

Aeroelastic Trim Drag Optimization of Mach 0.745 Transonic Truss-Braced Wing Aircraft with Variable-Camber Continuous Trailing-Edge Flap

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This paper presents an aeroelastic trim drag optimization study of the Mach 0.745 Transonic Truss-Braced Wing (TTBW) aircraft with the Variable-Camber Continuous Trailing-Edge Flap (VCCTEF). An aero-structural analysis solver VSPAERO with transonic small disturbance, integral boundary-layer, and wing-strut interference corrections coupled to finite-element code BEAM3D is developed to provide a rapid aircraft aeroelastic performance evaluation. The VSPAERO model has been validated against wind tunnel test data. Aeroelastic trim drag optimization studies are conducted for a VCCTEF configuration with 6-spanwise sections. Three different flight conditions corresponding to Mach 0.745 are selected for the TTBW aircraft aeroelastic trim drag optimization at the design and off-design cruise lift coefficients. The preliminary optimization results show that the TTBW aircraft with the optimized VCCTEF deflection achieves a drag reduction of about 9.1 counts, 5.9 counts, and 11.8 counts corresponding to the lift coefficients 0.68, 0.73, and 0.78, respectively. A high-fidelity CFD solver FUN3D is used to validate the aeroelastic trim drag optimization.

I. Introduction

The aircraft industry has been responding to the need for more energy-efficient aircraft by redesigning airframes to be aerodynamically and structurally more efficient. The Transonic Truss-Braced Wing (TTBW)^{1,2,3} aircraft shown in Figure 1 is designed to be aerodynamically efficient by employing an aspect ratio of about 19.55, which is significantly greater than those of conventional aircraft cantilever wings. The main idea is to use truss structures to alleviate the wing root bending moment, so that a significant increase in the wing aspect ratio could be afforded. The main wings are braced at approximately mid-span by two main struts. In addition, two jury struts, one on each wing, provide additional reinforcement. The additional braced structures cause some aerodynamic impacts to the wing. The design of a truss-braced wing is a Multidisciplinary Design Analysis and Optimization (MDAO) process that strives to achieve a delicate balance between aerodynamic and structural efficiencies. The MDAO studies have been conducted at each stage to improve the wing aerodynamics, structural efficiency, and flight performance using advanced N+4 turbofan engines. These MDAO studies have refined the geometry of the wing and configuration layout and have involved trade studies involving minimizing induced drag, profile drag, and wave drag due to the addition of the main strut and jury struts. Another option for managing the aeroelastic behavior of the aircraft is through control system design. The control system could be made to both suppress undesirable motion and shape the flexible structure in pursuit of improved performance goals.

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Figure 1 Boeing SUGAR Transonic Truss-Braced Wing (TTBW) Aircraft Concept

The concept of variable-camber continuous trailing-edge flap (VCCTEF) concept developed by NASA was proposed by Nguyen in 2010.^{4,5} The use of VCCTEF for the active control of an aeroelastic wing such as suppressing flutter, stabilizing the vehicle response to gusts, and reducing drag have been studied.^{6,7,8,9} Nguyen et al.⁶ first demonstrated the Common Research Model (CRM) real-time drag optimization wind tunnel experiment using VCCTEF at low speed. Lebofsky et al.⁷ conducted a maneuver load alleviation study with the VCCTEF for the TTBW aircraft. Ting et al.⁸ conducted a drag optimization study using NASA generic transport model (GTM) with VCCTEF. Up to 8.4% drag reduction can be achieved using a parabolic flap deflection profile configuration with three-cambered-segments. Bartels et al.⁹ utilized the VCCTEF with feedback control system to enhance the aeroelastic stability and performance of the TTBW aircraft. Nguyen et al.¹⁰ conducted aerodynamic optimization for the Mach 0.745 TTBW aircraft 1g shape with the VCCTEF. In a recent study,¹⁰ three different VCCTEF configurations with 6-, 10-, and 21-spanwise sections, respectively were utilized. The optimization results show that the 21-spanwise sections VCCTEF has the largest absolute drag coefficient reduction, however, the 6-spanwise sections VCCTEF provides a relatively better solution for drag reduction when the actuator weight penalty is considered. The study indicates the VCCTEF system offers potential payoff in drag reduction by actively controlling the shape of the wing for the TTBW aircraft.

This paper presents an aeroelastic trim drag optimization study of Mach 0.745 TTBW aircraft with a 6-spanwise section VCCTEF configuration at three different flight conditions. A simple VCCTEF actuator weight model based on aircraft data is used to estimate the weight penalty of the actuator in the design. An aero-structural analysis solver VSPAERO with transonic small disturbance, integral boundary-layer, and wing-strut interference corrections coupled to finite-element code BEAM3D is developed to provide a rapid aircraft aeroelastic performance evaluation. A high-fidelity CFD solver FUN3D is used to validate the VCCTEF optimization.

II. Aero-Structural Model of the Transonic Truss-Braced Wing

A. VSPAERO Model

In order to develop a rapid aeroelastic analysis that facilitates a vehicle MDAO process, a lower-fidelity aerodynamic model of the TTBW is necessary. VSPAERO is a solver that includes both the vortex lattice method and the full panel method based on generalized vortex rings. The core VSPAERO solver is based on an agglomerated multi-pole approach, coupled with a preconditioned linear solver, to reduce solution times. Adaptive wakes, time-accurate, unsteady analyses, and propeller modeling are all supported. The VSPAERO based tool has been implemented with a 2D transonic and viscous flow corrections via the TSD/IBL method and transonic wing-strut interference correction. More details about the develop tool can be found in Ref.¹⁰.

B. Finite-Element BEAM3D Model

BEAM3D is an in-house finite-element code that is used to model a general wing structure using beam, rod, and rigid elements. The code contains a number of analysis modules: a static deflection analysis module, an eigenvalue analysis module, a flutter analysis module, and an aeroservoelastic flight dynamic simulation module. The static deflection analysis module can be coupled to a flow solver such as VORLAX, VSPAERO, or CART3D to perform aero-structural and static aeroelastic deflection analyses. The eigenvalue analysis module computes the structural dynamic frequencies and the normal mode shapes of a wing structure. The flutter analysis module computes the frequencies and damping of the wing aeroelastic modes and performs a flutter speed search in the frequency domain using the Theodorsen's theory for unsteady aerodynamics or in the time domain using the R. T. Jones approximation to generate the aerodynamic mass, damping, and stiffness matrices. The aeroservoelastic flight dynamic simulation module provides the capability to couple the dynamic aeroservoelastic state-space model of a wing structure to a nonlinear 6-degree of freedom flight dynamic model of an aircraft to perform time-accurate simulations of the aircraft response to atmospheric gust inputs and flight control surface inputs.

