

Aeroelastic Simulation of Transonic Truss-Braced Wing Aircraft for Flight Dynamic Stability Analysis

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This paper presents aeroelastic simulation of the Mach 0.8 Transonic Truss-Braced Wing (TTBW) aeroelastic model using CFD solver FUN3D for the flight dynamic and control stability analysis. A jig twist optimization is performed to obtain a flight optimized jig twist for the flexible Mach 0.8 TTBW model. The developed aeroelastic model steady-state stability derivatives with respect to the angle of attack, angle of sideslip, and airspeed are calculated with perturbations in the angle of attack, angle of sideslip, and Mach number, respectively. A series of unsteady simulations is conducted for the developed aeroelastic model in pitch oscillation at various reduced frequencies. The dynamic stability derivatives are estimated using a frequency domain estimation method. The control derivatives of the elevator, rudder, and ailerons of the developed aeroelastic model are estimated for control stability analysis.

I. Introduction

Vehicle stability analysis is an important study to determine both static and dynamic stability of flight vehicles. A set of linearized flight dynamic equations of motion are established to predict the vehicle stability and its motion under applied aerodynamic forces and moments generated by flight control surfaces. Static stability of an aircraft depends on steady state stability derivatives. Dynamic stability depends on a larger set of stability derivatives which include both steady state and dynamic stability derivatives. The partial derivatives of the aerodynamic coefficients with respect to the dynamic states of the aircraft are usually called dynamic stability derivatives. The steady state stability derivatives with respect to the angular rates generally can be computed by various analytical techniques. On the other hand, dynamic stability derivatives with respect to the aircraft states and their time derivatives are more difficult to establish as these derivatives are generally frequency dependent. The frequency dependency manifests itself as a time delay in the aerodynamic response of the aircraft which can be important. The steady state and dynamic stability derivatives can be estimated experimentally by stability-and-control (S&C) forced oscillation wind tunnel experiments or analytically by unsteady flow simulations.

The Subsonic Ultra Green Aircraft Research (SUGAR) Transonic Truss-Braced Wing (TTBW) aircraft concept is a Boeing-developed N+3 aircraft configuration funded by NASA Aeronautics Research Mission Directorate (ARMD) Advanced Air Transport Technologies (AATT) project.^{1,2,3} The Mach 0.8 Transonic Truss-Braced Wing (TTBW) aircraft shown in Figure 1 is designed to be aerodynamically efficient by employing a large aspect ratio. The flight dynamic and control stability of the rigid TTBW 1g OML have been studied previously.^{4,5,6} However, the aeroelastic effects might change the aircraft stability and control characteristics.

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Figure 1 Boeing SUGAR Mach 0.8 Transonic Truss-Braced Wing (TTBW) Aircraft Concept

In this paper the aeroelastic simulations of the Mach 0.8 Transonic Truss-Braced Wing (TTBW) aeroelastic model are conducted using high-fidelity CFD solver FUN3D for the flight dynamic and control stability analysis. Firstly, a jig twist optimization is performed to obtain a flight optimized jig twist for the flexible Mach 0.8 TTBW model. Secondly, the developed aeroelastic model steady-state stability derivatives with respect to the angle of attack, angle of sideslip, and airspeed are calculated with perturbations in the angle of attack, angle of sideslip, and Mach number, respectively. Thirdly, a series of unsteady simulations is conducted for the developed aeroelastic model in pitch oscillation at various reduced frequencies. The dynamic stability derivatives are estimated using a frequency domain estimation method.⁵ Finally, the control derivatives of the elevator, rudder, and ailerons of the developed aeroelastic model are estimated for control stability analysis.

II. Computational Approach

A. Numerical Code

The computational fluid dynamics code used in this study is FUN3D,^{7,8} which 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 delimiting neighboring control volumes, the inviscid fluxes are computed using an approximate Riemann solver based on the values on either side of the interface. The Roe flux difference splitting⁹ is used in the current study. For second-order accuracy, interface values are obtained by extrapolation of the control volume centroidal values, based on gradients computed at the mesh vertices, using an unweighted least squares technique. The Venkatakrishnan¹⁰ limiter is used in the current study to limit the reconstructed values when necessary. In this study the tetrahedral mesh with prism layers are 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 backwards 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-Allmaras¹¹ (S-A) is used in this study. The static aeroelastic simulation module in FUN3D is used for the aeroelastic simulation.

B. Computational Model and Grid

Figure 2 illustrates the Mach 0.8 TTBW geometry. Figure 3 shows the surface meshes of the geometries. The volume meshes are comprised of tetrahedral elements and a prism layer near the wall. The mesh size is about 192 million nodes for the Mach 0.8 TTBW full model. The prism layer is used to resolve the turbulent boundary layer. The

y^+ of the first cell from the wall is less than 1.

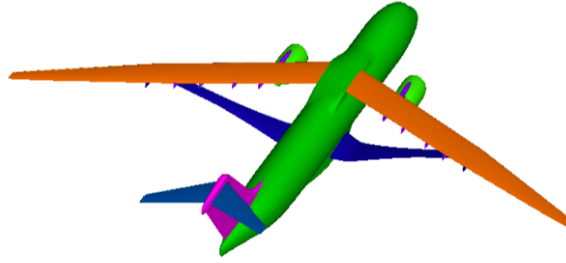


Figure 2 Mach 0.8 TTBW Aircraft Geometries.

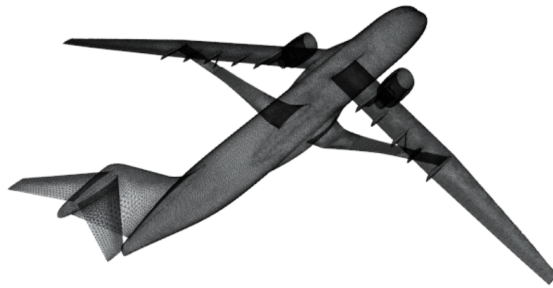


Figure 3 Mach 0.8 TTBW Aircraft CFD Meshes.

