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DAFoam: An Open-Source Adjoint Framework for Multidisciplinary Design Optimization with OpenFOAM

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The adjoint method is an efficient approach for computing derivatives that allow gradient-based optimization to handle systems parameterized with a large number of design variables. Despite this advantage, implementing the adjoint method for a partial-differential-equation-based primal solver is a time-consuming task. To lower the barrier for adjoint implementations, an object-oriented framework (DAFoam) is proposed to rapidly implement the discrete adjoint method for any steady-state OpenFOAM primal solver by adding or modifying only a few hundred lines of source code. In this paper, the DAFoam framework is introduced and the proposed object-oriented adjoint development process is illustrated. Using this strategy, the adjoint method is implemented for eight primal solvers, five turbulence models, and one radiation model in OpenFOAM. Excellent adjoint speed and scalability, with up to 10 million cells and 1536 CPU cores, and an average error in the adjoint derivatives of less than 0.1% are achieved. Finally, the implemented adjoint solvers and models are integrated into a gradient-based optimization framework, and four distinct design optimizations (multipoint aerodynamic optimization of a low-speed unmanned-aerial-vehicle wing, aerodynamic optimization of a transonic aircraft configuration, aerothermal optimization of a turbine internal cooling passage, and aerostructural optimization of a compressor rotor) are shown. DAFoam is available under an open-source license and is a powerful tool for the high-fidelity multidisciplinary design optimization of engineering systems, such as aircraft, ground vehicles, marine vessels, and turbomachinery.

I. Introduction

AEROSPACE engineering designs often require using a large number of design variables to parameterize complex design surfaces, such as aircraft wings. Changing these variables by hand is time consuming and is not likely to achieve the best possible design. Gradient-based optimization is a powerful approach to solve the aforementioned problem, because it automatically finds the set of design variables that maximizes the performance. To efficiently compute the derivatives, we can use the adjoint method, in which the computational cost is independent of the number of design variables. Therefore, the combination of adjoint method and gradient-based optimization enables the solution of complex design problems.

The adjoint method was first introduced in fluid mechanics by Pironneau [1], and then extended for aerodynamic shape optimization by Jameson [2]. Since then, the adjoint method has been widely used in gradient-based optimization for applications involving aerodynamics [3–10], hydrodynamics [11,12], heat transfer [13,14], and structures [15,16].

Many engineering systems are composed of multiple disciplines requiring multidisciplinary design optimization (MDO) techniques [17]. The adjoint method has been generalized to MDO problems [18,19] and implemented in the OpenMDAO framework [20]. Coupled-adjoint implementations have been used to solve aerostructural [21–24], hydrostructural [25], aerothermal [26], aeropropulsive [27,28], and aeroelastic [29,30] MDO problems.

There are two different approaches to formulate the adjoint equations for a partial differential equation (PDE)-based primal solver: continuous and discrete [31–33]. The continuous approach derives the adjoint formulation from the original governing equations, and then discretizes them for a numerical solution. This approach was used in previous studies, including Jameson [2] and Anderson and Venkatakrishnan [34], as well as the initial adjoint implementations for OpenFOAM [35,36] and SU2 [37]. The continuous adjoint is faster and requires less memory than the discrete adjoint. However, the accuracy of the continuous adjoint method suffers on coarse meshes [38], and it is challenging to implement for complex terms, such as those encountered in turbulence models [31–33].

On the other hand, the discrete approach starts directly from the discretized governing equations for the adjoint formulation. Therefore, the adjoint derivatives are consistent with the primal flow solutions, independent of the mesh density, a favorable feature that makes the optimization process more robust. Given this advantage, we opt to use the discrete adjoint approach in this study.

There are two main tasks when implementing the discrete adjoint method for a PDE-based primal solver, which are elaborated in Sec. II.A: 1) compute the partial derivatives or the matrix–vector products; and 2) solve the adjoint linear equation. In the past few decades, researchers have used various options for the aforementioned two tasks in discrete adjoint implementations [32,33]. The partial derivatives have been computed using the analytical method, finite differences, complex-step method [39], and algorithmic differentiation (AD) [40]. AD has also been used to efficiently compute the matrix–vector products in a matrix-free manner [33].

To solve the adjoint equation, both fixed-point iteration and Krylov methods have been proposed. The combination of these options has been used in a number of discrete adjoint solvers, such as ADflow [33,41], Cart3D [42], FUN3D [3], HYDRA [43], Jetstream [44–46], NSU3D [5,47], piggy- and reverseAcc-SimpleFoam [48], STAMPS [49], SU2 [37,50], and TAU-code [51].

Despite the progress cited previously, developing a discrete adjoint solver remains a time-consuming task. This is primarily because of the strong connection between the primal and adjoint solvers. As a consequence, developers need to have detailed knowledge of low-level implementations for both primal and adjoint solvers. In addition, to ensure adjoint consistency, modification and extension in the primal solver require corresponding changes in the adjoint solver. The aforementioned two factors cause the adjoint solver to have the same amount of development and maintenance effort as the primal

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solver does; a discrete adjoint solver typically contains thousands of lines of source code, and its development may take years. Although the aforementioned adjoint solvers provide a certain amount of flexibility for extension, such as adding new terms or boundary conditions, they do not offer rapid adjoint development options for a new set of PDEs. Having the capability to rapidly implement the adjoint method for a PDE-based primal solver from scratch is useful in practice, because it allows us to handle a wide range of engineering design problems involving multiple disciplines (e.g., aerodynamics, structures, and heat transfer), configurations (e.g., wings, wing–body–tail, and airframe–propulsion integration), and flow conditions (e.g., incompressible, subsonic, and transonic).

One way to address the large adjoint development effort is to use the reverse-mode AD to differentiate the entire primal solver (full-code AD) [48,52,53]. The full-code AD approach treats the primal solver as a black box, and therefore, it requires minimal development effort. However, the intermediate variables that are used in the primal nonlinear solution process need to be stored in memory, which is not feasible for large three-dimensional problems. Although advanced techniques (e.g., checkpointing and local pre-accumulation) can be used to trade speed for memory [48], the size of problems the full-code AD can handle is still limited [33].

The objective of this paper is to lower the barrier of adjoint development while maintaining the efficiency of adjoint computation. To this end, we propose DAFoam,[¶] an open-source object-oriented framework to rapidly develop discrete adjoint solvers with OpenFOAM [54]. OpenFOAM is an open-source multiphysics package that contains more than 80 PDE-based primal solvers involving a wide range of disciplines, such as aerodynamics, hydrodynamics, structures, heat transfer, combustion, and multiphase flow. Borrowing the idea of object-oriented primal solver development in OpenFOAM, DAFoam provides a high-level interface that allows us to implement the discrete adjoint method for existing or new steady-state OpenFOAM primal solvers by adding or modifying only a few hundred lines of source code. The central recipe of the proposed framework is to use a generalized framework for partial derivative computation and adjoint equation solution, and then provide an interface that allows developers to define solver-specific implementations, such as the residual functions and connectivity information.

In this paper, we introduce the overall structure of DAFoam and illustrate the object-oriented adjoint development process for the Navier–Stokes (NS) equations. Using the proposed recipe, we implement the adjoint method for eight primal solvers, five turbulence models, and one radiation model. We evaluate the performance of the adjoint implementations in terms of speed, scalability, memory usage, and accuracy. Moreover, we integrate the adjoint solvers into a gradient-based optimization framework, and showcase four distinct design optimizations using DAFoam: multipoint aerodynamic optimization of a low-speed unmanned-aerial-vehicle (UAV) wing, aerodynamic shape optimization of a transonic aircraft configuration, aerothermal optimization of a turbine internal cooling passage, and aerostructural optimization of a compressor rotor. The optimization setup for these cases, including the meshes, flow and optimization configurations, and DAFoam run scripts, is publicly available [55]. In sum, the main contribution of this work is the development of an open-source object-oriented adjoint framework DAFoam that allows rapid adjoint solver implementations for a wide range of PDEs.

The rest of the paper is organized as follows. In Sec. II, we introduce the DAFoam framework and detail the object-oriented adjoint development. The design optimization results are presented and discussed in Sec. III, and we summarize our findings in Sec. IV.

II. Methodology

The central recipe of the object-oriented adjoint framework of DAFoam is to divide the implementation into solver-agnostic and solver-specific parts. In this section, we first derive the discrete adjoint equations. Then, we elaborate on the solver-agnostic adjoint development, followed by the object-oriented interface that allows developers to specify the solver-specific implementations. To better illustrate the object-oriented adjoint development process, we use the adjoint source code for the incompressible NS equations as an example. Finally, we summarize the implemented adjoint solvers and models, and evaluate their performance in terms of speed, scalability, memory usage, and accuracy.

A. Adjoint Equations

As mentioned previously, we use the adjoint method to efficiently compute the total derivatives $\mathrm{d}f/\mathrm{d}\boldsymbol{x}$, in which f is the objective or constraint function (e.g., drag, lift, or torque), and $\boldsymbol{x}$ is the vector of design variables (e.g., positions of control points that morph the design surface). In the discrete approach, we assume that a discretized form of governing equations is available through the primal solver, and that the design variable vector $\boldsymbol{x} \in \mathbb{R}^{n_x}$ and the state variable vector $\boldsymbol{w} \in \mathbb{R}^{n_w}$ satisfy the discrete residual equations $\boldsymbol{R}(\boldsymbol{x}, \boldsymbol{w}) = 0$, in which $\boldsymbol{R} \in \mathbb{R}^{n_w}$ is the residual vector.

The functions of interest are then functions of both the design variables and the state variables: $f = f(\boldsymbol{x}, \boldsymbol{w})$. In general, we have multiple functions of interest (the objective and multiple design constraints), but in the following derivations, we consider f to be a scalar without loss of generality. As we will see later, each additional function requires the solution of another adjoint system. To obtain the total derivative $\mathrm{d}f/\mathrm{d}\boldsymbol{x}$, we apply the chain rule as follows:

$$\underbrace{\frac{\mathrm{d}f}{\mathrm{d}\boldsymbol{x}}}_{1\times n_x} = \underbrace{\frac{\partial f}{\partial \boldsymbol{x}}}_{1\times n_x} + \underbrace{\frac{\partial f}{\partial \boldsymbol{w}}}_{1\times n_w} \underbrace{\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}\boldsymbol{x}}}_{n_w\times n_x} \tag{1}$$

in which the partial derivatives $\partial f/\partial \boldsymbol{x}$ and $\partial f/\partial \boldsymbol{w}$ are relatively cheap to evaluate because they only involve explicit computations. The total derivative $\mathrm{d}\boldsymbol{w}/\mathrm{d}\boldsymbol{x}$ matrix, on the other hand, is expensive, because $\boldsymbol{w}$ is implicitly determined by the residual equations $\boldsymbol{R}(\boldsymbol{w}, \boldsymbol{x}) = 0$.