Figure 2 illustrates the TTBW finite-element model in BEAM3D. The left wing and main strut are modeled as the major structural elements. The jury strut is neglected in the model as its contribution is marginal. The mass and structural properties of the finite-element model are made available to NASA by Boeing.¹¹ The stiffness properties and the elastic definition of the wing and strut are included in the structural properties. Boeing also provides a full 3D NASTRAN model of the Mach 0.745 TTBW. This NASTRAN is used to validate the BEAM3D model. The full fuel weight corresponds to a take-off gross weight (TOGW) of 138,000 lbs. The inertias of the fuselage and tails are estimated in VSPAERO. There are 43 elements used for the wing and 32 elements used for the strut.

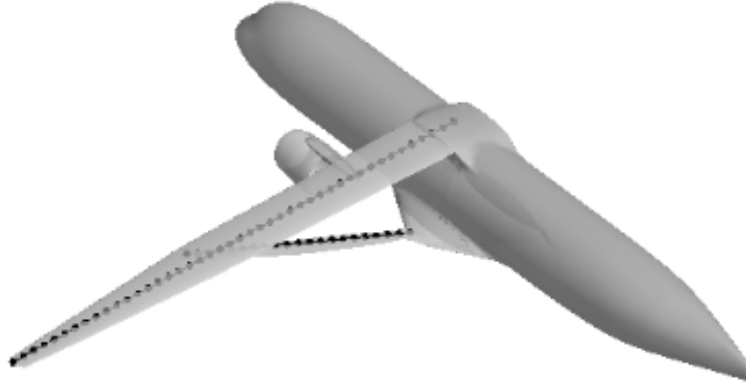


Figure 2 Finite Element Model of the Truss-Braced Wing

BEAM3D includes the nonlinear capability to model the tension-induced stiffening effect of the struts, which contributes to the overall stiffness matrix of the finite-element model. This is expressed as:¹²

$$K_i(x) = K_i^s + K_i^a + K_i^t(x), \quad (1)$$

where K_i is the total element stiffness matrix of the i -th element, K_i^s is the element structural stiffness matrix, K_i^a is the element aerodynamic stiffness matrix, and K_i^t is the element nonlinear stiffness matrix due to the strut tension, which is dependent on the displacement field $x(t)$ of the structure. The aerodynamic stiffness is computed from Theodorsen's theory and depends on the dynamic pressure, wing section lift curve slope, and other pertinent unsteady aeroelastic parameters.

C. Static Aeroelastic Analysis

For static aeroelastic analysis, an iterative solution method is implemented for the nonlinear tension-induced stiffness, as shown in Fig. 3. At each iteration between the VSPAERO model and the BEAM3D model, the iterative solution method iterates on the static deflection until it converges.

A static aeroelastic analysis is performed for the TTBW jig shape geometry. This jig shape geometry is based on an optimized flight jig twist study. The optimized flight jig twist from this study is applied to the original jig twist OML provided by Boeing.¹³ The VSPAERO model of the TTBW jig shape geometry with all the corrections is coupled to the BEAM3D model. Figure 4 shows the linear and nonlinear static aeroelastic deflections of the wings at Mach 0.745 and the design lift coefficient $C_L = 0.73$ computed by BEAM3D. For comparison, the linear static aeroelastic deflections are also computed in the Boeing 3D NASTRAN model of the Mach 0.745 TTBW configuration using the aerodynamic loads computed from the VSPAERO model upon convergence. Except for a minor discrepancy near the wing root, the linear static solutions of the wing bending deflection computed by NASTRAN and BEAM3D are in excellent agreement. The wing tip deflection at cruise is computed to be 23.3 inches by BEAM3D and 23.2 inches by NASTRAN. The nonlinear static solution of the wing tip deflection is computed to be 22.8 inches. Thus, the nonlinear tension-induced stiffening does not significantly alter the static aeroelastic deflections.

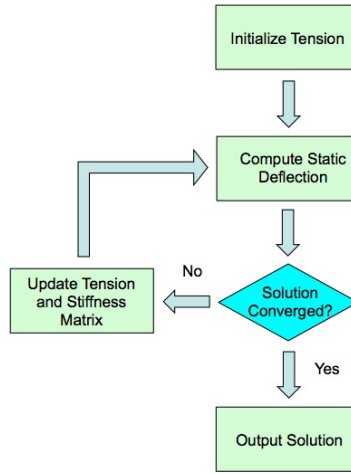


Figure 3 Iterative Solution for Nonlinear Finite-Element Model of Strut Tension Stiffening

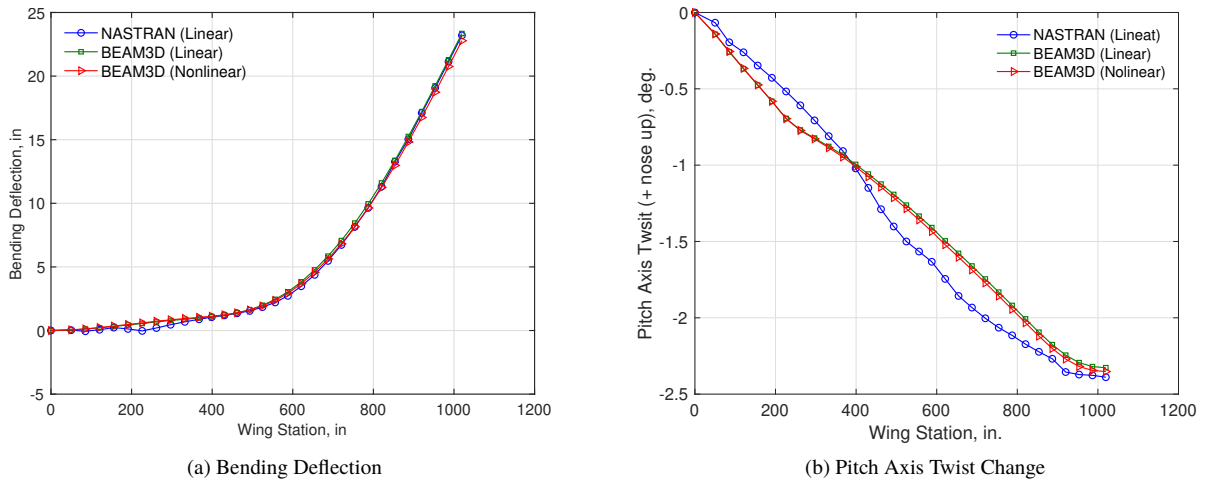


Figure 4 TTBW Wing Bending Deflection and Twist Change at Mach 0.745, $Re = 11.9 \times 10^6$, and $C_L = 0.73$

The wing twists about the aircraft pitch axis shown in Figure 4(b), or the y-axis, computed by BEAM3D and NASTRAN are in general agreement, but discrepancies do exist along the wing span. The wing twist computed by

NASTRAN is higher than that computed by BEAM3D by at most 0.3° outboard of the wing station and is lower than that computed by BEAM3D by at most 0.2° inboard of this wing station. These discrepancies could be due to the application of the distributed lift and pitching moment about the elastic axis in NASTRAN not being precisely on the elastic axis but rather along the nearest nodes. The overall wing twist at the tip is in better agreement between NASTRAN and BEAM3D with the NASTRAN computed value of -2.39° and BEAM3D computed values of -2.35° and -2.33° , corresponding to the linear and nonlinear static solutions, respectively.