C. Aeroelastic Simulation

A NASTRAN finite-element model (FEM) of the Mach 0.8TTBW is available from Boeing. The NASTRAN FEM comprises a detail structural model of the wing and struts, a shell structural model of the fuselage section that joins with the wing, and a beam-stick model of the rest of the fuselage and the tail empennage. This is shown in Figure 4. To reflect the estimated gross weights the fuel model in the Boeing NASTRAN model has been updated. The revised NASTRAN model is used to extract mode shapes for the aeroelastic analysis for the Mach 0.8 TTBW aircraft. Figure 5 shows the mode shapes of the first six non-rigid body modes.

The static aeroelastic simulation module in FUN3D is used for the aeroelastic simulation. The mode shapes are extracted from Boeing NASTRAN model with 50% fuel. Figure 6 shows the first six non-rigid body mode shapes which are interpolated from the NASTRAN mode shapes.

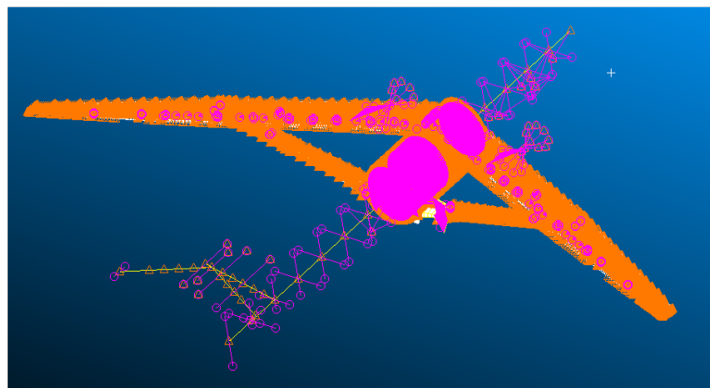
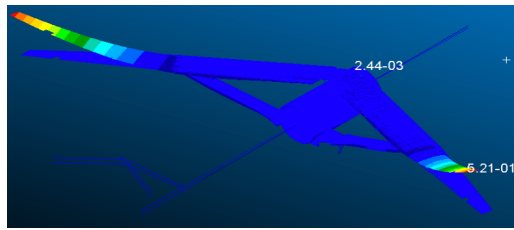
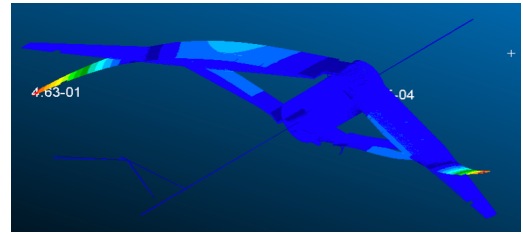


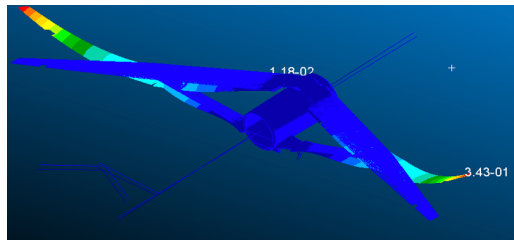
Figure 4 Boeing Mach 0.8 NASTRAN Finite-Element Model



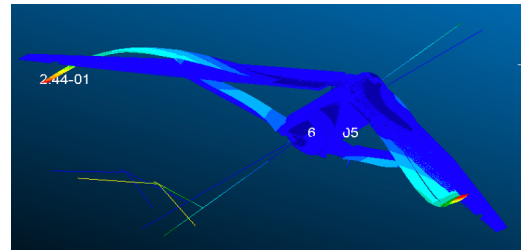
(a) 1st Mod



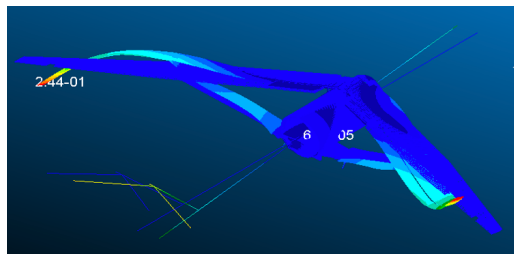
(b) 2nd Mode



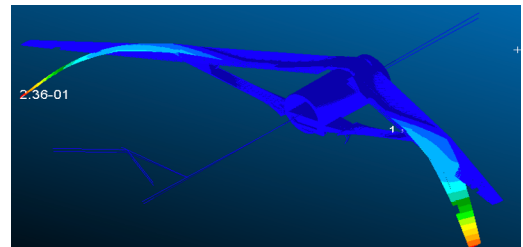
(c) 3rd Mode



(d) 4th Mode



(e) 5th Mode



(f) 6th Mode

Figure 5 Boeing Mach 0.8 TTBW NASTRAN Mode Shapes for 50% Fuel.