To obtain $\mathrm{d}\boldsymbol{w}/\mathrm{d}\boldsymbol{x}$, we can apply the chain rule for $\boldsymbol{R}$. We then use the fact that the governing equations should always hold, independent of the values of design variables $\boldsymbol{x}$. Therefore, the total derivative $\mathrm{d}\boldsymbol{R}/\mathrm{d}\boldsymbol{x}$ must be zero:

$$\frac{\mathrm{d}\boldsymbol{R}}{\mathrm{d}\boldsymbol{x}} = \frac{\partial \boldsymbol{R}}{\partial \boldsymbol{x}} + \frac{\partial \boldsymbol{R}}{\partial \boldsymbol{w}}\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}\boldsymbol{x}} = 0 \Rightarrow \underbrace{\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}\boldsymbol{x}}}_{n_w\times n_x} = -\underbrace{\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{w}}^{-1}}_{n_w\times n_w} \underbrace{\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{x}}}_{n_w\times n_x} \tag{2}$$

Substituting $\mathrm{d}\boldsymbol{w}/\mathrm{d}\boldsymbol{x}$ from Eq. (2) into Eq. (1), we get

$$\underbrace{\frac{\mathrm{d}f}{\mathrm{d}\boldsymbol{x}}}_{1\times n_x} = \underbrace{\frac{\partial f}{\partial \boldsymbol{x}}}_{1\times n_x} - \overbrace{\underbrace{\frac{\partial f}{\partial \boldsymbol{w}}}_{1\times n_w} \underbrace{\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{w}}^{-1}}_{n_w\times n_w}}^{\boldsymbol{\psi}^T} \underbrace{\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{x}}}_{n_w\times n_x} \tag{3}$$

Now, we can transpose the state Jacobian matrix $\partial \boldsymbol{R}/\partial \boldsymbol{w}$ and solve with $[\partial f/\partial \boldsymbol{w}]^T$ as the right-hand side, which yields the adjoint equation:

$$\underbrace{\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{w}}^T}_{n_w\times n_w} \underbrace{\boldsymbol{\psi}}_{n_w\times 1} = \underbrace{\frac{\partial f}{\partial \boldsymbol{w}}^T}_{n_w\times 1} \tag{4}$$

in which $\boldsymbol{\psi}$ is the adjoint vector. Once we have solved this equation, we can compute the total derivative by substituting the adjoint vector $\boldsymbol{\psi}$ into Eq. (3), yielding

$$\frac{\mathrm{d}f}{\mathrm{d}\boldsymbol{x}} = \frac{\partial f}{\partial \boldsymbol{x}} - \boldsymbol{\psi}^T \frac{\partial \boldsymbol{R}}{\partial \boldsymbol{x}} \tag{5}$$

For each function of interest, we need to solve the adjoint equations only once, because the design variable is not explicitly present in Eq. (4). Therefore, its computational cost is independent of the number of design variables, but it is proportional to the number of functions of interest. This approach is known as the adjoint method and is advantageous for many aerospace engineering design

[¶]Source code available online at https://github.com/mdolab/dafoam.

problems, in which we have only a few functions of interest but may use several hundred design variables.

To summarize, a discrete adjoint implementation requires computing the partial derivatives and solving the adjoint equations, and consists of the following four major steps:

1) Compute the partial derivatives $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ and $[\partial f/\partial \boldsymbol{w}]^T$.
2) Solve the linear equation (4) for the adjoint vector $\boldsymbol{\psi}$.
3) Compute the partial derivatives $\partial \boldsymbol{R}/\partial \boldsymbol{x}$ and $\partial f/\partial \boldsymbol{x}$.
4) Use Eq. (5) to compute the total derivative $\mathrm{d}f/\mathrm{d}\boldsymbol{x}$.

The aforementioned four steps do not assume any specific form of the residual function $\boldsymbol{R}(\boldsymbol{w}, \boldsymbol{x})$; therefore, they are applicable for any set of discrete PDEs. In light of this observation, DAFoam implements the four steps in a solver-agnostic manner, as detailed in Sec. II.B. To account for solver-specific implementations, DAFoam provides high-level interfaces to specify the detailed residual function form, as elaborated in Sec. II.C.

B. Solver-Agnostic Framework for Partial Derivative Computation and Adjoint Equation Solution

DAFoam uses the FD Jacobian approach [33] to implement the discrete adjoint, that is, the partial derivatives are computed using the coloring-accelerated finite difference method, and the adjoint equations are solved using a Krylov method. Figure 1 shows the process and data flow for the FD Jacobian adjoint approach. Here, we use the extended design structure matrix representation developed by Lambe and Martins [56]. The diagonal nodes represent the modules and the off-diagonal nodes represent the data. The black lines represent the process flow in the adjoint, whereas the thick gray lines represent the data flow. The number in each node represents the execution order. The superscripts i and n are the ith color and nth iteration, respectively, and the subscripts ref and perturb are the reference and perturbed values, respectively.

As shown in Fig. 1, we use the finite difference method to compute the partial derivatives $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ and $[\partial f/\partial \boldsymbol{w}]^T$, accelerated by a graph coloring algorithm. We loop the processes 0-1-2-0 to compute the columns associated with the ith color in $\partial \boldsymbol{R}/\partial \boldsymbol{w}$, and then repeat the loop for all colors. Finally, we output the fully assembled $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ to 6. Similarly, we compute $[\partial f/\partial \boldsymbol{w}]^T$ by looping the processes 3-4-5-3 and output to 6. The use of graph coloring is critical because naively computing $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ and $[\partial f/\partial \boldsymbol{w}]^T$ using finite differences requires calling the objective and residual computation routines n_w times, one for each column in $\partial \boldsymbol{R}/\partial \boldsymbol{w}$ and $\partial f/\partial \boldsymbol{w}$. This becomes computationally prohibitive for three-dimensional problems because n_w can be more than 10 million.

To reduce the computational cost, we use graph coloring [57] to exploit the sparsity of the Jacobians. To be more specific, we partition all the columns of a Jacobian matrix into different structurally orthogonal subgroups (colors), such that, in one structurally orthogonal subgroup, no two columns have a nonzero entry in a common row. With this treatment, we can simultaneously perturb multiple columns that have the same colors, because no two columns (states) impact the same row (residual). We then compute their partial derivatives by calling the residual and objective computation routines only once.

Using coloring to accelerate Jacobian computation for adjoint solvers was proposed by Burdyshaw and Anderson [58], Nielsen and Kleb [59], and Lyu et al. [7], in which the complex step [39] and AD [40] methods were used to compute the partial derivatives. Although these two methods provide an accurate derivative computation, in this study, we opt to use the finite difference method because it requires minimal modification to the primal codes, which ultimately facilitates the adjoint implementations. Moreover, its accuracy is well within the acceptable range for practical optimization problems (see the adjoint accuracy evaluation in Sec. II.D.2).

The graph coloring for $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ is challenging because $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ is an $n_w \times n_w$ matrix and because OpenFOAM uses unstructured meshes, which results in an irregular sparsity pattern for $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$. In our previous work, we developed a heuristic graph coloring algorithm that runs on distributed memory systems in parallel [60]. This coloring algorithm is applicable for any mesh topology, and allows us to compute $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ by calling the residual routines between 1000 and 3000 times, independent of the mesh size and the number of CPU cores.

Using the coloring scheme to compute $[\partial f/\partial \boldsymbol{w}]^T$ requires special attention because f is typically computed based on the integration of discrete state variables over the design surface (e.g., drag and lift); therefore, $[\partial f/\partial \boldsymbol{w}]^T$ is a dense vector. To enable coloring for $[\partial f/\partial \boldsymbol{w}]^T$, we divide f into n_d discrete mesh faces on the design surface: $\partial f/\partial \boldsymbol{w} = \sum_{i=1}^{n_d} \partial f_i/\partial \boldsymbol{w}$, in which f_i denotes the discrete f based on the ith mesh face on the design surface. With this treatment, we obtain a set of $\partial f_i/\partial \boldsymbol{w}$ vectors that are much sparser than $\partial f/\partial \boldsymbol{w}$. Next, we form an $n_d \times n_w$ matrix by using $\partial f_i/\partial \boldsymbol{w}$ as its ith row. We then use the coloring scheme to compute all the nonzero elements in this matrix. Finally, we sum all the rows of this matrix (i.e., $\partial f_i/\partial \boldsymbol{w}$) to obtain $\partial f/\partial \boldsymbol{w}$. He et al. [60] provided more details on this approach. The number of colors for $[\partial f/\partial \boldsymbol{w}]^T$ is at least one order of magnitude less than that for $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$.

After computing $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ and $[\partial f/\partial \boldsymbol{w}]^T$, we use the PETSc library [61] to solve the adjoint equations (4) for the adjoint vector $\boldsymbol{\psi}$ (loop 6-7-8-6; output 9). We use the generalized minimal residual (GMRES) iterative linear equation solver. The GMRES method uses the Krylov subspace $K_i = \mathrm{span}(r_0, Ar_0, A^2 r_0, \ldots, A^{i-1} r_0)$, in which $A = [\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ is the transpose of the state Jacobian, and the initial

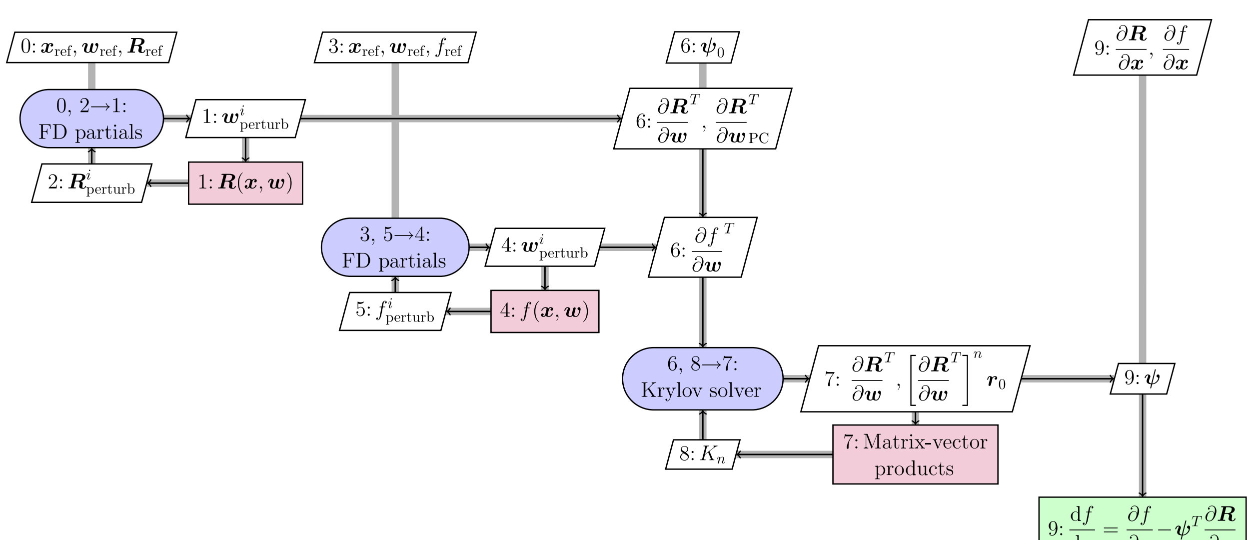


Fig. 1 Process and data flow for the solver-agnostic FD Jacobian adjoint approach [33] in DAFoam.

residual is $\boldsymbol{r}_0 = [\partial f/\partial \boldsymbol{w}]^T - [\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T \boldsymbol{\psi}_0$. We assemble and store a full $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ matrix in memory, and then explicitly pass it to PETSc for computing the matrix–vector products $r_0, Ar_0, A^2 r_0$, etc. We use a nested preconditioning strategy with the additive Schwarz method as the global preconditioner and the incomplete lower and upper (ILU) factorization approach with one or two levels of fill-in for the local preconditioning. To improve convergence, we construct the preconditioner matrix $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T_{\mathrm{PC}}$ by approximating the residuals and their linearizations [33,60]. This strategy is effective for solving the adjoint equation, as reported by He et al. [26,60].