Figure 5 shows the strut axial displacement and tension computed by BEAM3D as a function of the wing station at the design lift coefficient $C_L = 0.73$. The axial displacement of the struts is almost 0.6 inches and the tension carried by the strut is about 171,000 lbs.¹²

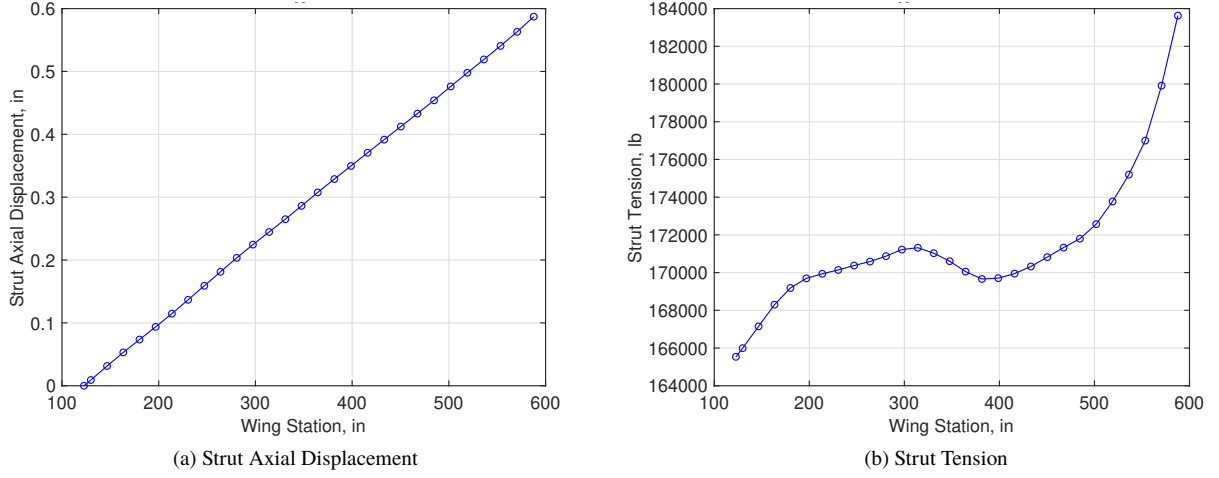


Figure 5 TTBW Strut Axial Displacement and Tension at Mach 0.745, $Re = 11.9 \times 10^6$, and $C_L = 0.73$

The VLM model is coupled to the transonic and viscous corrections as well as the BEAM3D model for the aero-structural iterations via the panel incidence angle using the following relationship:

$$\tilde{\alpha}_{inc}(y) = \alpha_{inc}(y) + \phi_y(y) + \gamma(y), \quad (2)$$

where $\tilde{\alpha}_{inc}$ represents the effective panel incidence angle along the wing span, α_{inc} is the jig shape incidence angle, and ϕ_y is the elastic twist about the pitch axis. The VSPAERO and BEAM3D models are iterated until the tip twist converges, typically after 2-5 iterations. If TSD/IBL coupling is not present, the virtual twist angle, $\gamma(y)$, is zero and plays no role in the aero-structural coupling; however, if both aero-structural and TSD/IBL coupling are desired, the tip twist convergence is calculated for each TSD/IBL iteration at the new virtual twist angle.

A basic schematic of the full aeroelastic modeling strategy is depicted by Figure 6. This process is used to generate the data presented in Figure 7, which shows the lift and drag coefficients computed by the VSPAERO model of the TTBW jig shape geometry coupled to the BEAM3D model. For comparison, the lift and drag coefficients computed by the VSPAERO model of the TTBW cruise 1g shape geometry and the wind tunnel data are also plotted. The lift and drag coefficients computed by VSPAERO coupled with the BEAM3D model of the TTBW jig shape geometry agree very well with the VSPAERO model of the cruise shape TTBW geometry and the wind tunnel data. The close agreements with wind tunnel data provide confidence in the in-house developed aero-structural analysis solver for the TTBW aircraft design.