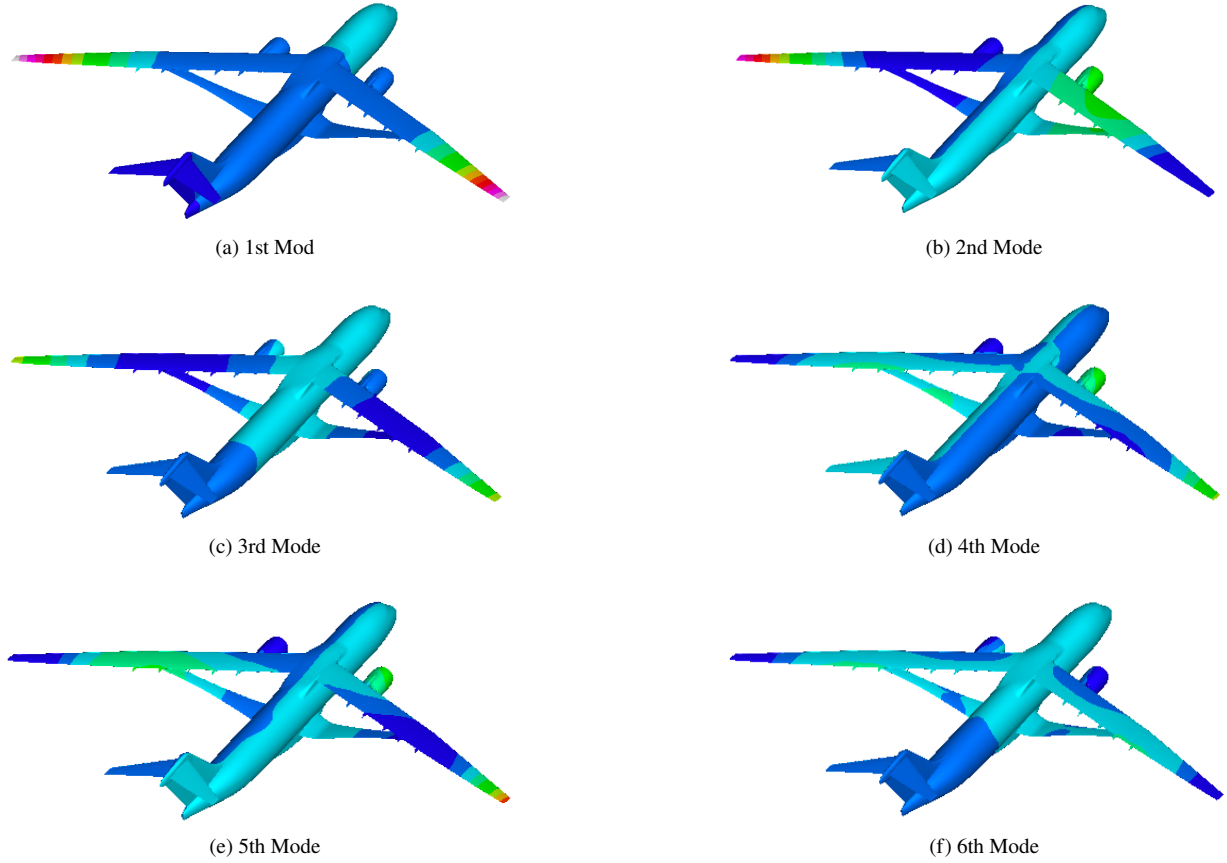


Figure 6 Mach 0.8 TTBW Mode Shapes for 50% Fuel.

III. Jig Twist Optimization

The wind tunnel jig shape OML geometry is not a flight jig shape, which accounts for the wing aeroelastic wash-out twist for the full-scale vehicle at the design flight condition, but is a jig shape designed for a wind tunnel model. Thus, the wind tunnel jig shape model is suitable for comparisons to wind tunnel data, but not necessarily suitable for generating a model of full-scale aerodynamic performance. Also, the aerodynamic performance of the wind tunnel jig shape geometry might not be optimized for the full-scale TTBW aircraft at cruise flight conditions. An optimization study is conducted to obtain a flight-optimized jig twist for the Mach 0.8 TTBW configuration.

The goal of the optimization scheme is to minimize the drag coefficient of the aero-structural model of the jig shape geometry for the TTBW aircraft at design condition. The cost function is defined as:

$$J(\alpha, c) = C_D, \quad (1)$$

while subject to the design lift and zero pitching moment constraints. Design variables are the coefficients of a shape function $c = [c_1, \dots, c_N]$ which parameterize the jig twist such that:

$$\theta(y) = \theta_{ini}(y) + \sum_{i=1}^N c_i \phi_i(y), \quad (2)$$

where $\theta(y)$ represents the jig twist distribution along the spanwise direction, $\theta_{ini}(y)$ is the initial jig twist distribution along the spanwise direction, corresponding to the wind tunnel optimized twist model, and $\phi_i(y)$ is a shape function of degree i . Shape functions are utilized in order to limit the number of design variables for optimization as well as provide a smoother converged optimized jig twist distribution. In this study the 5th order of Chebyshev polynomial is used as the shape function. Figure 7 shows the Chebyshev polynomial shape functions.

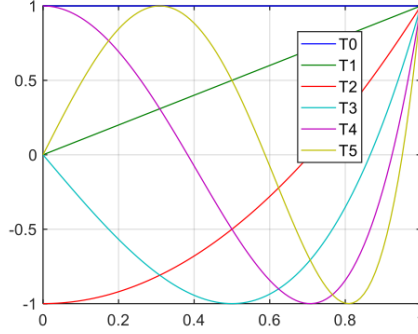


Figure 7 Chebyshev Polynomial Shape Functions

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

$$c_{i_{k+1}} = c_{i_k} - \epsilon \cdot \frac{\partial J}{\partial c_i}. \quad (3)$$

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.

The optimization procedure begins by initializing both the TTBW geometry and the parameterization of the jig twist. A baseline aero-structural solution is established by the wind tunnel jig twist model. A gradient is established based on the effect of the small perturbations such that the design variables can be updated relative to their respective cost function partial derivatives. This small perturbation iterative procedure is repeated until the cost function converges.

Two different optimizations are performed. The first one includes the angle of attack as design variable. This optimization was conducted in a previous study¹² to find a jig twist at a new angle of attack that minimizes the absolute drag. The other one constrains the angle of attack equal to the trim angle of attack of the TTBW 1g OML. The jig twist optimizations produce two different incremental flight optimized jig twist profiles as shown in the Figure 8 and Figure 9.

Figure 10 shows the pressure contour comparison of the 1g OML, wind tunnel jig OML, flight optimized jig twist I without angle of attack constrain and flight optimized jig II with angle of attack constrain. The aerodynamic parameters are presented in the Table 1. The flight optimized jig twist I without angle of attack constraint achieves 5.5 counts drag reduction compared with 1g OML. The flight optimized jig twist II with angle of attack constraint has 0.9 counts drag reduction compared with 1g OML.

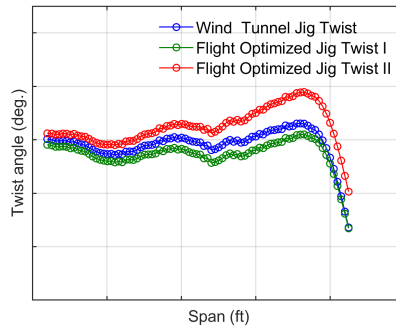


Figure 8 Flight Optimized Jig Twist Distribution.

