpha} f(\alpha) \\ &\text{s.t.:}\ \ g_i(\alpha) = 0 \\ &\qquad\ \ h_j(\alpha) \leq 0 \end{aligned}$$

Where f is the objective function, g is set of equality constraints, h is the set of inequality constraints, i is number of equality constraints, and j is number of inequality constraints

BosonQ Psi introduces a quantum-powered optimization solver known as Quantum-Inspired Design Optimization (QIDO). QIDO represents a revolutionary leap in optimization techniques, harnessing the principles of quantum mechanics for information processing. This heuristic approach enhances the precision of optimization results and accelerates the convergence process, enabling engineers and designers to reach optimal solutions more swiftly and accurately. This heuristic approach leads to more accurate optimization results and faster convergence.

In the context of compliance minimization of airfoil structures, the Quantum-Inspired Evolutionary Algorithm integrated into QIDO solver brings a different optimization landscape than classical methods. The low volume fraction of aerospace and automobile structures and the considerations of slenderness, buckling, and strength contribute to the complexity of optimizing low-weight, high-performance airfoil designs. By focusing on topology optimization methods, QIDO removes materials from unintended structures, meeting the demands for low-volume fraction aerospace structures, which increases the efficiency of the component.

Previous studies have shown that efficient topology optimization methods have successfully reduced the weights of components. For instance, topology optimization has reduced weights by 10% in wingbox ribs, resulting in significant stability and safety. Secondly, the study also refers to a 42% reduction in drag and cost reductions for aircraft manufacturing companies [6,7]. However, for middle-sized topology optimization problems on flexible wing structures, the number of design variables can reach up to 75,000 with associated degrees of freedom on the order of 10^5, making these problems incredibly complex for traditional optimization methods [8].

In airfoil design optimization, two widely adopted techniques by simulation software are the Gradient based methods such as optimality criteria (OC) method, the method of moving asymptotes (MMA), and the Evolutionary Structural Optimization (ESO) techniques. These techniques serve as valuable tools for achieving optimal structures by dynamically varying material density within predefined domains.

- **Gradient based methods (GBM):** GBMs such as OC and MMA employed to achieve efficient and lightweight designs by using sensitivity analysis. They operate mainly with the SIMP method by assigning varying material densities to different regions within the airfoil's design domain. The objective is to optimize the distribution of materials such that structural integrity is maintained while reducing unnecessary material usage. This technique ensures that material is allocated where it is needed most, leading to airfoil designs that are both structurally sound and resource efficient. The main drawback of these methods is the presence of fictitious intermediate density values leading to no clear boundary representation of the optimal structure.

- **Evolutionary Structural Optimization (ESO):** ESO methods uses the soft kill/ hard kill approaches to solve the topology optimization problem. However, it is hard for the ESO method to converge with sensitivity numbers such as $\rho(0) = 0$ and $\rho(1) = 1$ because sensitivity numbers are calculated based on different status of the element. In airfoil design, ESO facilitates the evolution of the structural layout over multiple iterations, helps removing underutilized material and redistributing it to regions experiencing higher stress. Therefore, ESO refines the airfoil's shape and structure. This technique allows engineers to iteratively explore and evolve designs, ultimately leading to optimal airfoil configurations.

Section 4: Application of QIDO to Airfoil Optimization

Figure 3: Illustration of an optimized airfoil (cross-section)

To illustrate the effectiveness of BQPhy's approach, we consider the optimization of airfoil shapes. The objective is to minimize the volume while maintaining the strength of the airfoil shape. The objective is to minimize the volume, subject to an equivalent strength criterion on the reserve factor (RF).

The problem defined is as below:

$$\min\ W(\rho) = \int_{\Omega} \rho\ A\, d\Omega$$

$$\text{s.t.:}\ \ K(\rho)u = F$$

$$RF \leq 4.0$$

$$0 < \rho_{min} \leq \rho_i \leq 1$$

Where, W(ρ) is the weight of the structure, F is the global load vector, K is the global stiffness matrix, and u is the global displacement vector (unknown). In the material density field ρ, the above equation can be related to the design variable points. The reserve factor is defined as the ratio between the given maximum compliance value to the compliance of the optimal structure.

The compliance can be calculated as: $Compliance_{struct} = u^T K(\rho)\ u.$

Additionally, binary design variable ρ presents the density of individual elements in the given structure with Solid elements represented as ρ(1), and the void element as ρ(0).