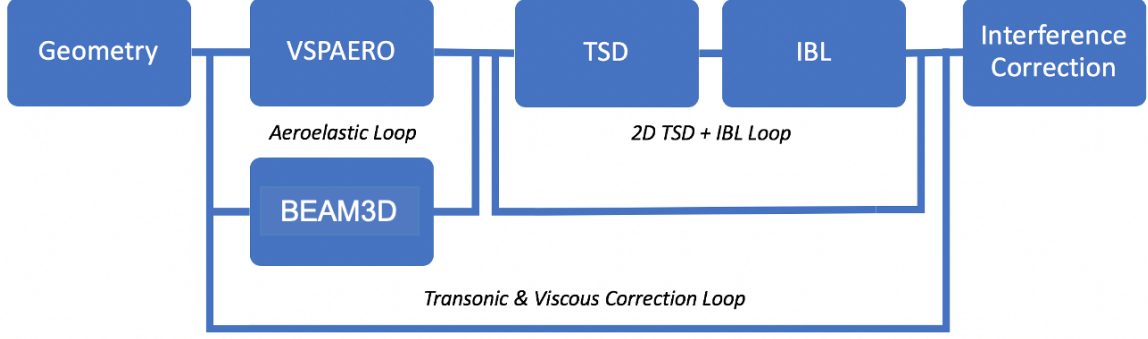


Figure 6 Full Aeroelastic Modeling Scheme

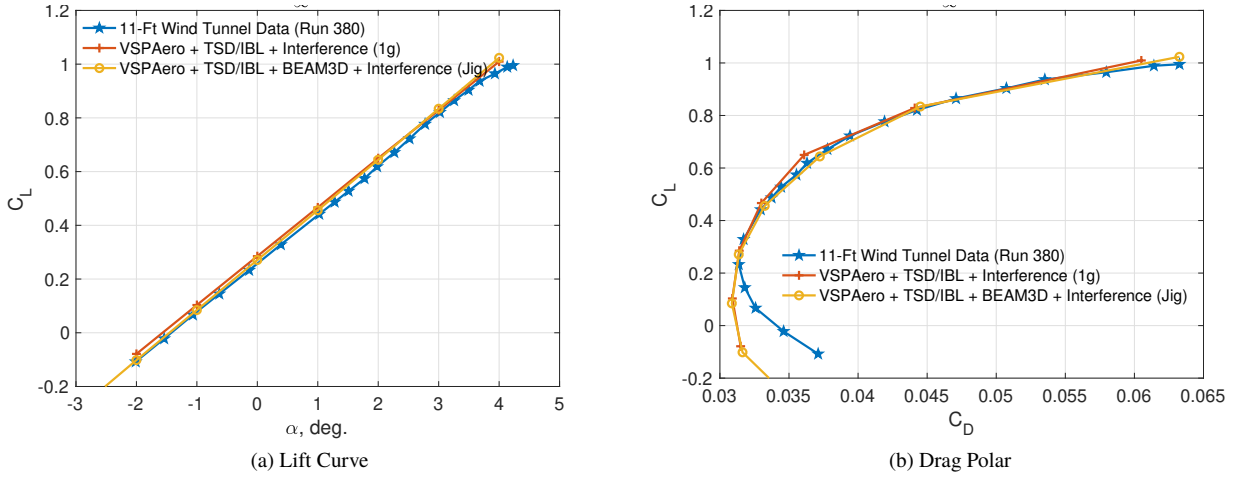


Figure 7 TTBW Lift Curve and Drag Polar at Mach 0.745 and $Re = 2.6 \times 10^6$

III. Aeroelastic Trim Drag Optimization Study

A. Aeroelastic Trim Drag Optimization

The goal of the optimization scheme is to minimize the trim drag coefficient of the jig shape geometry for the TTBW aircraft at three different flight conditions via changing VCCTEF deflections. The baseline of the aeroelastic trim drag optimization is the flight-optimized jig OML geometry, which is optimized from the jig OML geometry.¹³ The jig OML geometry of the Mach 0.745 TTBW configuration comes with a pre-twist wing geometry designed for a wind tunnel test, which is not suitable for generating a model of full-scale aerodynamic performance. The cost function is defined as:

$$J(\alpha, \delta_i, \delta_h) = C_D + \lambda_1(C_L^* - C_L) + \lambda_2(C_m^* - C_m - \frac{Tz_e}{q_\infty S \bar{c}}) \quad (3)$$

where λ_1 and λ_2 are the adjoint variables, δ_h is the horizontal tail incidence angle, T is the engine thrust which is equal to the drag force, z_e is the offset of the thrust centerline from the aircraft center of gravity (CG), q_∞ is the dynamic pressure, S is the wing reference area, $\bar{c}$ is the mean aerodynamic chord (MAC), C_L^* is the design lift coefficient and C_m^* is the zero trim pitching moment coefficient. δ_i represents the VCCTEF deflections along the spanwise direction, i is the

index of the VCCTEF. The lift and pitching moment constraints are added to the optimization algorithm. The pitching moment contribution by the engine thrust is included. Three different lift coefficients $C_{L_1} = 0.68$, $C_{L_2} = 0.73$, and $C_{L_3} = 0.78$ are selected in the aeroelastic trim drag optimization, which correspond to the 20% fuel, 50% fuel, and 80% fuel flight conditions.

The steepest descent algorithm for updating the design variables can be represented by the following equations:

$$\alpha_{k+1} = \alpha_k - \epsilon \frac{\partial J}{\partial \alpha} \quad (4)$$

$$\delta_{i_{k+1}} = \delta_{i_k} - \epsilon \frac{\partial J}{\partial \delta_i} \quad (5)$$

$$\delta_{h_{k+1}} = \delta_{h_k} - \epsilon \frac{\partial J}{\partial \delta_h} \quad (6)$$

Here, the design variable at iteration k is updated based on the partial derivative of the cost function with respect to the design variable, which is calculated using a small-perturbation, second-order central difference scheme, and ϵ is a step size term.

Since the 6-spanwise section VCCTEF configuration provides a relatively better solution than the other VCCTEF configurations for drag reduction when the actuator weight penalty is considered,¹⁰ only the 6-spanwise sections VCCTEF configuration is utilized in this aeroelastic trim drag optimization. The planform of the 6-VCCTEF configuration is shown in Fig. 8. Figure 9 shows a NASA supercritical SC(2) transonic airfoil illustrated with a 2-cambered segment VCCTEF as the exact TTBW airfoil cannot be shown. The deflection angle is positive when the flap is deflected downward. The deflection angle of the outer cambered segment is independent of the inner cambered segment deflection. The total number of the design deflection angles is 12.

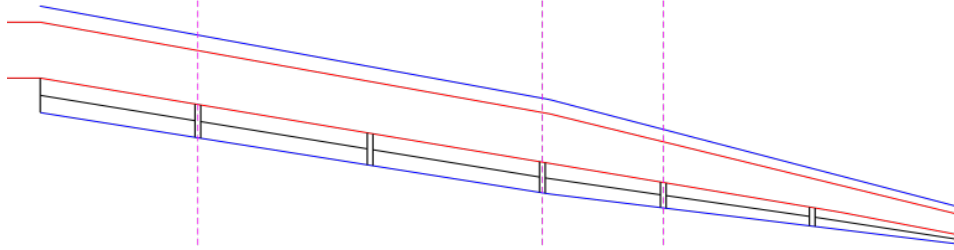


Figure 8 6-spanwise Sections VCCTEF Configuration

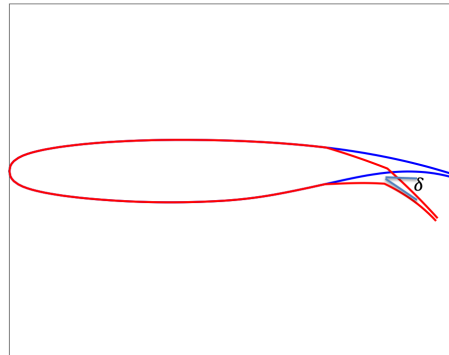


Figure 9 2-Cambered Segment VCCTEF

B. VCCTEF Actuator Weight Model

In order to trade the drag reduction benefit of the VCCTEF against the weight increase in the actuator system, a representative actuator weight model is developed. The weight of a control surface is due to both the structural weight of the control surface and the weight of the servo-actuator system. Available structural weight data for a transport is used to scale the control surface weight model for the VCCTEF. An average weight per unit surface area of 5.2630 psf is estimated from this data source. This weight data is based on an aluminum structure. For composite structures, an average weight reduction of 28% is used. Therefore, the average weight per unit surface area for composite structures is estimated to be 3.7893 psf.