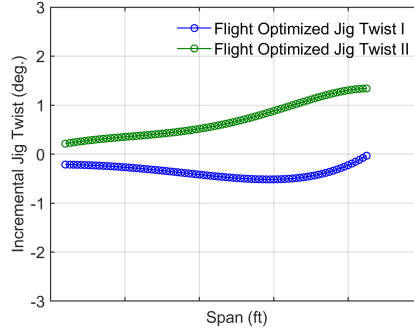


Figure 9 Incremental Flight Jig Twist Distribution.

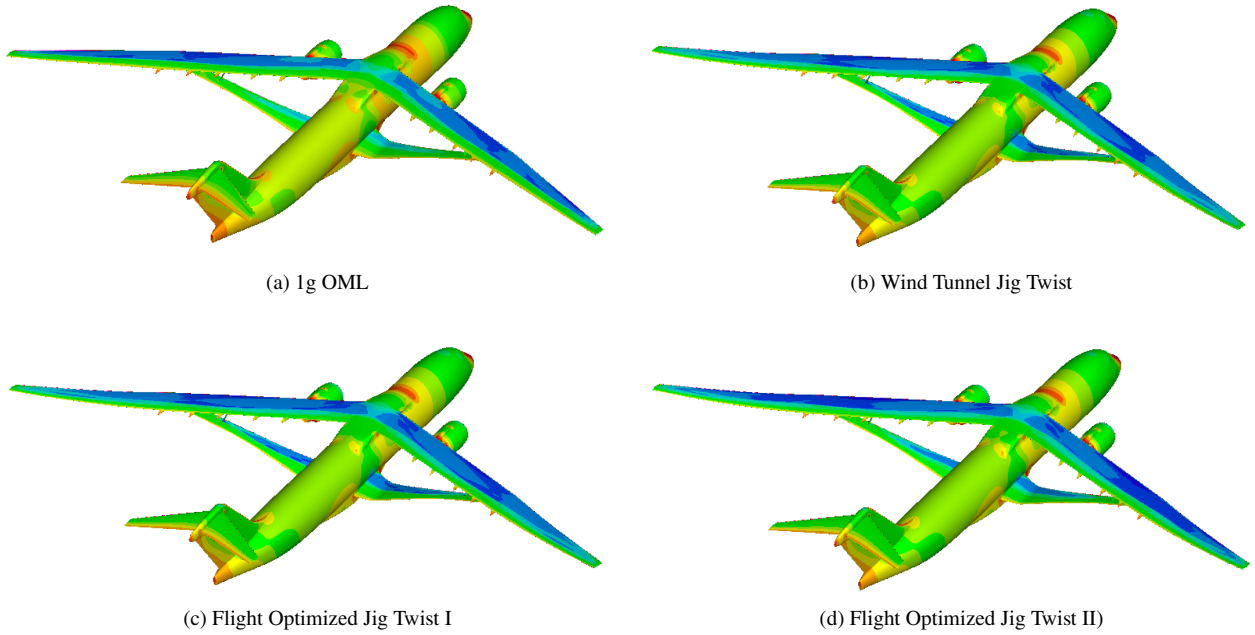


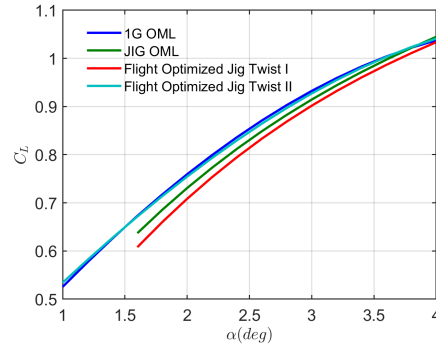
Figure 10 Pressure Coefficient Contour on the Mach 0.8 TTBW Surfaces at $M_\infty = 0.8$ and $C_L = 0.695$

Table 1 Jig Twist Optimization Results for $C_L = 0.695$ and $h = 40,000$ ft

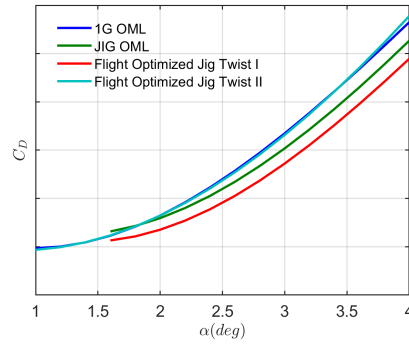
Model	$\alpha_{trim}(\text{deg.})$	ΔC_D (counts)	$\Delta C_D / C_{D_{1g}}$
1g OML	1.72	-	-
Wind Tunnel Jig Twist	1.84	-	-
Flight Optimized Jig Twist I	1.96	5.5	1.64%
Flight Optimized Jig Twist II	1.72	0.9	0.27%

Angle of attack sweeps are performed to compare the aerodynamic performance. Figure 11 shows the lift, drag, and pitching moment coefficients of the Mach 0.8 TTBW models. The flight optimized jig twist I without the angle of attack constraint causes a significant shift in the lift curve, thereby making it difficult to compare the results of 1g OML. The

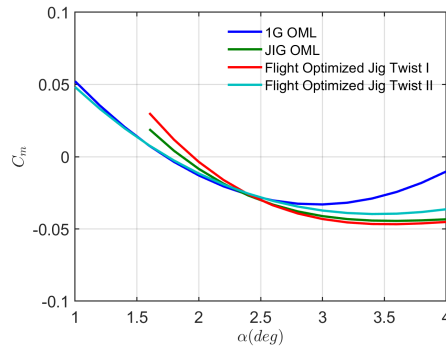
lift and drag coefficients of the flight optimized jig twist II with angle of attack constraint are in very close agreement to 1g OML simulation. The pitching moment coefficient of the flight optimized jig twist II generally agrees with the 1g OML result but differs at high angles of attack. A pitch break is observed for the flight optimized jig twist II at an angle of attack of about 3.5 degrees. In contrast, the pitch break angle of attack for the 1g OML occurs at about 2.89 degrees. The increase in the pitch break angle of attack is due to the aeroelastic relief. Since the flight optimized jig twist II is in good agreement with the 1g OML at the design trim condition, this jig twist is used to establish a new jig twist aeroelastic OML for use in aeroelastic analysis.