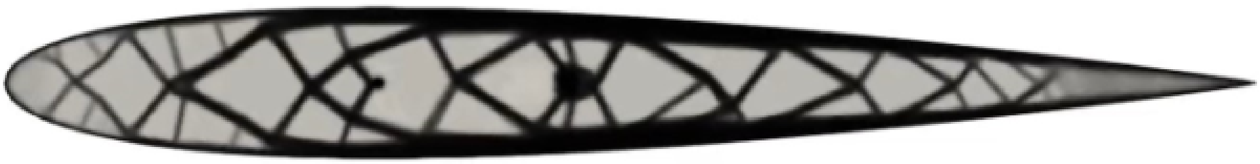

Figure 4: The Optimal Airfoil design obtained from BQPhy's QIDO.

The optimized airfoil design, which has also maintained the strength criteria, is shown in Figure 4. To meet the structural integrity requirements, we kept a constraint on the compliance such that strength criterion RF <= 4. BQPhy successfully reduces the volume of the airfoil without compromising its strength. Our QIDO solver was able to reduce 60% of weight in less than 50 iterations. This quantum-based approach offers better optimal airfoil designs to the users with higher accuracy and less computational power.

Compliance minimization:

In our second use case, the optimization aimed to minimize compliance using a volume fraction as 0.5, which means 50% reduction in the total volume. The optimization problem is defined as:

$$\min C_{\text{Structure}} = u^T K(\rho)\, u$$

$$\text{s. t.: } K(\rho)u = F$$

$$\int_\Omega \rho \; A \, d\Omega = W(\rho)$$

$$0 < \rho_{\min} \leq \rho_i \leq 1$$

$C_{\text{structure}}$ represents minimum compliance of the airfoil structure, W(ρ) is the weight of the structure, and F is the global load vector, K(ρ) is the global stiffness matrix, and u is the global displacement vector (unknown). Binary design variable ρ presents the density of individual elements in the given structure with ρ (1) = Solid, and ρ (0) = Void elements.

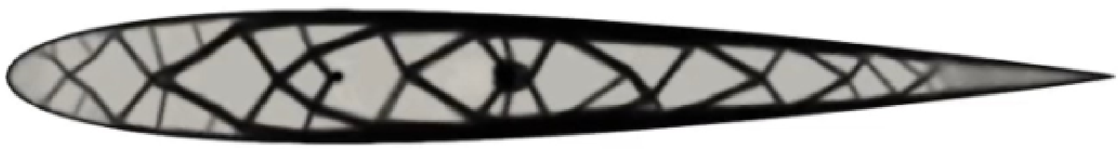

Figure 5: Compliance minimization using BQPhy

Figure 5 showcases the airfoil structure that has undergone optimization for minimizing compliance, preserving only 50% of its original volume. The remarkable efficiency of BQPhy's QIDO solver is evidenced by its successful compliance optimization while fulfilling the strength criteria. This is ensuring the structural integrity of the airfoil. These findings establish QIDO as an effective solution for tackling intricate optimization problems within the aerospace industry.

Section 5: Potential of BQPhy’s Quantum Powered Simulations

In conclusion, the potential of BQPhy's Quantum-Powered Simulation Tool to enhance engineering optimization capabilities for complex shapes such as aircraft wing designs is immense. BQPhy's quantum-inspired approach not only accelerates convergence but also elevates the precision of results, all while significantly reducing the required computational resources. As airfoil shape continues to be a vital component in aerodynamic and automotive design, BQPhy's optimization techniques and methods offer more accurate performance outcomes. With its groundbreaking technology, BQPhy charts a course towards a future where engineering optimization knows no bounds, redefining what is possible and pushing the boundaries of innovation to new horizons.

BQP's Quantum algorithms can run on current HPCs.

Accurate identification of global minima for more optimal design.

Fewer design iterations reduces overall simulation time.

Requires less compute resources hence reduced cost of HPC.

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This white paper does not make any guarantees or warranties regarding the applicability, performance, or suitability of the described methodologies for specific airfoil design applications. The results may vary depending on the specific design parameters, materials, and environmental conditions.

The simulations in this paper are based on certain assumptions and simplifications to make the analysis more manageable. Please take this into account when considering the practical implications of the findings.

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