For the Mach 0.745 TTBW, the total surface area of the 6-spanwise two-segment VCCTEF as shown in Fig. 8 is computed to be 224.68 ft². This results in a control surface weight of about 852 lbs. A clean wing without control surfaces that occupies the same surface area is assumed to be half of the control surface weight. Therefore, a weight penalty due to the control surface weight is 426 lbs.

To estimate the servo-actuator weight, a hinge moment analysis is conducted. Servo-actuator drives for transport aircraft can be classified as hydraulic actuator, electro-mechanical actuator, or shape memory actuator (SMA). SMA has a significant torque-to-weight ratio advantage, but has a much slower bandwidth that is not suitable for flight control requirements.¹⁴ As an example, SMA with 500 ft-lbs could weigh about 8 lbs. On the other hand, an EMA with gear box for a 160 ft-lbs rated torque could weigh 41 lbs. The motor rated torques are sized based on the hinge moments.¹⁰ Based on the hinge moments, a motor with a rated torque that exceeds 15 ft-lb torque should be sufficient.

Assuming that the two outboard spanwise flap sections are multi-functional capable for both drag optimization and roll control, there is no weight penalty due to these two outboard spanwise flap sections. Thus, the total servo weight for SMA is 80 lbs and the total weight for EMA is 410 lbs. The total weight of the flap system is the sum of the structural weight and the servo-actuator weight. The weight model is described by

$$W_{flap} = f_{unc} W_{structure} + n_{flap} W_{servo} \quad (7)$$

where f_{unc} is a factor to account for weight uncertainty which is assumed to be 1.5, $W_{structure}$ is the weight penalty of the control surfaces (control surface weight minus the wing weight occupying the same area) which is estimated to be 426 lbs, n_{flap} is the number of flaps for drag optimization minus the number of flaps used for both drag optimization and roll control, and W_{servo} is the weight of a servo-actuator which is assumed to be 8.1 lbs for SMA and 41 lbs for EMA. Table 1 shows the total weight for the 6-VCCTEF layout. For the purpose of weight-drag trade used in the drag optimization, the EMA weight estimates are used.

Table 1 Actuator weight and Flight Conditions

	n_{flap}	W_{EMA}	$W_{EMA}/W_{w/a}$	q_{∞} (psf)	h (ft)	$Re(\times 10^6)$
Jig	-	-	-	152.2	40,000	13.1
6-VCCTEF	10	1049	0.0128	154.15	39,735	13.3

C. Optimization Results

The aeroelastic trim drag optimization results are presented in the Table 2 - 4. Table 5 - 7 show the VCCTEF deflection angles. In these tables δ_{1-6} are the inner cambered flap segment deflection angles numbered from wing root to wing tip, δ_{7-12} are the outer cambered flap segment deflection angles numbered from wing root to wing tip, and δ_h is the horizontal tail incidence angle. The flaps deflection angles are plotted in the Fig.10. After the design the flaps are deflected upward and the angle of attacks are slightly increased. The aeroelastic trim drag are reduced by 1.51%, 0.45%, and 2.03% at the three flight conditions. The wing bending displacement distributions are shown in Fig. 11. After the design, the wing tip displacements are slightly reduced.

Table 2 Aeroelastic Trim Drag Optimization Results from VSPAERO for $C_{L_1} = 0.68$

	C_L	C_D	α (deg)	ΔC_D (counts)	$\Delta C_D / C_{D_{jig}}$	D (lbs)	$\Delta D / D_{jig}$	L/D
Flight Opt. Jig OML	0.68	0.03300	1.7520	-	-	3709.466	-	20.606
6-VCCTEF-12DV	0.68	0.03209	2.2668	9.1	2.76%	3653.390	1.51%	21.190

Table 3 Aeroelastic Trim Drag Optimization Results from VSPAERO for $C_{L_2} = 0.73$

	C_L	C_D	α (deg)	ΔC_D (counts)	$\Delta C_D / C_{D_{jig}}$	D (lbs)	$\Delta D / D_{jig}$	L/D
Flight Opt. Jig OML	0.73	0.03460	2.0653	-	-	3889.319	-	21.098
6-VCCTEF-12DV	0.73	0.03401	2.4125	5.9	1.71%	3871.979	0.45%	21.464

Table 4 Aeroelastic Trim Drag Optimization Results from VSPAERO for $C_{L_3} = 0.78$

	C_L	C_D	α (deg)	ΔC_D (counts)	$\Delta C_D / C_{D_{jig}}$	D (lbs)	$\Delta D / D_{jig}$	L/D
Flight Opt. Jig OML	0.78	0.03610	2.3613	-	-	4057.931	-	21.607
6-VCCTEF-12DV	0.78	0.03492	2.8532	11.8	3.27%	3975.581	2.03%	22.337

Table 5 VCCTEF Deflection Angles (deg.) for $C_{L_1} = 0.68$

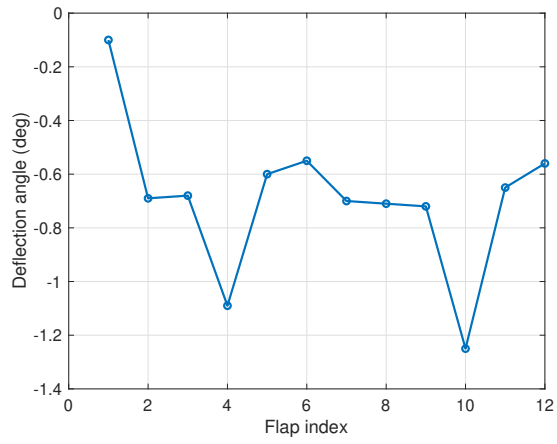
	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	δ_9	δ_{10}	δ_{11}	δ_{12}	δ_h
6-VCCTEF-12DV	-0.10	-0.69	-0.68	-1.09	-0.60	-0.55	-0.70	-0.71	-0.72	-1.25	-0.65	-0.56	-0.207

Table 6 VCCTEF Deflection Angles (deg.) for $C_{L_2} = 0.73$

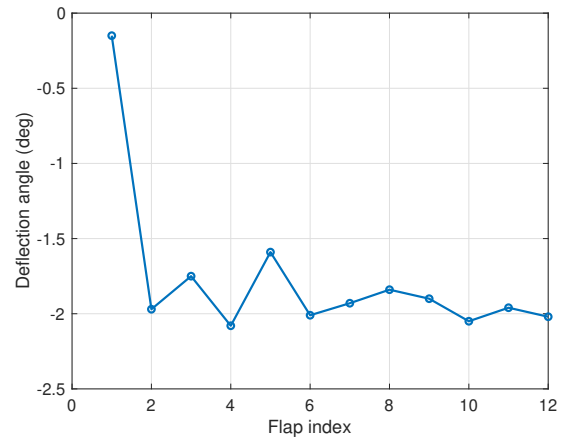
	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	δ_9	δ_{10}	δ_{11}	δ_{12}	δ_h
6-VCCTEF-12DV	-0.15	-1.97	-1.75	-2.08	-1.59	-2.01	-1.93	-1.84	-1.90	-2.05	-1.96	-2.02	-0.685