No coloring scheme is needed for $\partial \boldsymbol{R}/\partial \boldsymbol{x}$ and $\partial f/\partial \boldsymbol{x}$. Instead, we use a brute-force finite difference approach by successively perturbing the design variables and computing the perturbed residuals and objective function [33,60]. After computing $\partial \boldsymbol{R}/\partial \boldsymbol{x}$, $\partial f/\partial \boldsymbol{x}$, and $\boldsymbol{\psi}$, we compute the total derivative $\mathrm{d}f/\mathrm{d}\boldsymbol{x}$ in step 9.

C. Solver-Specific Adjoint Implementation

The FD Jacobian adjoint approach described in Sec. II.B is applicable to any primal solver. In this section, we elaborate on the object-oriented adjoint framework of DAFoam that allows developers to rapidly implement solver-specific adjoints. The DAFoam framework builds on the observation that, for different primal solvers, their adjoint implementations differ in the following three major aspects: 1) elements in the residual $\boldsymbol{R}$ and state variable $\boldsymbol{w}$ vectors, 2) stencils of Jacobians, and 3) form of residual computation routine $\boldsymbol{R} = \boldsymbol{R}(\boldsymbol{w}, \boldsymbol{x})$.

In DAFoam, we provide high-level interfaces that allow developers to easily specify the aforementioned three variations, as shown in Fig. 2. This is done by adding child classes for each primal solver and providing solver-specific implementations. To be more specific, the elements in the states and residuals are set in the `AdjointSolverRegistry` child classes, the stencils of Jacobians are specified in the `AdjointJacobianConnectivity` child classes, and the residual function computation is given in the `AdjointDerivative` child classes. The primal solvers of OpenFOAM support selecting various turbulence models at run time. To enable a similar feature for the adjoint solvers, we treat the turbulence state variable separately. The turbulence-model-related adjoint implementations are provided in the `AdjointRASModel` child classes. Once all the child classes are properly added and compiled, we can compute adjoint derivatives for any specified primal solver and model at run time.

Listing 1: Sample code to register residuals and states for simpleDAFoam

```
// Register scalar volume field p
volScalarStates.append("p");
// Register vector volume field U
volVectorStates.append("U");
// Register scalar surface field phi
surfaceScalarStates.append("phi");
// Create derived variable names (e.g., residuals)
this ->setDerivedInfo();
```

In the following, we use simpleFoam, one of the built-in primal solvers of OpenFOAM, as an example to illustrate the object-oriented adjoint implementation process. The governing equations for simpleFoam are the incompressible NS equations:

$$\nabla \cdot \boldsymbol{U} = 0 \tag{6}$$

$$\nabla \cdot (\boldsymbol{U}\boldsymbol{U}) + \frac{1}{\rho} \nabla p - \nu_{\mathrm{eff}} \nabla \cdot (\nabla \boldsymbol{U} + \nabla \boldsymbol{U}^T) = 0 \tag{7}$$

in which $\boldsymbol{U}$ is the velocity vector; p is the pressure; and $\nu_{\mathrm{eff}} = \nu + \nu_t$ is the effective kinematic viscosity with ν and ν_t being the molecular and turbulent kinematic viscosity, respectively. Although simpleFoam supports multiple turbulence models, here, we use the one-equation Spalart–Allmaras (SA) turbulence model as an example:

$$\nabla \cdot (\boldsymbol{U}\tilde{\nu}) - \frac{1}{\sigma}\{\nabla \cdot [(\nu + \tilde{\nu})\nabla \tilde{\nu}] + C_{b2}|\nabla \tilde{\nu}|^2\} - C_{b1}\tilde{S}\,\tilde{\nu} + C_{w1} f_w \left(\frac{\tilde{\nu}}{d}\right)^2 = 0 \tag{8}$$

in which $\tilde{\nu}$ is related to the turbulent viscosity ν_t via $\nu_t = \tilde{\nu}\chi^3/(\chi^3 + C_{v1}^3)$, $\chi = \tilde{\nu}/\nu$. Spalart and Allmaras [62] included more details on the terms and parameters in Eq. (8).

Listing 2: Sample code to specify the momentum residual connectivity for simpleDAFoam

```
ResConInfo.set
(
  "URes",
  {
    // Level zero connected states
    {"U","p","nut","phi"},
    // Level one connected states
    {"U","p","nut"},
    // Level two connected states
    {"U"}
  }
);
// Connectivity for other residuals
...

// replace "nut" in ResConInfo with the
// corresponding turbulence state variables
// for the selected turbulence model
adjRAS.correctAdjStateResidualTurbCon
(
  ResConInfo["URes"]
);
...

// add residual connectivity for the
// selected turbulence model
adjRAS.setAdjStateResidualTurbCon
(
  ResConInfo
);
```

The continuity (6) and momentum (7) equations are coupled by using the SIMPLE algorithm [63], along with the Rhie–Chow interpolation [64]. The turbulence equation (8) is solved in a segregated manner. The finite volume method is used to discretize the preceding equations on collocated meshes, such that we obtain a discrete form of residual function $\boldsymbol{R}(\boldsymbol{w}, \boldsymbol{x})$. To implement the discrete adjoint method in DAFoam, we follow the following three steps:

1) Create a child class `AdjointSolverRegistrySimpleFoam` to specify the elements in $\boldsymbol{R}$ and $\boldsymbol{w}$. According to the governing equations (6–8), simpleFoam has six residuals (R_u, R_v, R_w, R_p, R_{ν_t}, and R_ϕ) and six state variables (u, v, w, p, ν_t, and ϕ), in which ϕ is the surface flux. The reason for treating ϕ as an independent state was explained in [60]. Therefore, we append these state names to the registry list, as shown in Listing 1. To facilitate the solver-agnostic adjoint implementation, we need to separately register the states based on their field types (i.e., volume-scalar, volume-vector, or surface-scalar variables). Then, we call `setDerivedInfo` to register the derived variable names [e.g., the reference value for $\boldsymbol{U}$ (`URef`) and the residual for $\boldsymbol{U}$ (`URes`)]. There is no need to register turbulence states here because this is done in the child classes of `AdjointRASModel`.

2) Create a child class `AdjointJacobianConnectivitySimpleFoam` to specify how many levels of surrounding $\boldsymbol{w}$ are connected to $\boldsymbol{R}$. This information will be used by the graph coloring scheme to compute the colors. To set the connectivity, we simply assign the stencil levels to the Jacobian connectivity lists, as shown in Listing 2. Figure 3 shows the connectivity for the $\boldsymbol{U}$ residual in the case of a two-dimensional structured mesh. The $\boldsymbol{U}$ residual (`URes`) depends on $\boldsymbol{U}$, p, ν_t, and ϕ at the residual cell (level zero, denoted in green). For one level of surrounding cells, `URes` depends on $\boldsymbol{U}$, p, and ν_t. For two levels of surrounding cells, `URes` depends on $\boldsymbol{U}$ only.

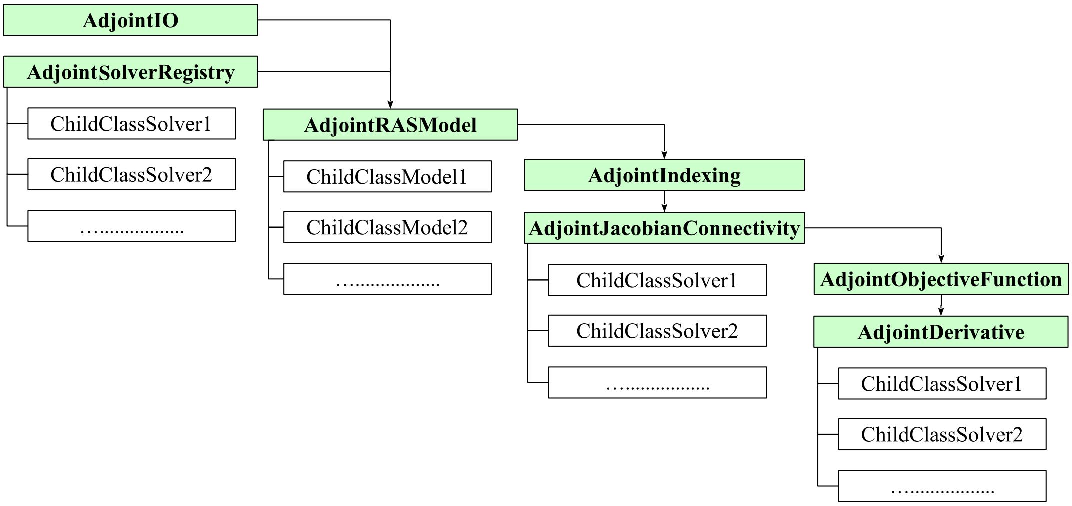


Fig. 2 Object-oriented code structure for rapid discrete adjoint implementation in DAFoam; for a new adjoint solver, we need to add child classes for registering states, specifying residual connectivity, and computing residuals.

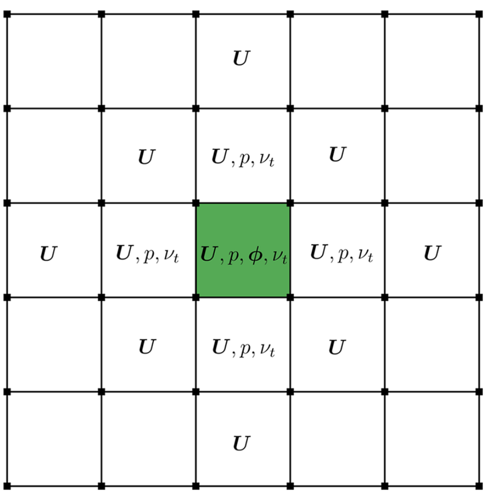


Fig. 3 Connectivity of the U residual for a two-dimensional structured mesh; the residual cell is in green.