(a) Lift Curve



(b) Drag Curve



(c) Pitching Moment Curve

Figure 11 Lift, Drag, and Pitching Moment for the TTBW Models at Mach 0.8, h = 40,000ft

IV. Stability and Control Characteristics

A. Steady-state Derivative Calculation

The steady-state stability derivatives of the developed aeroelastic OML with respect to the angle of attack, angle of sideslip, and airspeed are calculated using perturbations in the angle of attack by ± 0.1 degrees, in the angle of sideslip by ± 0.1 degree, and in the Mach number by ± 0.005 , respectively. Figure 12-14 show the pressure contours for the Mach 0.8 TTBW angle of attack perturbation and angle of sideslip perturbation.

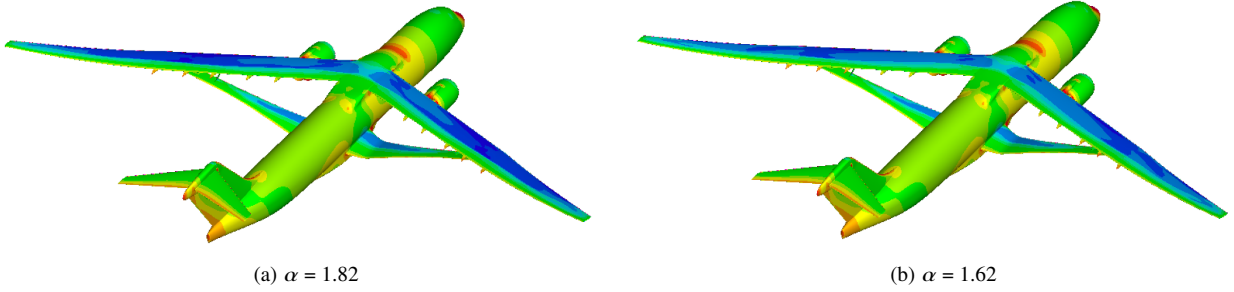


Figure 12 Pressure Coefficient Contour on the Mach 0.8 TTBW Aeroelastic OML for Angle of Attack Perturbation.

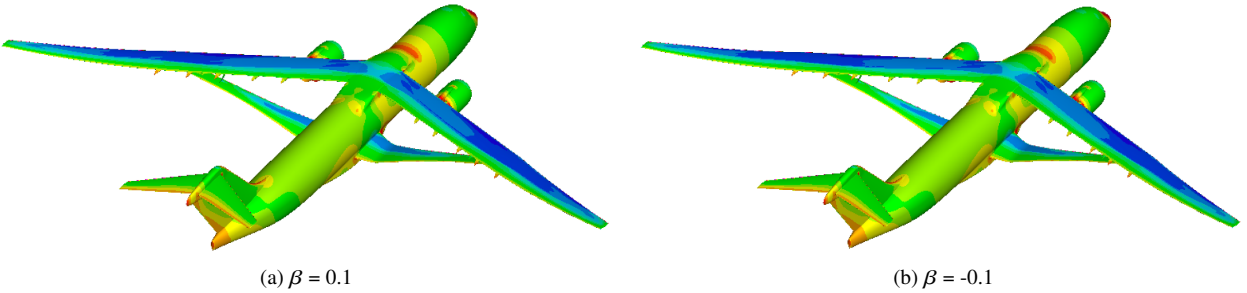


Figure 13 Pressure Coefficient Contour on the Mach 0.8 TTBW Aeroelastic OML for Angle of Sideslip Perturbation.

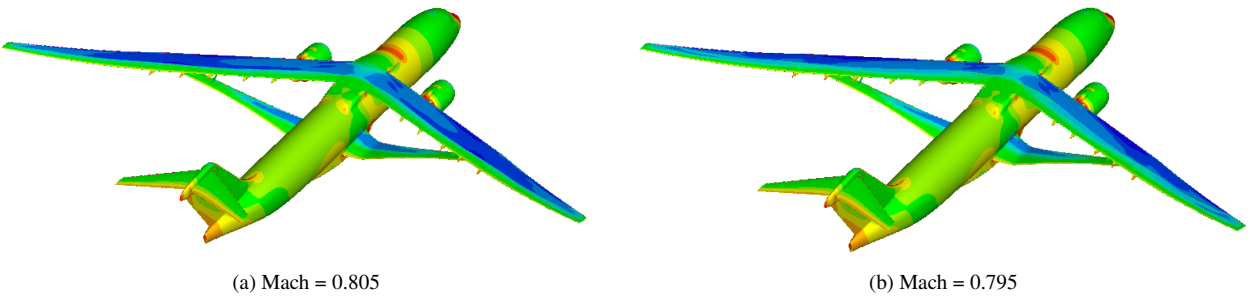


Figure 14 Pressure Coefficient Contour on the Mach 0.8 TTBW Aeroelastic OML for Mach number Perturbation.

The steady-state derivatives are then compared to the results of TTBW 1g OML. Table 2 - Table 4 show the comparison of the steady-state derivatives with respect to the angle of attack, angle of sideslip, and airspeed. The

angle of attack and airspeed derivatives are reduced due to aeroelastic effects. However, the aeroelastic effects enhance the angle of sideslip derivatives, thereby improving the lateral-directional stability characteristics of the TTBW in the roll-yaw axes.

	1g OML	Flight Optimized Jig Twist II	Difference (%)
C_{L_α}	13.3577	12.7191	4.78
C_{D_α}	0.5273	0.4603	12.71
C_{m_α}	-3.6312	-3.5516	2.19

Table 2 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Angle of Attack

	1g OML	Flight Optimized Jig Twist II	Difference (%)
C_{y_β}	-0.6863	-1.0167	48.14
c_{l_β}	-0.2108	-0.2981	41.41
c_{n_β}	0.02667	0.07301	173.75