Table 7 VCCTEF Deflection Angles (deg.) for $C_{L_3} = 0.78$

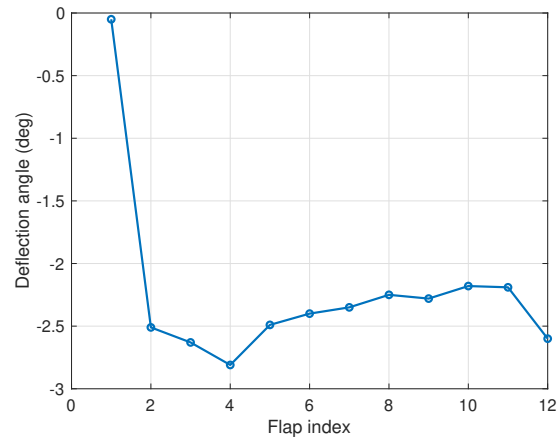
	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	δ_9	δ_{10}	δ_{11}	δ_{12}	δ_h
6-VCCTEF-12DV	-0.05	-2.51	-2.63	-2.81	-2.49	-2.40	-2.35	-2.25	-2.28	-2.18	-2.19	-2.60	-0.939



(a) $C_{L_1} = 0.68$



(b) $C_{L_2} = 0.73$



(c) $C_{L_3} = 0.78$

Figure 10 TTBW Optimized 6-VCCTEF Deflection Angles

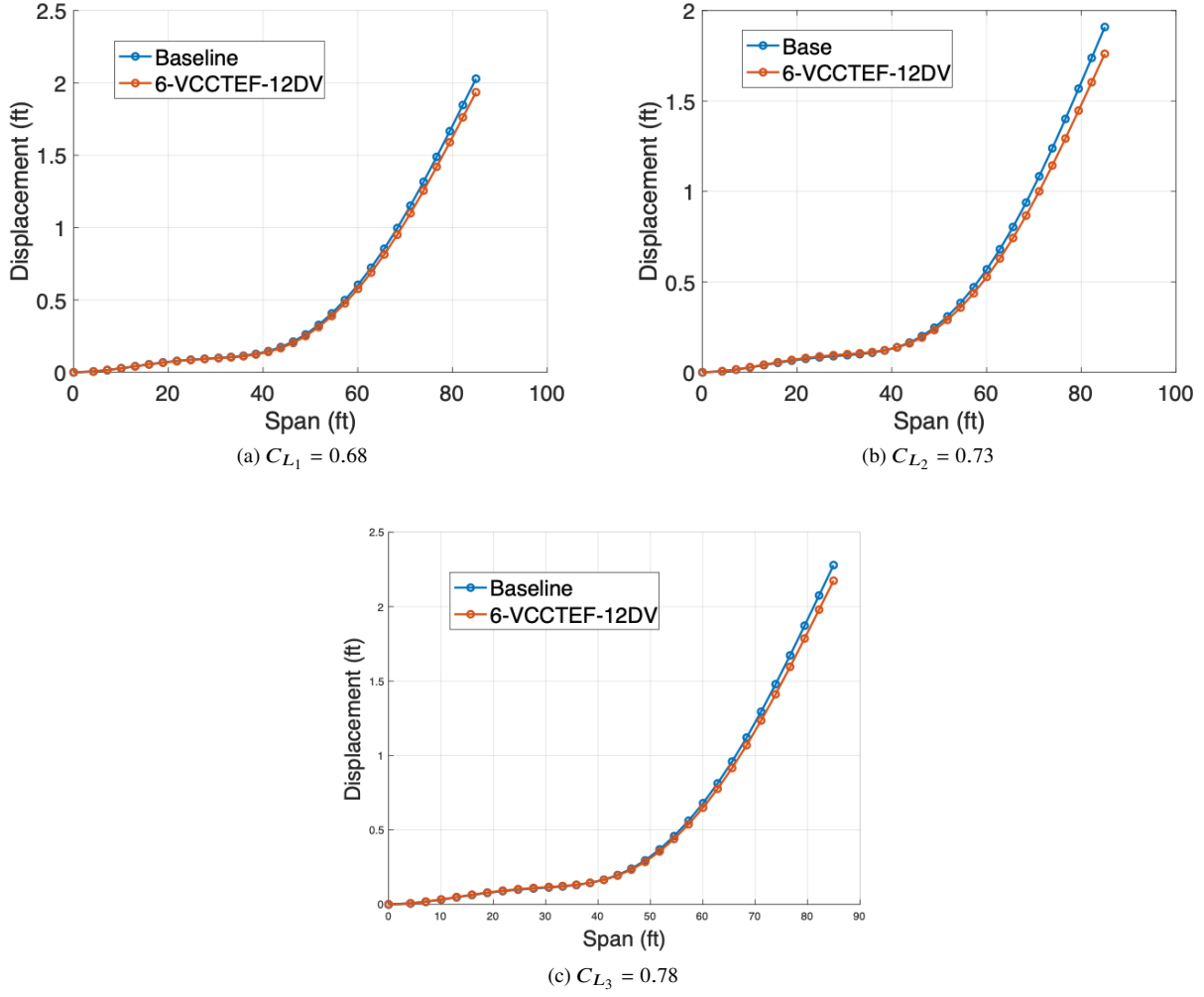


Figure 11 Wing Bending Deflection of Mach 0.745 TTBW

D. High-fidelity CFD Validation

To validate the aeroelastic trim drag optimization, a validation study using high-fidelity CFD solver FUN3D is performed. FUN3D^{15,16} solves the unsteady three-dimensional Navier-Stokes equations on mixed-element grids using a vertices-centered finite-volume method. Information exchange for flow computation on different partitions using multiple CPUs is implemented through the MPI (Message Passing Interface) protocol. It employs an implicit upwind algorithm in which the inviscid fluxes are obtained with a flux-difference-splitting scheme. At interfaces that delimits the neighboring control volumes, the inviscid fluxes are computed using an approximate Riemann solver based on the values on either side of the interfaces. The Roe flux difference splitting¹⁷ is used in the current study. For second-order accuracy, the interface values are obtained by extrapolation of the control volume centroidal values, based on the gradients computed at the mesh vertices, using an unweighted least squares technique. The Venkatakrishnan¹⁸ limiter is used in the current study to limit the reconstructed values when necessary. In this study, the tetrahedral mesh with prism layers is used. In FUN3D, for tetrahedral meshes, the full viscous fluxes are discretized using a finite-volume formulation in which the required velocity gradients on the dual faces are computed using the Green-Gauss theorem. The solution at each time-step is updated with a backward Euler time-differencing scheme. At each time step, the system of equations is approximately solved with either a multi-color point-implicit procedure or an implicit-line relaxation scheme. Local time-step scaling is employed to accelerate convergence to steady-state. To model turbulent flows, the

one-equation model of Spalart-Allmaras¹⁹ (S-A) is used in this study. The static aeroelastic simulation module in FUN3D is used for the aeroelastic simulation. The mode shapes are extracted from Boeing provided NASTRAN model. Figure 12 shows the Mach 0.745 TTBW aircraft first bending mode. Figure 12 shows the surface deformation near the wing tip for the FUN3D static aeroelastic simulation.