Similarly, we add connectivity information for all the other residuals. The levels of connected states for a residual can be obtained by analyzing the stencil of each term in the discrete residual equations. For example, the pressure term ∇p depends on one level of surrounding p, and the Laplacian term $\nu_{\text{eff}} \nabla \cdot (\nabla \boldsymbol{U} + \nabla \boldsymbol{U}^T)$ depends on one level of ν_t and two levels of $\boldsymbol{U}$. Alternatively, we can obtain the connectivity level by successively perturbing all the surrounding states for a single-cell residual, and evaluating which state impacts this residual. For complex residual equations, the latter is preferred. Next, we replace ν_t with the corresponding turbulence state variables in the `ResConInfo` list by calling `correctAdjStateResidualTurbCon` (e.g., replacing ν_t with $\tilde{\nu}$ for the SA model, and replacing ν_t with k and ε for the k– ε model). Finally, we call `setAdjStateResidualTurbCon` to add turbulence residual connectivity. As mentioned previously, we treat the turbulence-model-related adjoint implementations separately; `correctAdjStateResidualTurbCon` and `setAdjStateResidualTurbCon` are implemented in the child classes of AdjointRASModel.

3) Create a child class `AdjointDerivativeSimpleFoam`, and provide a function to compute $\boldsymbol{R}$ based on $\boldsymbol{w}$ and $\boldsymbol{x}$. Generally, this task is time consuming because the residual functions in a primal solver typically include low-level implementation details and can become complex as more governing equations are involved. Fortunately, each primal solver in OpenFOAM has standardized high-level residual computation routines that we can reuse to facilitate the adjoint implementations. Listing 3 shows the code corresponding to the $\boldsymbol{U}$ residual computation as an example. Note that this listing illustrates the idea of reusing the primal codes for residual computation; the actual `calcResiduals` function in simpleDAFoam is slightly different. In the primal solver simpleFoam, a finite volume matrix (FVM) object `UEqn` has been already created containing all the relevant terms (pressure, divergence, deviatoric, and Laplacian) for the $\boldsymbol{U}$ equation (lines 4–10). Then, simpleFoam solves the linear equation `UEqn&U=0` to obtain $\boldsymbol{U}$ (line 12). In the adjoint implementation, we reuse the `UEqn` from the primal solver (lines 20–26), and perform a matrix–vector product `UEqn&U` to compute `URes` (line 27), in which & denotes the matrix–vector product operation in OpenFOAM. This strategy allows us to rapidly identify and construct the residual computation functions without specific knowledge of the low-level implementations of primal solvers. We need to specify residual computation codes for all other residuals. In addition, we need to update intermediate variables that depend on the state variables and are used in the residual computation; for example, the density needs to be updated based on the updated pressure and temperature. For simpleDAFoam, we do not need to update any intermediate variable (lines 34–37).

In summary, we can follow the aforementioned steps to rapidly implement the discrete adjoint method for existing or new steady-state primal solvers in OpenFOAM. We can also follow a similar route (register state names, set connectivity, and provide residual functions) to implement the adjoint for different turbulence models in the `AdjointRASModel` child classes. We need to add or modify only a few hundred lines of source code. The major differences in adjoint implementations between different primal solvers and models are the details of the residual computation functions. As mentioned previously, we can reuse the built-in FVM objects of OpenFOAM, a high-level interface to construct the linear equation matrices. This convenient feature allows us to rapidly construct the corresponding residual computation functions without specific knowledge of the low-level implementation details.

D. Performance Evaluation

Using the object-oriented adjoint framework of DAFoam shown in Sec. II.C, we implement the adjoint method for eight primal solvers, five turbulence models, and one radiation model, as listed in Tables 1 and 2. These solvers and models include a wide range of disciplines (aerodynamics, heat transfer, structures, and radiation) and flow conditions (incompressible, subsonic, transonic, as well as full and transitional turbulence). The naming convention is to add "DA" (discrete adjoint) to the original name of a primal solver in OpenFOAM. Taking simpleDAFoam as an example, it is based on the built-in steady-state incompressible solver simpleFoam of OpenFOAM. We can use simpleDAFoam to simulate the flow and compute the adjoint derivatives in a gradient-based optimization framework.

Table 1 Summary of implemented adjoint solvers

Adjoint solver	Governing equations
laplacianDAFoam	Laplacian equation
simpleDAFoam	Incompressible NS equations
simpleTDAFoam	Incompressible NS equations with heat transfer
buoyantBoussinesqSimpleDAFoam	Incompressible NS equations with heat transfer, buoyancy, and radiation
rhoSimpleDAFoam	Compressible NS equations (subsonic)
rhoSimpleCDAFoam	Compressible NS equations (transonic)
buoyantSimpleDAFoam	Compressible NS equations with heat transfer, buoyancy, and radiation
solidDisplacementDAFoam	Linear elastic equation

Table 2 Summary of implemented turbulence models

Turbulence model	Description
SpalartAllmaras	SA one-equation model
kEpsilon	Standard $k-\varepsilon$ two-equation model
realizableKE	Realizable $k-\varepsilon$ model
kOmegaSST	Menter $k-\omega$ SST two-equation model
kOmegaSSTLM	Langtry–Menter four-equation transitional model based on kOmegaSST

SST = shear-stress transport.

Listing 3: Sample code to compute flow residuals for simpleDAFoam

```
// **************************************************************
// Original U equation solution code in simpleFoam for reference
{
  fvScalarMatrixUEqn                          // U FVM matrix
  (
      fvm::div(phi, U)                        // Divergence term
    + fvc::grad(p)                            // Pressure term
    - fvm::laplacian(nuEff, U)                // Laplacian term
    - fvc::div(nuEff*dev2(T(fvc::grad(U))))   // Deviatoric term
  );
  UEqn.relax();    // Set under -relaxation
  UEqn.solve();    // Solve the equation UEqn&U=0 to get U
}
// *************************************************************

// Residual computation function in simpleDAFoam
void calcResiduals()
{
  // Reuse the FVM matrix UEqn from the primal solver
  fvVectorMatrix UEqn
  (
      fvm::div(phi, U)                          // Divergence term
      + fvc::grad(p)                            // Pressure term
      - fvm::laplacian(nuEff, U)                // Laplacian term
      - fvc::div(nuEff*dev2(T(fvc::grad(U))))   // Deviatoric term
  );
  volVectorField URes = UEqn&U     // Matrix -vector product for the U residual

  ...                                           // Compute other residuals
}

// Update any intermediate variables that depend on the state variables and
// are used in the residual computation
void updateIntermediateVariables()
{
  // no intermediate variable for simpleDAFoam
}
```

1. Speed, Scalability, and Memory Usage

Now, we evaluate the speed, scalability, and memory usage of the preceding adjoint implementations. We use case 3 from the AIAA Aerodynamic Design Optimization Discussion Group (ADODG),[**] which consists of an unswept rectangular wing with a NACA 0012 airfoil profile. We run the flow simulations and adjoint computation using simpleDAFoam at Reynolds number 10^6 and Mach number 0.15. The objective function is the drag coefficient C_D and the nominal flight condition is at a lift coefficient C_L of 0.375. The design variables are the twists (γ) at eight spanwise locations. We used this configuration to benchmark the performance of DAFoam adjoint solvers in Kenway et al. [33]. We generate a fine structured mesh with 10,141,696 cells, and the computational domain extends 20 chords from the surface. The primal solver runs for 3000 steps, at which point the residuals drop 13 orders of magnitudes and stall. For the adjoint computation, we set the relative residual tolerance for the adjoint linear equation solution to 10^{-6}, which is a typical value in an optimization process. There is no need to converge the residual of adjoint linear equations any more than this because the adjoint total derivatives are accurate only up to four significant digits (Sec. II.D.2) due to the errors in the finite-difference-based partial derivative computation (Sec. II.B).

**Data available online at http://mdolab.engin.umich.edu/content/aerodynamic-design-optimization-workshop.

Table 3 Wall-clock run time for the flow and adjoint computation with increasing number of CPU cores

Node	Cores	Flow run time, s (%)	Adjoint run time, s (%)	Adjoint/flow
8	192	810 (100.0)	1809 (100.0)	2.2
16	384	433 (93.5)	976 (92.7)	2.3
32	768	242 (83.7)	481 (94.0)	2.0
64	1536	156 (64.9)	262 (86.3)	1.7

The mesh contains 10,141,696 cells. The adjoint computation scales well up to 1536 cores.

Table 3 shows the speed and scalability of flow and adjoint computations. All the simulations are conducted on Stampede2 [65] using the Skylake nodes. The Skylake nodes are equipped with an Intel Xeon Platinum 8160 CPU running at 2.1 GHz, and each node has 48 CPU cores and 196 GB of memory. The values in parentheses are the parallel efficiencies, defined as $192t_{192}/(nt_n) \times 100\%$, in which t is the wall-clock run time and n is the number of CPU cores. The adjoint derivative computation scales better than the flow simulation, especially when using more CPU cores. For example, with 1536 CPU cores, the parallel efficiencies for the flow and adjoint are 65% and 86%, respectively. In addition, the run-time ratio between the adjoint and flow solutions varies between 1.7 and 2.2, which is within the acceptable range for performing practical optimization. The run times for the partial derivative computation and adjoint linear equation solution are similar. In terms of memory usage, the flow solution takes 73.2 GB memory, whereas the adjoint computation requires 1146.2 GB memory. The large peak memory requirement is the current bottleneck of our adjoint implementation, which is in part because we explicitly form and store the transpose state Jacobian matrix $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ and its preconditioner matrix $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T_{\text{PC}}$ in memory. Because of the use of SIMPLE algorithm and Rhie–Chow interpolation, the pressure residual depends on three levels of surrounding cells in simpleDAFoam [33,60]. In contrast, for density-based flow solvers, such as ADflow [33,41] and SU2 [37], the flow residuals depend at most on two levels of surrounding cells. The larger stencil in simpleDAFoam results in a denser $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ matrix, which requires a large amount of memory to store. In addition, the denser preconditioner matrix $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T_{\text{PC}}$ causes a larger memory overhead when using a nonzero fill-in level in the ILU factorization. To alleviate the large memory requirement, we can use the Jacobian-free GMRES adjoint solution strategy detailed by Kenway et al. [33], in which the $[\partial \boldsymbol{R}/\partial \boldsymbol{w}]^T$ matrix is not explicitly computed or stored. For ADflow, the Jacobian-free approach saved up to 30% memory, compared with the FD Jacobian method [33]. Implementing the Jacobian-free approach in DAFoam and optimizing its performance will be conducted in a future work.

