Active aeroelastic wing application on a forward swept wing configuration

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ABSTRACT
Active aeroelastic wing is introduced to benefit the forward swept wing (FSW) aeroelastic performance owing to the FSW’s elaborate aeroelastic problem. In this research, a computational aeroelastic (CAE) code was developed to conduct aeroelastic simulations, which presents challenges of data interpolation and flow capturing since torsional deformations instead of bending dominate in FSW deformation and separations on FSW occur earlier due to the boundary layer accumulation. Two simulations are conducted to verify the adaptability and accuracy of CAE method on FSW. CAE simulations are conducted on a straight FSW with control surfaces in two phases. The results from first phase obtained at Mach 0.8 demonstrate that negative deflection of LE and positive deflection of TE can effectively depress the torsion angle and root-bending moment at identical lift. Deflections of LE 0°, TE +20° can reduce LE and TE wingtip displacement by 36.53% and 39.87%, respectively, resulting in 78.97% decline of torsion angle. The second-phase calculations, conducted at Mach 0.9 at different dynamic pressures, illustrate depression of FSW torsion and deformation by LE and TE downward deflection. The LE and TE control effectiveness is always beyond 1 and the control power of the FSW increases with increasing dynamic pressure.

1. Introduction
The forward swept wing (FSW), which is a challenging configuration, is subject to aeroelastic torsion divergence problems at high dynamic pressure (Rongrong, Zhengyin, & Gang, 2016; Weisshaar, 1979). The aeroelastic torsion divergence problem is caused by the aerodynamic center (AC) always positioning in front of the structure stiffness center, which results in a head-up twist on the FSW. This characteristic increases the local angle of attack (AOA), and generally generates more lift and aeroelastic torsional deformation until the structure fails because of the uncontrollable aerodynamic forces. This feature seriously restrains the application of FSWs on commercial airplanes.

A traditional remedy for this problem is to increase the stiffness of the wing structure. However, this generates an unacceptable structural weight penalty. Advanced composite material tailoring technology mitigates the twist in the FSW and increases the torsional divergence speed without the weight penalty. It has been successfully applied on the forward swept demonstrator X-29. The composite material tailoring technique utilizes the anisotropic structural behavior to strengthen the local directional stiffness of the structure to solve the problem (Rongrong, Zhengyin, Kun, & Gang, 2018).

The composite material tailoring technology is demonstrated from the perspective of structure and material design to solve the FSW divergence. From the perspective of fluid control, we are inspired by the active aeroelastic wing (AAW) to improve the aeroelastic performance of the FSW; that is, the aerodynamic distribution could be changed by active deflections of control surfaces to reduce the local stress crest value (Brown, 2003).

In traditional aircraft design, control surfaces are generally regarded as rigid devices to guarantee control power. Designers tend to stiffen wings to reduce aeroelastic deformation, while wing flexibility is considered to be negative because it reduces control effectiveness. The concept of AAWs was proposed by Rockwell International Corporation in the mid-1980s. This idea is multidisciplinary, integrating aerodynamics, structural aeroelastic and control systems, and exploits, rather than avoids, wing deformations to save structural weight, improve aerodynamic performance and enhance control power for conventional configurations (Perry, Cole, & Miller, 1992). The AAW is expected to liberate aircraft designers from choosing configurations with lower aspect ratios or adding an aileron-reversal constraint to stiffen the wing, which would make it too heavy. This new technology could take full advantage of...
slender wing configurations to improve range and control power performance significantly (Alyanak & Pendleton, 2017).

The control power increment with increased wing flexibility was proved by Pendleton, Bessette, Field, Griffin, and Miller (2000), Pendleton et al. (2007) and Pendleton, Lee, and Wasserman (1992). Multiple control surfaces were mounted on an F-16 Agile Falcon and a stiffness-reduced F/A-18. Control surface deflections were shown to improve beneficial wing torsion under higher dynamic pressure conditions and to eliminate the potential aileron reversal. The tests demonstrated higher control powers caused by smaller control surface inputs and the utility of AAW control laws. The control power and handling requirements at the three highest dynamic pressures were verified to be enough for roll performance by controlling aeroelastic wing twist through AAW technology without differential stabilators.

Andersen, Forster, and Kolonay (1997) investigated a rectangular wing and a fighter aircraft roll trim effect through multiple control surfaces. Leading-edge (LE) surfaces were able to influence the aircraft trim through a larger scale of dynamic pressures, and when AAW technology was adopted the flexibility was beneficial to the wing’s roll maneuver.

Weisshaar and Duke (2006) utilized a full-span deforming control surface to provide effective induced drag reduction at high speeds by reshaping the spanwise lift distribution. Active controllers, such as common ailerons and LE devices, could decrease the subsonic induced drag.

This research is motivated by AAW technology. We aim to solve the aeroelastic torsion problem of the FSW through the active control of control surfaces. To examine the potential benefits of incorporating the concept of AAW with the FSW, and to verify the torsional deformation suppression effects, we investigated AAW technology applied on the FSW to improve aeroelastic performance.