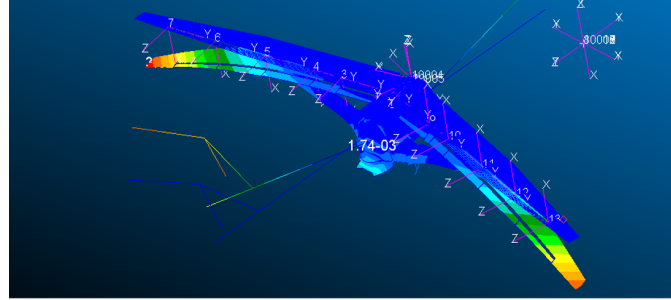


Figure 12 Mach 0.745 TTBW 1st Bending Mode

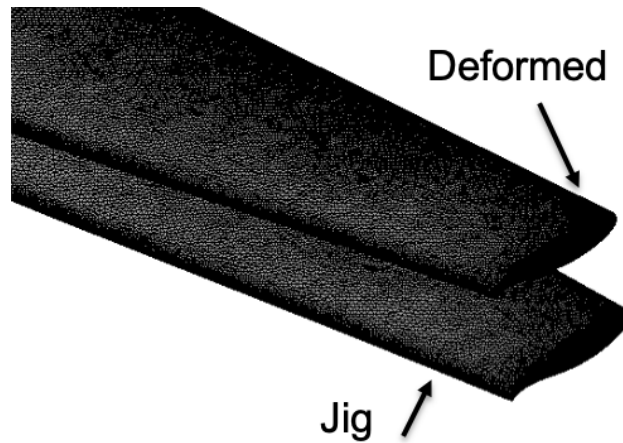


Figure 13 Mach 0.745 TTBW 1st Bending Mode

Deflected control surfaces are created using the process developed in Ref.⁹ The various control surfaces undergo rigid body rotations about the hinge line. A radial basis function smoother applied between flap segments ensures surface continuity between flaps. The surface with the commanded flap rotations is input into the FUN3D code and the volume mesh is deformed. Figure 14 illustrates the flap deflections of the 6-spanwise VCCTEF configuration at design $C_L = 0.73$. Figure 15 shows a close-up view of the CFD mesh of the VCCTEF geometry.

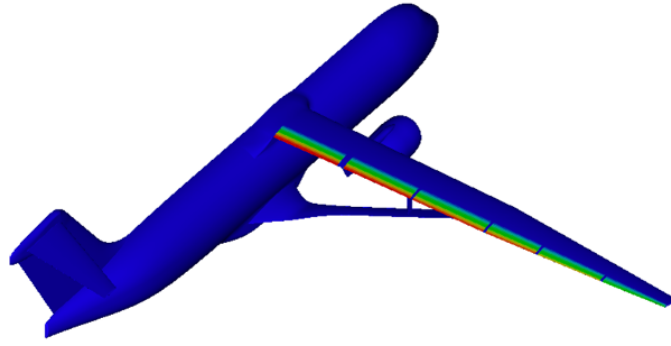


Figure 14 VCCTEF Deflection Layout

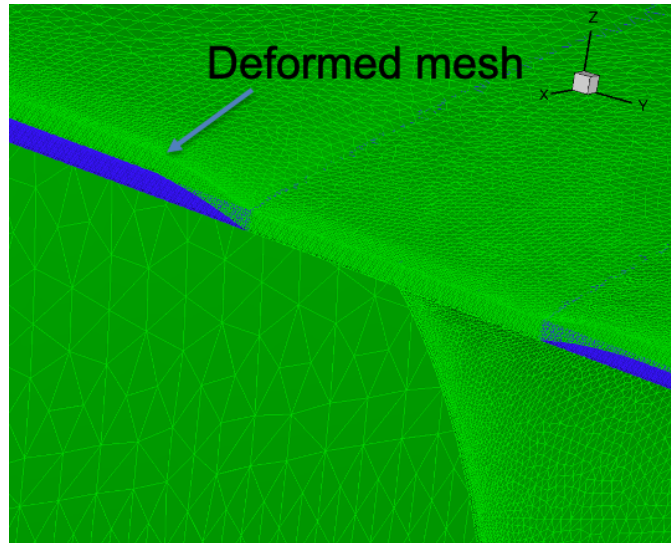


Figure 15 Close-up View of Deformed CFD Mesh

Figures 16-18 present the pressure contour comparison of the Jig and 6-VCCTEF-12DV design cases at the three design points $C_{L_1} = 0.68$, $C_{L_2} = 0.73$ and $C_{L_3} = 0.78$. The optimized VCCTEF deflections result in a more uniform distribution of the pressure on the aircraft wing surface and thereby helps reduce the drag of the aircraft at the three design conditions.

Table 8- 10 lists the FUN3D simulation results at the three flight design conditions. The optimized VCCTEF deflection results in a drag coefficient reduction of 7.5 counts, 5.1 counts, and 10.5 counts at the three flight conditions as compared to the flight optimized jig twist geometry. The drag reduction results computed by FUN3D agree well with the VSPAERO results. The difference in the drag coefficient ranges from 0.8 to 1.6 counts between the VSPAERO and FUN3D simulations. This confirms the optimization results found by the VSPAERO model.