2. Adjoint Accuracy

To verify the adjoint derivative accuracy, we consider all the implemented adjoint solvers and models. For the flow solvers, we use the ADODG case 3 with a coarse mesh of 102,912 cells. The average y^+ is 32.6; therefore, we use wall functions for all turbulence models. The Mach numbers for the incompressible, subsonic, and transonic conditions are 0.15, 0.5, and 0.7, respectively. As mentioned previously, the adjoint solvers compute derivatives at all eight spanwise locations; however, we show only one representative derivative at the 40% spanwise location, $\mathrm{d}C_D/\mathrm{d}\gamma_{40\%}$, for all solvers and models.

For the structural analysis solver (solidDisplacementDAFoam), we use the Rotor 67 case (an axial compressor rotor) [66] with a rotational speed of 840 rad $\cdot$ s^{-1}. We generate a triangular unstructured mesh with 91,475 cells. The objective function is an aggregation of the von Mises stresses σ_v^a of the rotor subjected to the centrifugal force, and the design variable is the rotational speed. To compute σ_v^a, we use the Kreisselmeier–Steinhauser (KS) function to aggregate σ_v over all the mesh cells [67], such that σ_v^a is a conservative approximation of the maximal von Mises stress.

For the heat transfer solver (laplacianDAFoam), we use a flange model with 5712 cells. The heat transfer is imposed by adding a 200 K temperature difference between the internal and external boundaries. The objective function is the average temperature $\bar{T}$ in the flange, and the design variable is the temperature at the internal boundary T_i.

We directly compute the total derivatives using the finite difference method and use them as the reference derivative values. To control the errors in the finite difference method, we perform step-size studies by adding various perturbation magnitudes (ranging from 10^{-5} to 10^{-2} with a common ratio of 0.1) to the design variable, and then compare the reference total derivative values. We conduct similar step-size studies for the partial derivatives in the adjoint computation; the tested step-size magnitudes range from 10^{-9} to 10^{-4} with a common ratio of 0.1. The best step size varies depending on cases; however, 10^{-3} and 10^{-7} are the most common perturbation step sizes for the reference total derivatives and the partial derivative computation, respectively.

Finally, we evaluate the accuracy of adjoint derivative computation, as shown in Table 4. For all the implemented solvers and models, there is a good agreement between the adjoint derivatives and the reference values computed using the brute-force finite difference method mentioned previously. The average relative error is less than 0.1%. This level of error is acceptable for performing gradient-based optimization, as shown in our previous studies [12,26,60].

III. Results and Discussion

In this section, we integrate the implemented adjoint solvers and models into a gradient-based optimization framework described in our previous work [60]. We then perform four distinct optimizations that cover a wide range of disciplines, configurations, and flow conditions: 1) multipoint aerodynamic optimization for a low-speed UAV wing, 2) trimmed aerodynamic optimization for a transonic aircraft configuration, 3) aerothermal optimization for a turbine internal cooling passage, and 4) aerostructural optimization for an axial compressor rotor.

The main objective of this section is to demonstrate the benefit of having the flexibility to rapidly implement the discrete adjoint method. Therefore, a comprehensive optimization analysis that evaluates the impacts of different flow conditions, configurations, turbulence models, and mesh densities for each of these applications is outside the scope of the paper.

A. Multipoint Aerodynamic Optimization of a Low-Speed UAV Wing

We perform a multipoint aerodynamic optimization of a low-speed UAV wing. The goal is to demonstrate the multipoint optimization capability of DAFoam for incompressible conditions. We use the adjoint solver simpleDAFoam, and the governing equations are the incompressible NS equations, as shown in Eqs. (6) and (7). We use the SA turbulence model (8) for all the optimizations in this study.

The wing geometry is taken from a multimission UAV prototype called Odyssey [68]. The wing planform is rectangular with an aspect ratio of 8.57, a span of 4.572 m, and an Eppler 214 airfoil. There is no twist or sweep in the baseline wing geometry. For the flow simulation, we use a structured hexahedral mesh with 548,352 cells identical to that of our previous work ([69] fig. 5). We use ANSYS ICEM-CFD to generate the surface mesh, and then we extrude the surface mesh to the volume mesh using a hyperbolic mesh marching method [70] implemented in the pyHyp package.[††] The average y^+ is 33.7. The simulation domain extends to 30 chord lengths. The Mach number is 0.074 and the Reynolds number is 9×10^5.

In our previous work, we performed a single-point aerodynamic optimization of the same UAV wing [60]. In this study, we use a similar design variable and constraint setup, but we consider multipoint optimization, as detailed in Table 5. We select three flight conditions with $C_L = 0.6, 0.75$ (nominal), and 0.9. The objective is the weighted C_D with weights of 0.25, 0.5, and 0.25 for the three flight conditions, respectively.

All optimizations are conducted using MACH,[‡‡] an open-source framework for high-fidelity gradient-based optimization. We use the free-form deformation (FFD) method to parameterize the design surface [71] through the pyGeo package.[§§] For volume mesh

[††]Source code available online at https://github.com/mdolab/pyhyp.
[‡‡]Source code available online at https://github.com/mdolab/mach-aero.
[§§]Source code available online at https://github.com/mdolab/pygeo.

Table 4 Adjoint derivatives reasonably match the reference values

Solver	Turbulence model	Reference	Adjoint	Error, %
	ADODG case 3 aerodynamics, Mach number 0.15, $\mathrm{d}C_D/\mathrm{d}\gamma_{40\%} \times 10^{-4}$			
simpleDAFoam	SA	−7.4141337	−7.4143066	0.002
	$k-\varepsilon$	−7.6683056	−7.6684497	0.002
	Realizable $k-\varepsilon$	−7.5622189	−7.5648494	0.035
	$k-\omega$ SST	−7.4261818	−7.4254367	0.010
	$k-\omega$ SSTLM	−7.3058416	−7.3105428	0.064
simpleTDAFoam	SA	−7.4041615	−7.4043562	0.003
buoyantBoussinesqSimpleDAFoam	SA	−7.1222484	−7.1223115	0.001
	ADODG3 wing aerodynamics, Mach number 0.5, $\mathrm{d}C_D/\mathrm{d}\gamma_{40\%} \times 10^{-4}$			
rhoSimpleDAFoam	SA	−7.9530799	−7.9513823	0.021
	$k-\varepsilon$	−8.2006894	−8.2124952	0.144
	Realizable $k-\varepsilon$	−8.1720642	−8.1724885	0.005
	$k-\omega$ SST	−8.0006496	−8.0162433	0.195
	$k-\omega$ SSTLM	−7.9764931	−7.9875446	0.138
buoyantSimpleDAFoam	SA	−7.5714023	−7.5709535	0.006
	ADODG3 wing aerodynamics, Mach number 0.7, $\mathrm{d}C_D/\mathrm{d}\gamma_{40\%} \times 10^{-3}$			
rhoSimpleCDAFoam	SA	−1.4533128	−1.4524513	−0.059
	Rotor 67 blade rotating at $\omega = 840\ \mathrm{rad\cdot s^{-1}}$, $\mathrm{d}\sigma_v^a/\mathrm{d}\omega \times 10^4$			
solidDisplacementDAFoam	—	−9.6106984	−9.6109359	0.002
	Flange heat transfer, $\mathrm{d}\bar{T}/\mathrm{d}T_i \times 10^{-1}$			
laplacianDAFoam	—	3.5956891	3.5956890	< 0.001

The average error is less than 0.1%.
SST = shear-stress transport.

Table 5 Multipoint aerodynamic optimization setup for the low-speed UAV wing, which has 129 design variables and 416 constraints

	Function or variable	Description	Quantity
Minimize	$f = \sum_{i=1}^{3} w^i C_D^i$	Weighted drag coefficients	
With respect to	Δz	Deformation of FFD points in the vertical direction	120
	γ	Twist	6
	α	Angle of attack	3
		Total design variables	129
Subject to	$C_L = 0.6$, 0.75, or 0.9	Lift-coefficient constraints for each flight condition	3
	$t \geq 0.5 t_{\mathrm{baseline}}$	Minimum-thickness constraint	400
	$V \geq V_{\mathrm{baseline}}$	Minimum-volume constraint	1
	$\Delta z_{\mathrm{LE}}^{\mathrm{upper}} = -\Delta z_{\mathrm{LE}}^{\mathrm{lower}}$	Fixed leading-edge constraint	6
	$\Delta z_{\mathrm{TE}}^{\mathrm{upper}} = -\Delta z_{\mathrm{TE}}^{\mathrm{lower}}$	Fixed trailing-edge constraint	6
	$-0.5\ \mathrm{m} < \Delta z < 0.5\ \mathrm{m}$	Design-variable bounds	
		Total constraints	416

deformation, we use an analytic inverse-distance method [72] through the IDWarp package.[¶¶] As in our previous work, we use 120 FFD points to control the local wing shape at six spanwise locations ([69] fig. 5). In addition, the twists at these six spanwise locations are selected to be the design variables along with the angle of attack at the three flight conditions. The root twist is fixed. The total number of design variables is 129. We constrain the lift coefficients for each flight condition. In addition, we limit the local wing thickness to be greater than 50% of the baseline thickness. Finally, we constrain the total volume of the optimized wing to be greater than or equal to that of the baseline wing, and the leading and trailing edges of the wing are fixed. In total, we have 416 constraints for this case. We use SNOPT [73] as the optimizer for all the optimizations in this study through the pyOptSparse interface [74].[***] We set the optimality and feasibility tolerances to 10^{-6}. We run the optimizations until the optimizer either reaches the aforementioned tolerances or aborts due to numerical difficulties to further improve the design. We also manually terminate the optimizations if the objective function changes less than 0.001% in five steps.

The comparison of pressure, spanwise lift, twist, and maximum thickness distributions between the baseline and optimized designs is shown in Fig. 4. The optimization converges in 25 steps, achieving a 3.7% drag reduction. This is lower than the single-point optimization (5.6% drag reduction) reported in our previous work [60], which is expected. However, compared with the previous single-point optimization ([60] fig. 16), the leading edge is less sharp at all spanwise locations, which is better for off-design performance. Similar to the single-point optimization, the optimized design achieves the desired elliptical lift distribution by fine-tuning the twist, thickness, and camber distribution.

B. Trimmed Aerodynamic Optimization of a Transonic Aircraft Configuration

We perform a trimmed aerodynamic shape optimization of an aircraft wing–body–tail configuration. The goal is to demonstrate the optimization capability of DAFoam for complex aircraft configurations at transonic conditions, similarly to our previous efforts [23,24,75,76] using a dedicated Reynolds-averaged Navier–Stokes

¶¶Source code available online at https://github.com/mdolab/idwarp.
***Source code available online at https://github.com/mdolab/pyoptsparse.