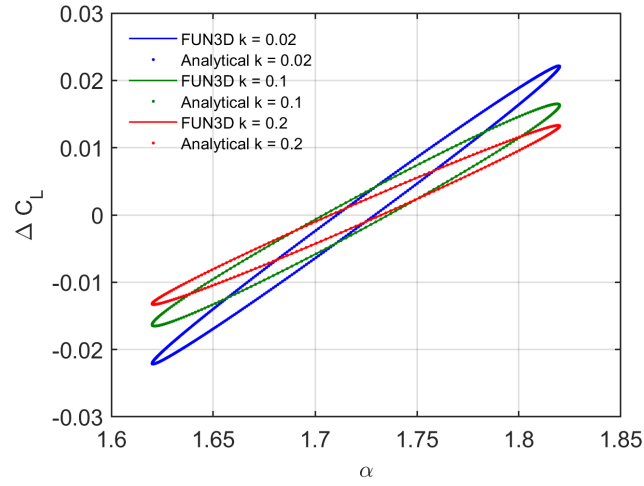
Table 3 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Angle of Sideslip

	1g OML	Flight Optimized Jig Twist II	Difference (%)
C_{L_u}	1.5873	1.1895	25.06
C_{D_u}	0.1518	0.1160	23.53
C_{m_u}	-0.07356	-0.05140	30.13

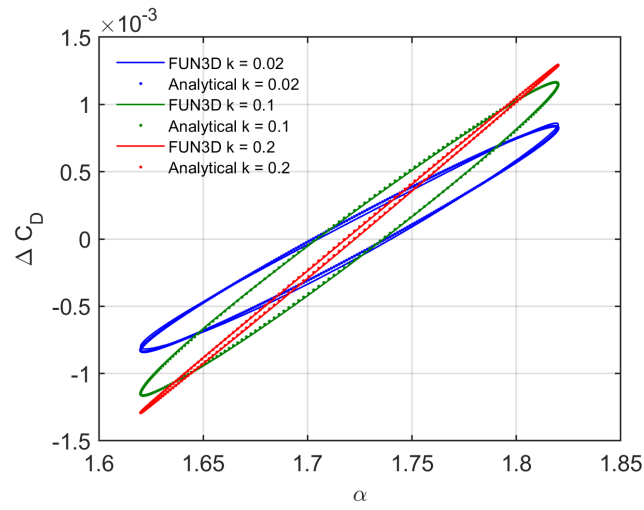
Table 4 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Airspeed

B. Unsteady Simulations and Frequency-Domain Formulation

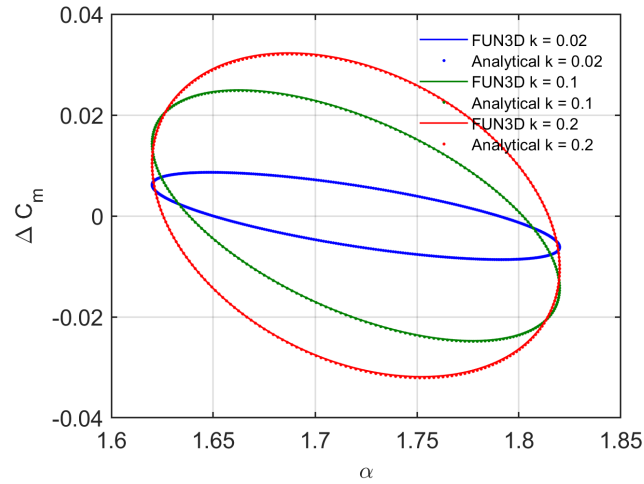
A series of unsteady simulations is conducted for the Mach 0.8 TTBW aeroelastic OML in pitch oscillation at various reduced frequencies $k = (\omega \bar{c}) / (2V_\infty)$. The dynamic stability derivatives are estimated using a frequency domain estimation method.⁵ In this method, the time-domain data are transformed into the frequency-domain data by Fourier series. Transfer functions of the dynamic stability derivatives are then estimated by a frequency-domain regression. The form of the transfer functions is designed to provide the estimation of the various contributions of the steady-state and dynamic stability derivatives. Figure 13-14 presents the lift, drag, and pitching moment coefficients against the pitch angle for the unsteady pitch oscillation for the Mach 0.8 TTBW aircraft with the reduced frequency 0.01, 0.02, 0.1 and 0.2.



(a) Lift Coefficient

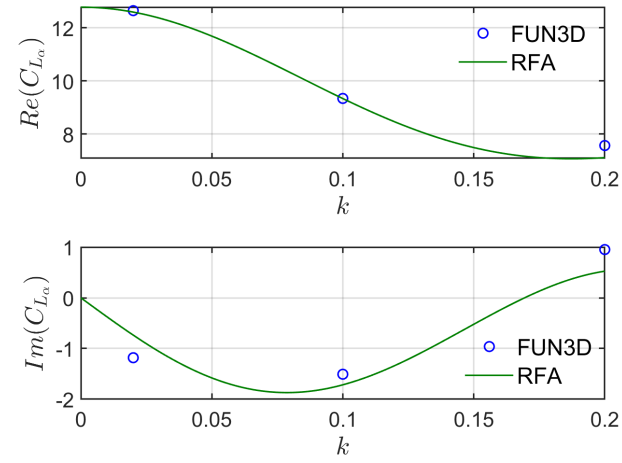


(b) Drag Coefficient

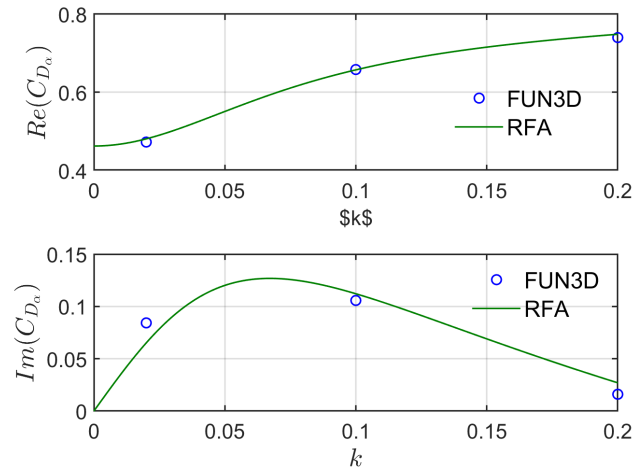


(c) Pitch Moment Coefficient

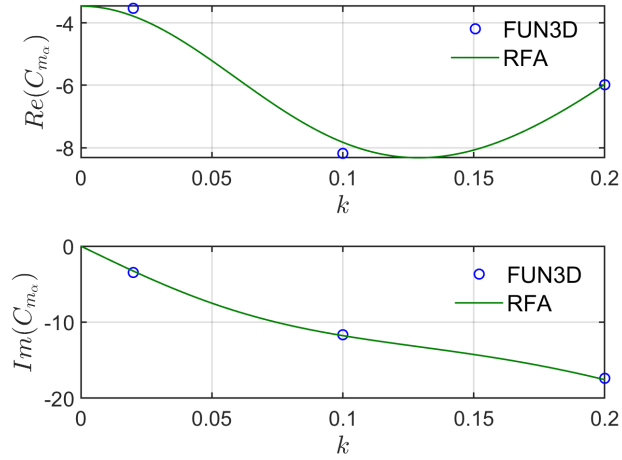
Figure 15 Pitch Oscillation Aerodynamics vs Pitch Angle for the Mach 0.8 TTBW Aeroelastic OML.