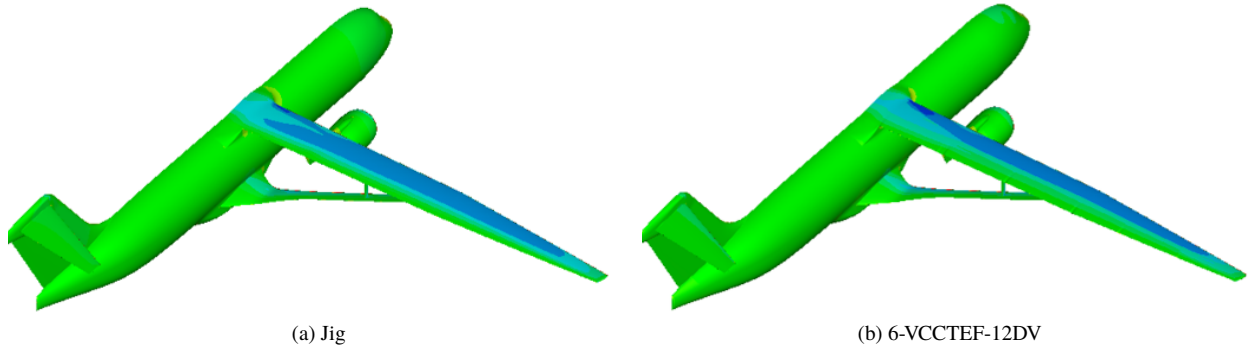


Figure 16 Pressure Coefficient Contour on the TTBW Geometries at Mach 0.745 and $C_{L_1} = 0.68$

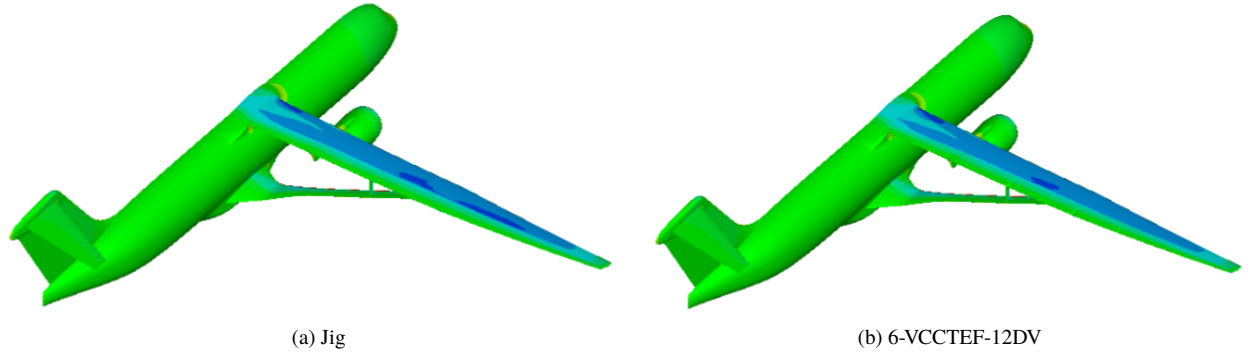


Figure 17 Pressure Coefficient Contour on the TTBW Geometries at Mach 0.745 and $C_{L_2} = 0.73$

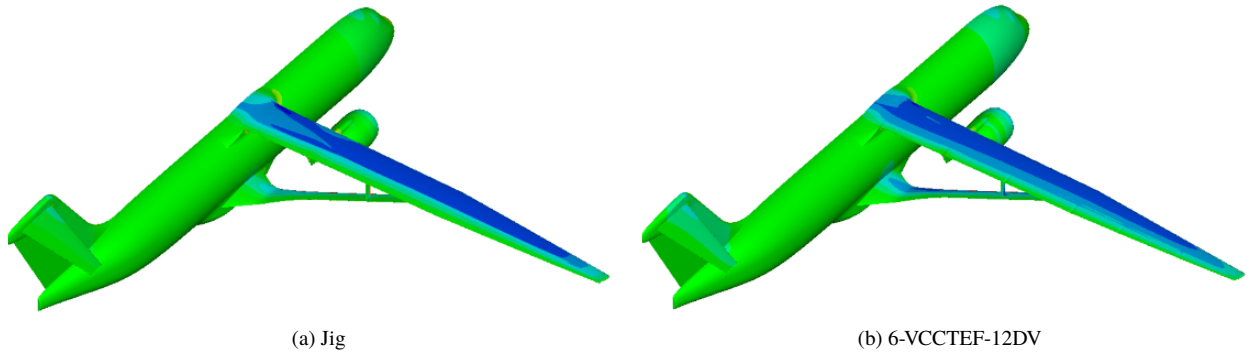


Figure 18 Pressure Coefficient Contour on the TTBW Geometries at Mach 0.745 and $C_{L_3} = 0.78$

Table 8 Aeroelastic Trim Drag Optimization Results from FUN3D for $C_{L_1} = 0.68$

Model	$\alpha(\text{deg.})$	C_L	C_D	$\Delta C_{D_{FUN3D}}(\text{counts})$	$\Delta C_{D_{VSPAERO}}(\text{counts})$
Flight Opt. Jig OML	1.468	0.6800	0.03320	-	-
6-VCCTEF-12DV	2.312	0.6800	0.03245	7.5	9.1

Table 9 Aeroelastic Trim Drag Optimization Results from FUN3D for $C_{L_2} = 0.73$

Model	α (deg.)	C_L	C_D	$\Delta C_{D_{FUN3D}}$ (counts)	$\Delta C_{D_{VSPAERO}}$ (counts)
Flight Opt. Jig OML	1.756	0.7300	0.03482	-	-
6-VCCTEF-12DV	2.255	0.7300	0.03431	5.1	5.9

Table 10 Aeroelastic Trim Drag Optimization Results from FUN3D for $C_{L_3} = 0.78$

Model	α (deg.)	C_L	C_D	$\Delta C_{D_{FUN3D}}$ (counts)	$\Delta C_{D_{VSPAERO}}$ (counts)
Flight Opt. Jig OML	1.912	0.7800	0.03620	-	-
6-VCCTEF-12DV	2.531	0.7800	0.03515	10.5	11.8

Conclusions

An aeroelastic trim drag optimization study for the Mach 0.745 TTBW aircraft with the VCCTEF is performed based on the in-house developed tool VSPAERO coupled to finite-element code BEAM3D for rapid aero-structural analysis. The lift and drag coefficients predicted by the solver agree well with the wind tunnel data of the Mach 0.745 TTBW model. The 6-spanwise section VCCTEF configuration is used for the aeroelastic trim drag optimization. Three flight conditions corresponding to Mach 0.745 and $C_{L_1} = 0.68$, $C_{L_2} = 0.73$, and $C_{L_3} = 0.78$ are used for the aeroelastic trim drag optimization study. The optimization results show a drag reductions of 1.51%, 0.45%, and 2.03% corresponding to $C_{L_1} = 0.68$, $C_{L_2} = 0.73$, and $C_{L_3} = 0.78$, respectively.. The high-fidelity CFD solver FUN3D simulation results confirm the aeroelastic trim drag optimization results obtained by the VSPAERO/BEAM3D aeroelastic model.

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