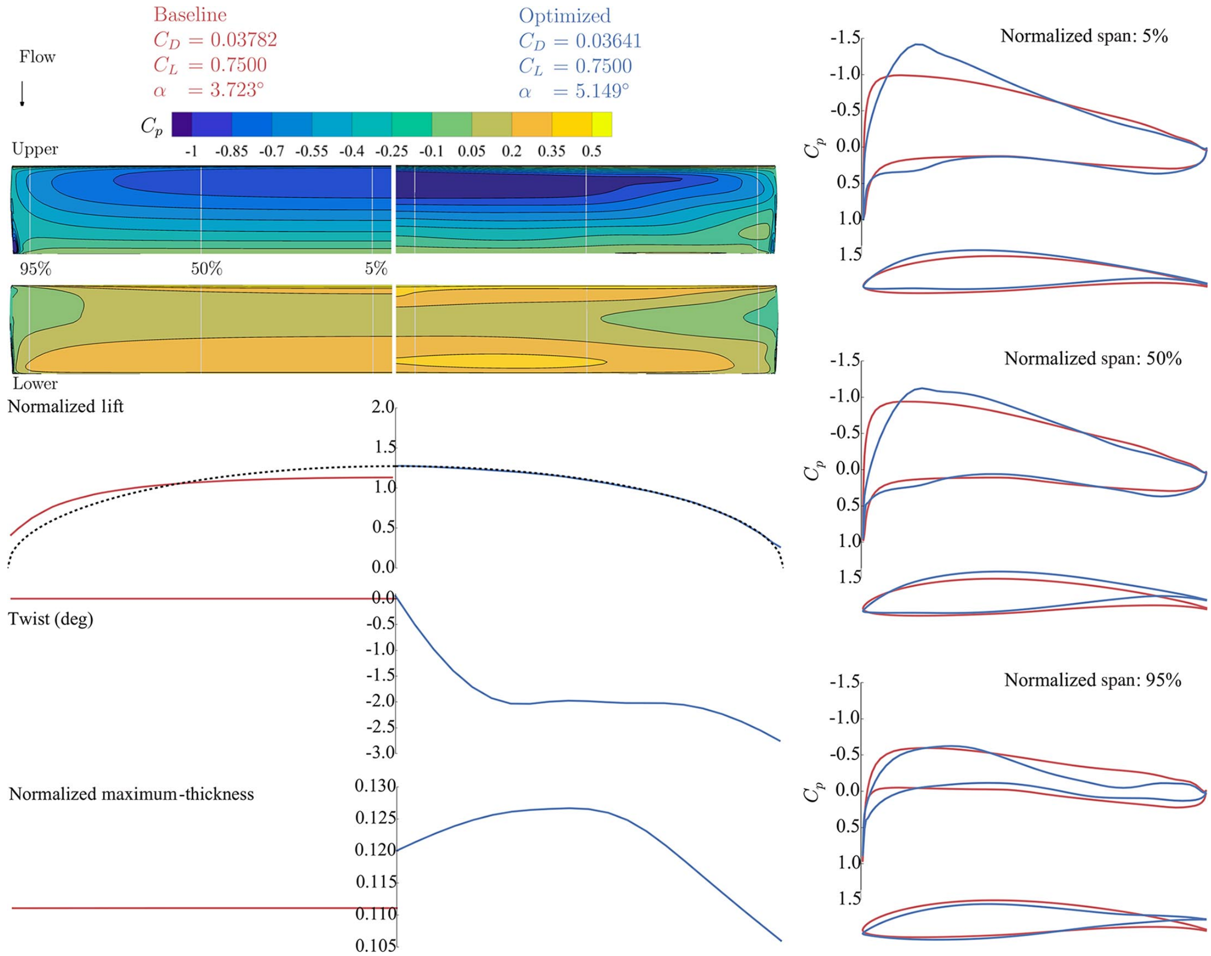


Fig. 4 Multipoint aerodynamic optimization results for the UAV wing; we achieved the desired elliptical lift distribution; the drag is reduced by 3.7%, and the constraints are satisfied.

solver ADflow [33,41]. We use the adjoint solver rhoSimpleCDAFoam, and the governing equations are the compressible NS equations:

$$\nabla \cdot (\rho \boldsymbol{U}) = 0 \tag{9}$$

$$\nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) + \nabla p - \mu_{\text{eff}} \nabla \cdot (\nabla \boldsymbol{U} + \nabla \boldsymbol{U}^T) = 0 \tag{10}$$

$$\nabla \cdot (\rho e \boldsymbol{U}) + \nabla \cdot (0.5\rho |U|^2 \boldsymbol{U} + p\boldsymbol{U}) - \alpha_{\text{eff}} \nabla \cdot (\nabla e) = 0 \tag{11}$$

in which ρ is the density, e is the internal energy, μ is the dynamic viscosity, and α is the thermal diffusivity. The heat and mechanical source terms are ignored. The governing equations (9–11) are solved using the compressible form of the SIMPLEC algorithm [77], which is a modified SIMPLE algorithm for compressible flows.

The aircraft geometry is obtained from the Common Research Model (CRM), which is representative of a modern transonic commercial transport aircraft with a size similar to that of a Boeing 777. This configuration is also known as the Drag Prediction Workshop 4 geometry [78], and was studied in our previous work [23,24,75,76]. The Mach number is 0.85 and the Reynolds number is 5×10^6. We generate unstructured hexahedral meshes with a total of 872,404 cells using the built-in utility snappyHexMesh of OpenFOAM, as shown in Fig. 5. The average y^+ is 307.8.

Table 6 summarizes the trimmed aerodynamic optimization setup. The objective function is C_D. The design variable and constraint setup are similar to our previous work [75,76]. We use 216 FFD points to control the local wing shape at nine spanwise locations (Fig. 5). In addition, the wing twists at these nine spanwise locations are selected to be the design variables, along with the tail rotation and the angle of attack. The root twist is fixed. The total number of design variables is 227. We constrain the lift coefficients to be equal to 0.5 and the pitching moment to be equal to zero. In addition, we limit the local wing thickness to be greater than 20% of the baseline thickness. Finally, we constrain the total volume of the optimized wing to be greater than or equal to that of the baseline wing, and the leading and trailing edges of the wing are fixed. In total, we have 771 constraints for this case.

The comparison of pressure, spanwise lift, wing twist, tail rotation, and maximal thickness distributions between the baseline and optimized geometries is shown in Fig. 6. The optimization converges in 31 steps, achieving 3.6% drag reduction. This is partially achieved by fine-tuning the wing shape and twist distribution to change the spanwise lift closer to the desired elliptical distribution. In addition, the shock wave at the upper wing surface is eliminated in the optimized design, as confirmed by the sectional pressure distributions. By adjusting the tail rotation, the pitching moment changes from −0.08427 (baseline) to −0.00036 (optimized), and the pitching-moment constraint is satisfied.

C. Aerothermal Optimization of a Turbine Internal Cooling Passage

We perform an aerothermal optimization of a turbine internal cooling channel. The goal is to demonstrate the flexibility of DAFoam to handle complex PDEs that involve multiple disciplines. We use the adjoint solver buoyantBoussinesqSimpleDAFoam, and the governing equations are the incompressible NS equations, coupled to heat transfer, buoyancy, and radiation equations:

$$\nabla \cdot \boldsymbol{U} = 0 \tag{12}$$

$$\nabla \cdot (\boldsymbol{U}\boldsymbol{U}) + \frac{1}{\rho}\nabla p - \nu_{\text{eff}} \nabla \cdot (\nabla \boldsymbol{U} + \nabla \boldsymbol{U}^T) - \rho g = 0 \tag{13}$$

$$\nabla \cdot (T\boldsymbol{U}) - \alpha_{\text{eff}} \nabla \cdot (\nabla T) + \frac{aG - 4e\sigma T^4}{\rho C_p} = 0 \tag{14}$$

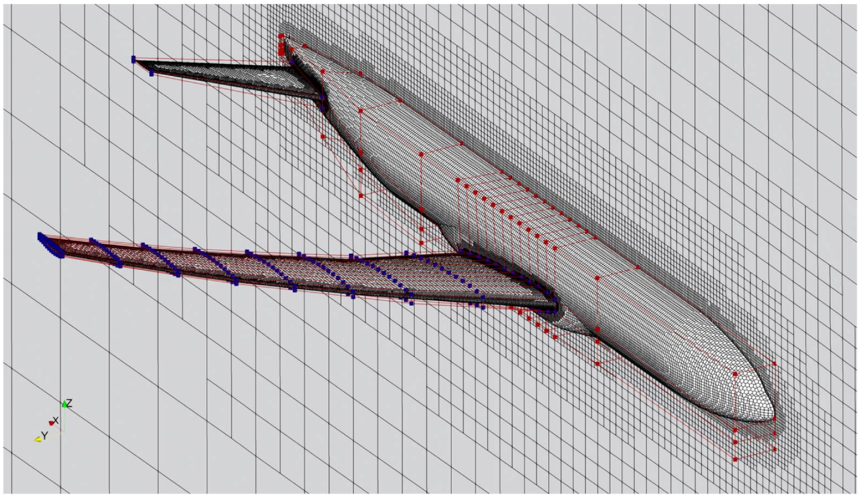


Fig. 5 Unstructured hexahedral mesh for the CRM wing–body–tail case; the squares are the FFD control points to morph the design surface geometry; only the blue FFD points are allowed to move.

$$\gamma\nabla\cdot(\nabla G) - aG + 4e\sigma T^4 = 0 \tag{15}$$

in which g is the gravitational acceleration, T is the temperature, C_p is the specific heat at constant pressure, and σ is the Stefan–Boltzmann constant. We use the P1 radiation model [79], in which a and e are the absorption and emission coefficients, respectively, and G is the incident radiation intensity. The emission contribution and scattering are ignored.

The baseline geometry is a U-bend channel benchmark, representative of a section of serpentine internal cooling passages [80]. It has a square cross section with a hydraulic diameter $D_h = 0.075$ m, and an upstream section going from $x = 0$ (inlet) to $x = 10D_h$, a 180 degree bend section, and a downstream section from $x = 10D_h$ back to $x = 0$ (outlet); refer to ([26] fig. 4). We generate a structured mesh with 409,600 cells using the built-in utility blockMesh of OpenFOAM. The average y^+ is 1.3. The Reynolds number is 4.2×10^4, based on D_h. In our previous work, we performed aerothermal optimization of the same U-bend channel [26]. In this subsection, we consider a case that adds buoyancy and radiation effects. We add the gravitational acceleration $g = (-9.81, 0, 0)$ in the streamwise direction, and use a 10 K temperature difference between the mainstream and the walls to drive heat transfer.

The objective function is a combination of total pressure loss coefficient C_{PL} and average Nusselt number $\overline{Nu}$, and their weights are 0.2 and –0.8, respectively. We use 63 FFD points to morph the bend section, and we have 113 degrees of freedom (design variables) in total ([26] fig. 5). To ensure practical shape, we impose 38 geometry constraints, as shown in Table 7. More detailed optimization configurations can be found in He et al. [26].