(a) Lift Coefficient



(b) Drag Coefficient



(c) Pitch Moment Coefficient

Figure 16 Pitch Oscillation Aerodynamics vs Reduced Frequency for the Mach 0.8 TTBW Aeroelastic OML.

Table 5 shows the comparison of the steady-state derivatives with respect to the angle of attack from the unsteady simulations. The unsteady simulation results also show the aeroelastic effects reduces the angle of attack derivatives. In order to estimate the dynamic stability derivative with respect to the pitch rate the contribution by the angle of attack must be subtracted from the aerodynamic coefficients. This requires performing a series of plunge simulations to isolate the angular of attack contributions to the aerodynamic coefficients. Then the differences in the aerodynamic coefficients between the pitch and plunge oscillations are used to estimate the dynamic stability derivatives with respect to the pitch rate.⁵

	1g OML	Flight Optimized Jig Twist II	Difference (%)
C_{L_α}	13.4427	12.7721	4.99
C_{D_α}	0.4832	0.4629	4.20
C_{m_α}	-3.5403	-3.4667	2.07

Table 5 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Angle of Attack

C. Control Derivatives Calculation

The planform of the control surfaces of the TTBW Mach 0.8 aircraft is shown in Fig. 17. The control surfaces elevator, rudder, and aileron are modeled using the process developed in Ref.¹⁶ The various control surfaces undergo rigid body rotations about the hinge line. In this study the gap between the control surfaces are modeled using a blended mesh strategy. A radial basis function smoother applied between control surface segments ensures surface continuity between the control surfaces. The surface with the commanded control surface rotations is input into the FUN3D code and the volume mesh is deformed. Figure 18 shows the modes for the elevator, rudder, and aileron.

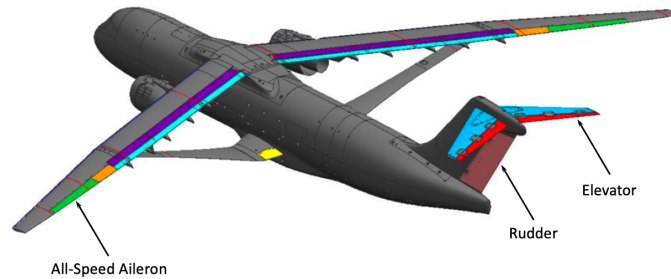
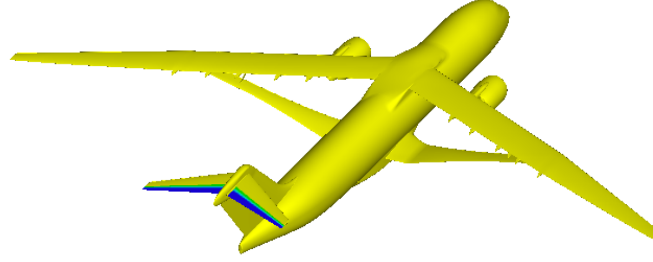
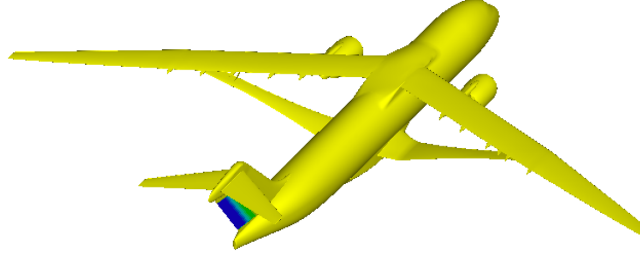


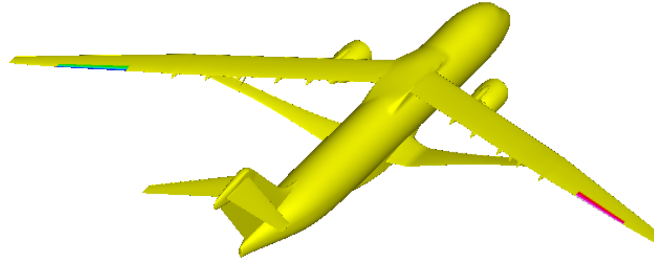
Figure 17 High-lift Devices and Control Surfaces Configuration (Credit: Harrison et al.¹⁵)



(a) α = Elevator



(b) α = Rudder



(c) α = Aileron

Figure 18 Models for Elevator, Rudder and Aileron.

The control derivatives with respect to the deflection angle are calculated with perturbations in the deflection angle by ± 1.0 degree. Figure 19 - Figure 21 show the pressure contours for the Mach 0.8 TTBW aeroelastic OML with elevator, rudder and aileron deflection angle perturbation. Table 6 - Table 8 shows the comparison of the control derivatives. Based on the simulation results the aeroelastic effects reduces the elevator and all speed aileron control derivatives. The aeroelastic effects have relative less impact on the rudder control derivatives. The $C_{n_{\delta_a}}$ of 1g OML is reverse in sign which might indicate control reversal. This needs further investigation. In this paper the derivatives are calculated in the deflection angle by ± 1.0 degree. The aircraft control surfaces are generally deflected with a large deflection angle. The large deflection angle might induce flow separation. The flow separation on the control surface might change the control derivatives significantly. In the future, the large deflection of the aeroelastic OML control surfaces will be modeled to investigate the flow separation nonlinear effects.