Figure 7 compares the velocity and Nusselt number of the baseline and optimized designs. The optimization converges in 34 steps. We obtain a simultaneous improvement for aerodynamics (20.5% reduction in C_{PL}) and heat transfer (5.6% increase in Nusselt number). Similar to what we observed in a previous work [26], the aerodynamic loss reduction is primarily achieved by creating a smoother U-bend section that reduces the flow separation, as evident in the velocity contour and streamline comparison. In addition, the channel shrinks before and after the U-bend section, which increases the velocity magnitude and the convective heat transfer, as shown in the local Nusselt number contours and the streamwise Nusselt number distributions. However, we observe a smaller separation bubble in the baseline design compared with the previous work ([26] fig. 11a), for which buoyancy and radiation were not included. In addition, we obtain higher reduction in aerodynamic loss (20.5% compared with 11.7% [26]), although a small separation region is present in the optimized design.

D. Aerostructural Optimization of an Axial Compressor Rotor

We perform an aerostructural optimization of an axial compressor rotor. The goal is to demonstrate the capability of DAFoam to integrate two adjoint solvers (flow and structural analyses) for MDO. These two adjoint solvers are rhoSimpleDAFoam and solidDisplacementDAFoam. The governing equations for rhoSimpleDAFoam are the compressible NS equations, written in the multiple-reference-frame form:

Table 6 Trimmed aerodynamic optimization setup for the CRM wing–body–tail configuration, which has 227 design variables and 771 constraints

	Function or variable	Description	Quantity
Minimize	C_D	Drag coefficients	
With respect to	Δz	Displacement of FFD points in the vertical direction	216
	γ	Wing twist	9
	η_{tail}	Tail rotation	1
	α	Angle of attack	1
		Total design variables	227
Subject to	$C_L = 0.5$	Lift-coefficient constraint	1
	$C_M^y = 0$	Pitching-moment constraint	1
	$t \geq 0.2t_{\mathrm{baseline}}$	Minimum-thickness constraint	750
	$V \geq V_{\mathrm{baseline}}$	Minimum-volume constraint	1
	$\Delta z_{\mathrm{LE}}^{\mathrm{upper}} = -\Delta z_{\mathrm{LE}}^{\mathrm{lower}}$	Fixed leading-edge constraint	9
	$\Delta z_{\mathrm{TE}}^{\mathrm{upper}} = -\Delta z_{\mathrm{TE}}^{\mathrm{lower}}$	Fixed trailing-edge constraint	9
	$-10\text{ m} < \Delta z < 10\text{ m}$	Design-variable bounds	
		Total constraints	771

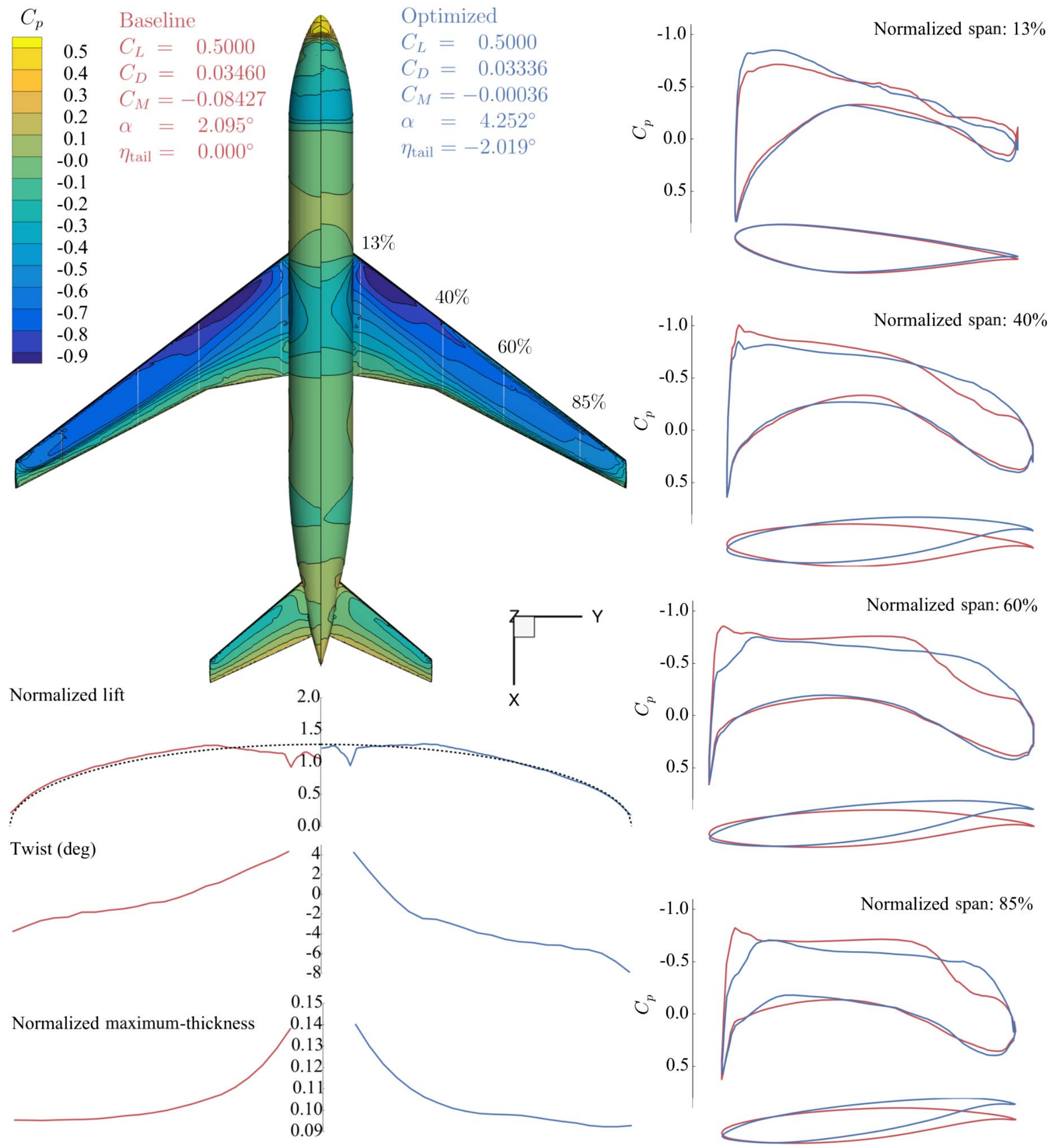


Fig. 6 Trimmed aerodynamic optimization results for the CRM wing–body–tail configuration; the drag is reduced by 3.6%, and the constraints are satisfied.

$$\nabla \cdot (\rho \boldsymbol{U}_r) = 0 \tag{16}$$

$$\nabla \cdot (\rho \boldsymbol{U}_r \boldsymbol{U}_a) + \boldsymbol{\omega} \times \boldsymbol{U}_a + \nabla p - \mu_{\text{eff}} \nabla \cdot (\nabla \boldsymbol{U}_a + \nabla \boldsymbol{U}_a^T) = 0 \tag{17}$$

$$\nabla \cdot (\rho e \boldsymbol{U}_r) + \nabla \cdot (0.5 \rho |U|_a^2 \boldsymbol{U}_r + p \boldsymbol{U}_r) - \alpha_{\text{eff}} \nabla \cdot (\nabla e) = 0 \tag{18}$$

in which $\boldsymbol{U}_a$ and $\boldsymbol{U}_r$ are the absolute and relative velocities, respectively, and they are related through $\boldsymbol{U}_a = \boldsymbol{U}_r + \boldsymbol{\omega} \times \boldsymbol{x}$ with $\boldsymbol{\omega}$ being the rotational speed vector and $\boldsymbol{x}$ being the cell-center coordinate vector. The preceding governing equations are solved using the compressible form of SIMPLE algorithm based on the absolute velocity in the stationary frame; however, the flux for the convective term in the momentum (17) and energy (18) equations are computed using the relative velocity in the rotating frame.

The governing equations for solidDisplacementDAFoam are the linear elastic equations with the centrifugal force:

$$\frac{\partial^2 \rho \boldsymbol{D}}{\partial t^2} - \nabla \cdot (\mu \nabla \boldsymbol{D} + \mu \nabla \boldsymbol{D}^T + \lambda \boldsymbol{I} \text{tr}[\nabla \boldsymbol{D}]) - \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{x}) = 0 \tag{19}$$

Table 7 Aerothermal optimization setup for the turbine internal cooling channel, which has 113 design variables and 38 constraints

	Function or variable	Description	Quantity
Minimize	f	Weighted C_{PL} and $\overline{Nu}$	
With respect to	Δx, Δy, and Δz	Displacement of FFD points	113
Subject to	$g_z^{\text{sym}} = 0$	Zero slope at symmetry plane	29
	$\Delta y_{\text{in}1} + \Delta y_{\text{in}2} > t_{\min}$	Nonoverlapping inner walls	9
	Bound (Δx, Δy, Δz)	Design-variable bounds to confine the design surfaces within the bounding box	
		Total constraints	38

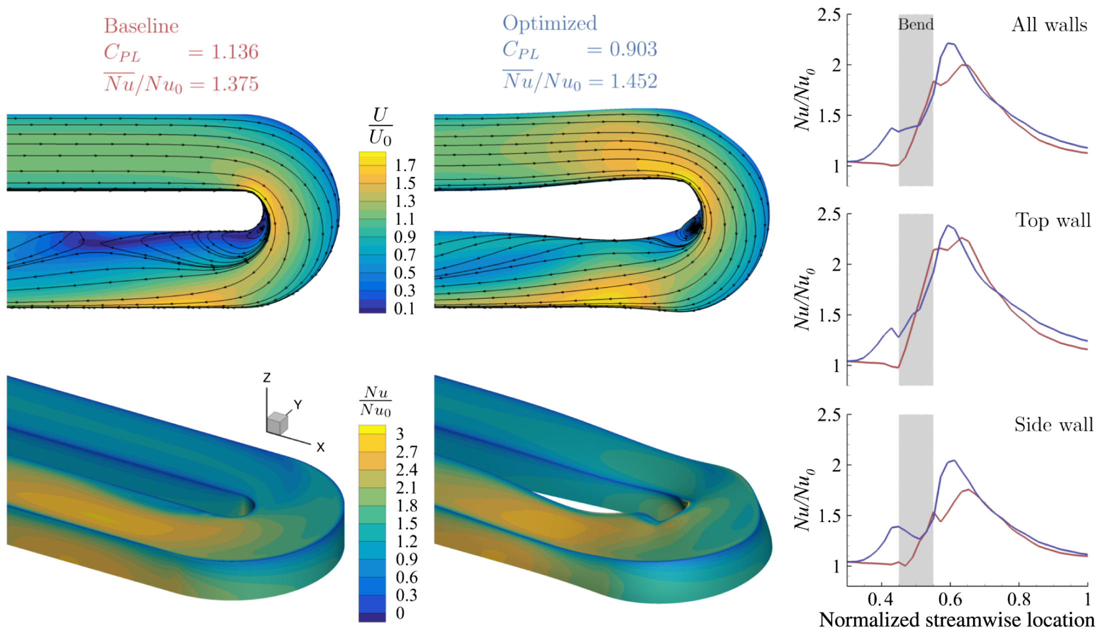
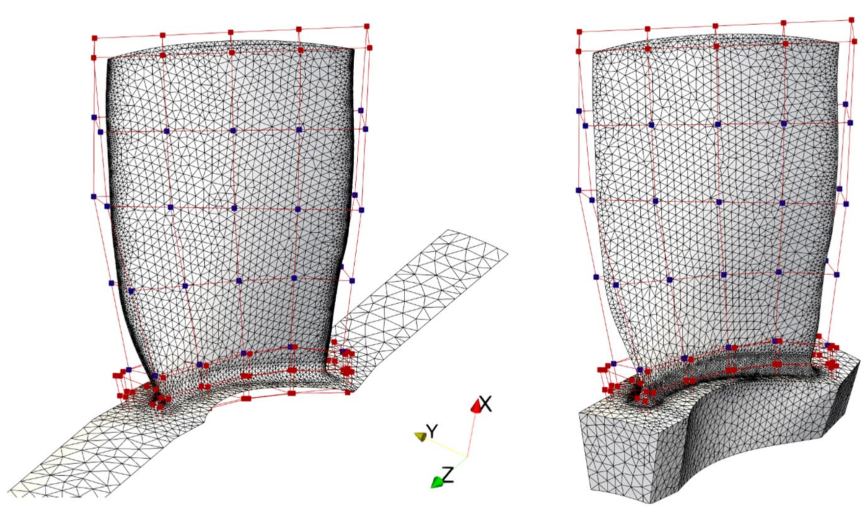


Fig. 7 Aerothermal optimization results for the turbine internal cooling channel, where simultaneous improvements for the aerodynamics and heat transfer are achieved.



a) Fluid **b) Solid**

Fig. 8 Unstructured triangular meshes for the Rotor 67 case; the squares are the FFD control points to morph the design surface geometry; only the blue FFD points are allowed to move.

in which $\boldsymbol{D}$ is the structural displacement, t is the time, $\boldsymbol{I}$ is a 3×3 identity matrix, tr denotes the trace of a matrix, and μ and λ are the Lamé constants for the material. The governing equations are solved by time marching the solutions until the steady state is reached. At each time step, the three components of structural displacement vector are solved in a segregated manner.

The baseline geometry is Rotor 67, which has 22 blades with a tip radius R_T of 255.4 mm and an aspect ratio of 1.56 [66]. We consider the no tip-clearance configuration and run the simulations at 50% design speed ($840\,\mathrm{rad} \cdot \mathrm{s}^{-1}$) with a total pressure ratio $p_0^{\mathrm{out}}/p_0^{\mathrm{in}} = 1.1$. The inlet absolute Mach number is 0.29 and the chordwise Reynolds number is 8.5×10^5. We simulate only one blade with rotationally periodic boundary conditions. We find that the contribution of the pressure force to the maximum stress is one order of magnitude lower than that of the centrifugal force. Therefore, the pressure load is ignored, and the only external force for the

Table 8 Aerostructural optimization setup for the Rotor 67 case, which has 120 design variables and 3 constraints

	Function or variable	Description	Quantity
Minimize	C_M^z	Normalized torque	
With respect to	Δx, Δy, Δz	FFD displacement in the x, y, and z directions	120
Subject to	$\dot{m} = \dot{m}_{\mathrm{baseline}}$	Constant mass flow rate	1
	$p_0^{\mathrm{out}}/p_0^{\mathrm{in}} = [p_0^{\mathrm{out}}/p_0^{\mathrm{in}}]_{\mathrm{baseline}}$	Constant total pressure ratio	1
	$\sigma_v^a \le [\sigma_v^a]_{\mathrm{baseline}}$	von Mises stress constraint	1
	$-2\ \mathrm{mm} < (\Delta x, \Delta y, \Delta z) < 2\ \mathrm{mm}$	Design-variable bounds	
		Total constraints	3

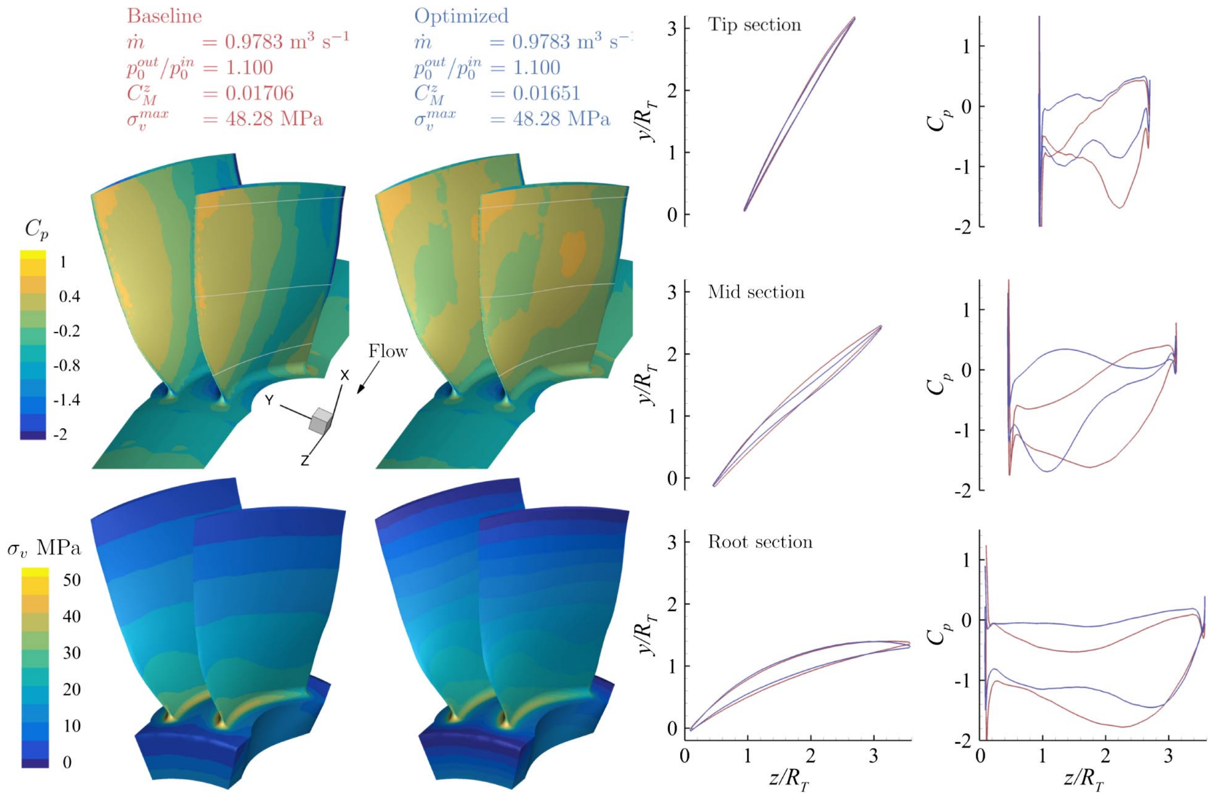


Fig. 9 Aerostructural optimization results for the Rotor 67 case; the torque is reduced by 3.2%, and the constraints are satisfied.

blade structure is the centrifugal force due to rotation. In addition, the maximum blade structural displacement is less than 0.01 mm. Therefore, we assume that the blade is rigid, and therefore, the fluid–structure interaction is ignored. As shown in Fig. 8, we use ANSYS ICEM-CFD to generate a triangular unstructured mesh with 361,256 cells for the fluid domain with an average y^+ of 224.4, and a 94,711-cell mesh for the solid domain.

Table 8 summarizes the aerostructural optimization setup. The objective function is the normalized torque C_M^z. We use 40 FFD points to morph the shape of the rotor blade, as shown in Fig. 8. These FFD points can move in the x, y, and z directions, for a total of 120 design variables. The FFD point displacements between the fluid and solid domains are identical. To ensure that the optimized design satisfies the aerodynamic coupling for the other compressor components, we constrain the mass flow rate $\dot{m}$ and total pressure ratio to be equal to their baseline values, similar to Wang et al. [81]. In addition, we impose a stress constraint to force σ_v^a to be less than or equal to the baseline value to avoid structure failure. As mentioned previously, σ_v^a is a conservative approximation of the maximum von Mises stress.

Figure 9 shows the comparison of pressure and stress distributions between the baseline and optimized designs. The optimization converges in 20 steps and achieves a 3.2% reduction in torque. This is primarily achieved by fine-tuning the blade shape, and therefore, the pressure distribution. For example, we observe that the aft-loaded pressure distribution in the baseline design is shifted forward, especially at the midspan. In addition, the change in blade shape is a compromise between aerodynamic and structural considerations; the mass flow rate, total pressure ratio, and maximal stress constraints are well satisfied in the aerostructural optimization.

IV. Conclusions

In this paper, an open-source object-oriented framework (DAFoam) is proposed to rapidly implement the discrete adjoint method for any of the steady-state primal solvers in OpenFOAM. This can be accomplished by adding or modifying only a few hundred lines of source code. The central recipe in the proposed approach is to use a generalized framework for partial derivative computation and adjoint equation solution, and then provide a high-level interface to add the solver-specific implementations.

For the solver-agnostic adjoint implementation, DAFoam uses the finite difference method to compute the partial derivatives, accelerated by a heuristic parallel graph coloring scheme. The adjoint equations are then solved using the GMRES method. For the solver-specific part, DAFoam provides an object-oriented interface that requires developers to specify only the functions to compute the residuals along with names of state variables and stencil levels. The residuals are computed by reusing the FVM objects that have been already defined in the OpenFOAM primal solvers. This convenient feature allows users to easily construct the residual functions without specific knowledge of their low-level implementations.

Using the aforementioned strategy, the adjoint method is implemented for eight primal solvers, five turbulence models, and one radiation model. These adjoint implementations exhibit excellent scalability with up to 10 million cells and 1536 CPU cores. The runtime ratio between adjoint and flow computations ranges from 1.7 to 2.2, and the average error in the adjoint derivatives is less than 0.1%.

Finally, the implemented adjoint solvers and models are integrated into a gradient-based optimization framework MACH, and four distinct design optimizations are performed that involve aerodynamics, heat transfer, structures, and radiation. Performance improvements for all of these four cases are obtained: 3.7% drag reduction for the multipoint aerodynamic optimization of the UAV wing, 3.6% drag reduction for the aerodynamic optimization of CRM wing–body–tail configuration, 20.5% reduction in aerodynamic loss and 5.6% increase in heat transfer for the aerothermal optimization of the U-bend cooling passage, and 3.2% torque reduction for the aerostructural optimization of the Rotor 67 blade. The optimization setup for these cases, including the meshes, flow and optimization configurations, and run scripts, are publicly available [55].

DAFoam is available under an open-source license and is a powerful tool for the high-fidelity MDO of engineering systems, such as aircraft, ground vehicles, marine vessels, and turbomachinery.

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