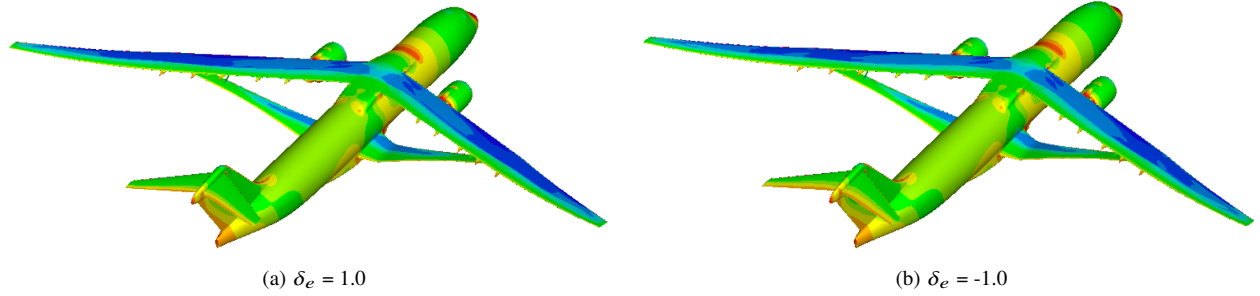


Figure 19 Pressure Coefficient Contour on the Mach 0.8 TTBW Aeroelastic OML for Elevator Deflection Angle Perturbation.

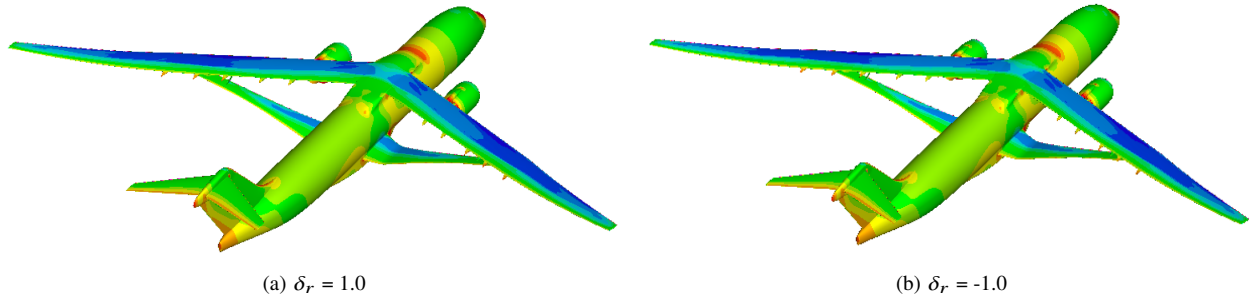


Figure 20 Pressure Coefficient Contour on the Mach 0.8 TTBW Aeroelastic OML for Rudder Deflection Angle Perturbation.

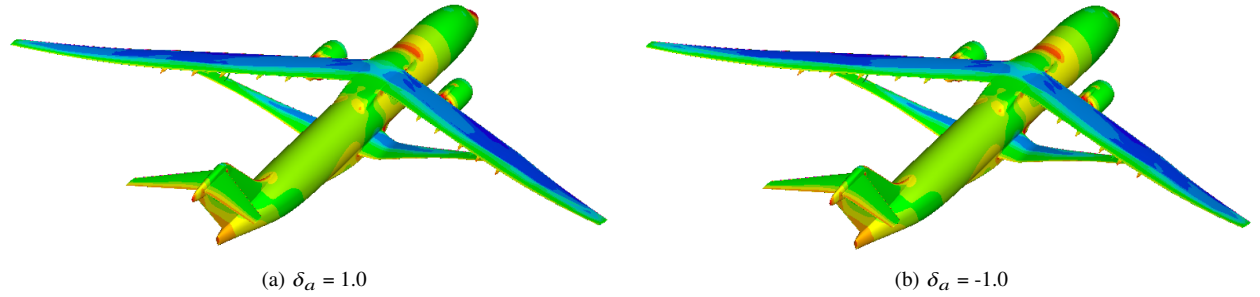


Figure 21 Pressure Coefficient Contour on the Mach 0.8 TTBW Aeroelastic OML for Aileron Deflection Angle Perturbation.

	1g OML	Flight Optimized Jig Twist II	Difference (%)
$C_{L\delta_e}$	0.9869	1.2752	29.21
$C_{D\delta_e}$	0.0068	0.0208	205.88
$C_{m\delta_e}$	-7.6521	-7.5245	1.67

Table 6 Comparison of the Mach 0.8 TTBW Elevator Derivatives.

	1g OML	Flight Optimized Jig Twist II	Difference (%)
$C_{Y_{\delta_r}}$	0.3200	0.3230	0.94
$C_{l_{\delta_r}}$	0.0265	0.02430	8.37
$C_{n_{\delta_r}}$	-0.1137	-0.1179	3.69

Table 7 Comparison of the Mach 0.8 TTBW Rudder Derivatives.

	1g OML	Flight Optimized Jig Twist II	Difference (%)
$C_{Y_{\delta_a}}$	-0.0187	-0.0157	16.04
$C_{l_{\delta_a}}$	0.2530	0.1950	22.92
$C_{n_{\delta_a}}$	0.0013	-0.0077	692.31

Table 8 Comparison of the Mach 0.8 TTBW All Speed Aileron Derivatives.

Conclusions

In this paper the aeroelastic simulations of the Mach 0.8 Transonic Truss-Braced Wing (TTBW) model are conducted using high-fidelity CFD solver FUN3D for flight dynamic stability and control analysis. An aeroelastic OML is developed by a jig twist optimization to obtain a flight jig twist for the flexible Mach 0.8 TTBW model. With the angle of attack constraint the flight optimized jig twist OML achieves 0.9 counts drag reduction compared to the 1g OML at the trim condition. The steady-state stability derivatives and control derivatives are calculated and compare with 1g OML results. Based on the simulation results the aeroelastic effects reduces the longitudinal stability and elevator and aileron control derivatives. The aeroelastic effects have relatively less impact on the rudder control derivatives. However, the aeroelastic effects enhance the angle of sideslip derivatives, which potentially improve the lateral-directional stability of the TTBW. The 1g OML indicates yaw aileron control reversal, which needs further investigation.

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