Since wind-tunnel tests and flight tests are too expensive for preliminary research, we adopt the high-speed developing numerical simulation method to conduct this research, as it is relatively cheap and efficient (Akbarian et al., 2018; Ardabili et al., 2018; Ghalandari, Kooshshahi, Mohamadian, Shamshirband, & Chau, 2019; Ramezanizadeh, Alhuyi Nazari, Ahmadi, & Chau, 2019). For the FSW aeroelastic problem, a computational aeroelastic (CAE) method (Zhang, Ding, Ji, & Zhang, 2016) was developed by integrating computational fluid dynamics (CFD) with computational structural dynamics (CSD). A CFD solver was constructed with Reynolds-averaged Navier–Stokes (RANS) equations to describe the flow field precisely. For the CSD solver, we adopted the modal method to obtain the structural deformations. The inverse distance-weighted (IDW) method was adopted to update the deformed volume grid. Steady aeroelastic studies are conducted with a designed FSW model with the deformation of the leading edge (LE) and trailing edge (TE) control surfaces at different dynamic pressures. The deformation and torsion of the FSW due to deflection of the control surfaces are apparently obtained. Finally, further analyses of aerodynamic mechanisms are performed.

2. Framework of computational aeroelastic method

An in-house coded loosely coupled CAE method is developed by integrating a CFD solver with a CSD solver using Fortran. A loosely coupled method means that the codes of CFD and CSD exist as independent modules which can be replaced or improved without any effects on each other. The CAE method in this study consists of three independent components, which are illustrated in Figure 1, i.e. a grid-treating module, a CFD module and a CSD module (in rectangular blue frames on the right-hand side). The grid-treating module is used to process the unstructured mesh deformation determined by the CSD solver due to aeroelasticity. RANS equations based on processed unstructured hybrid grids are selected to obtain external aerodynamic forces and moments. The external forces and moments are taken into the static aeroelastic equations to investigate the elastic effects on the FSW. The elastic deformations will be delivered to the grid-treating module to obtain the new grid of the next iteration. The iterations continue until the given residuals are reached.

2.1. Mesh deformation technique

During an aeroelastic simulation, the external forces cause elastic deformation in the flexible wing structure. The deformed boundary positions are obtained by aggregating the original rigid wing position and the elastic deformation obtained by solving static aeroelastic equations. Once the new boundaries have been updated, the volume grid can be subsequently reconstructed. Since the new boundaries can be obtained from the CSD calculation, a simple way to reconstruct the volume grid is to design a special weighted function to transfer the boundary surface deformations into the interior mesh nodes in the fluid field. One of the most commonly used methods is the (IDW) method (Witteveen & Bijl, 2009), which builds the weighted function by the distance from the boundary surface nodes to the interior mesh nodes. The
A function for interpolation can be written as:

$$w(x_i) = \frac{\sum_{ib} \Xi(B) \left[ \left( ||\Delta x_{ib}|| \right)^a \cdot w(x_{ib}) \right]}{\sum_{ib} \Xi(B) \left[ \left( ||\Delta x_{ib}|| \right)^a \right]} \tag{1}$$

where $\Xi(B)$ consists of all boundaries nodes, $w(x_i)$ and $w(x_{ib})$ are the displacement vectors at interior node $i$ and boundary node $ib$, respectively; and $\Delta x_{ib} = x_{ib} - x_i$ is the distance vector between $ib$ and $i$. Exponent $a$ indicates the propagating speed of the displacement, which generally can be set within the range of 3–5. For viscous flow simulation the value of $a$ can be gradually increased to guarantee the small-scale grid quality of the boundary layer. To increase interpolation efficiency, we employed the distributed KD-tree structure method (Luke, Collins, & Blades, 2012).

### 2.2. Fluid governing equations

Three-dimensional unsteady Navier–Stokes equations based on a cell-centered finite volume method are constructed as fluid-governing equations. The equation can be written in integral form on a control volume $\Omega$ with the volume boundary donated as $\partial \Omega$ and relevant control surface $dS$, as follows:

$$\frac{\partial}{\partial t} \int_{\Omega} Q dV + \int_{\partial \Omega} F(Q, V_{\text{grid}}) \cdot n dS = \int_{\partial \Omega} F^V(Q) \cdot n dS \tag{2}$$

where $Q$ is the conservative variables vector; $F(Q, V_{\text{grid}})$ and $F^V(Q)$ are the inviscid and viscous flux vectors, respectively; $V = [u_x, u_y, u_z]^T$ is the fluid velocity; $V_{\text{grid}} = [u_{x,\text{grid}}, u_{y,\text{grid}}, u_{z,\text{grid}}]^T$ is the velocity of $\Omega$ caused by elastic deformation; and $n$ is the surface normal vector of $\partial \Omega$:

$$Q = \begin{bmatrix} \rho \\ \rho u_i \\ e \end{bmatrix}, F(Q, V_{\text{grid}}) = \begin{bmatrix} \rho (V - V_{\text{grid}}) \\ \rho u_i (V - V_{\text{grid}}) + P \\ (e + P) (V - V_{\text{grid}}) + p V_{\text{grid}} \end{bmatrix}, F^V(Q) \cdot n$$

$$= \begin{bmatrix} 0 \\ \sigma_{ij} n_j \\ (u_i \sigma_{ij} - q_i) n_j \end{bmatrix} \tag{3}$$

where $\rho$, $e$, $P$ and $T$ are the density, total energy, pressure and temperature, respectively.

$$\sigma_{ij} = (\mu + \mu_i) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} (\mu + \mu_i) \sigma_{kk} \frac{\partial u_k}{\partial x_i}, q_i$$

$$= \frac{1}{\gamma - 1} \left( \frac{\mu}{\Pr} + \frac{\mu_i}{\Pr_i} \right) \frac{\partial T}{\partial x_i} \tag{4}$$

where $\sigma_{ij}$ is the stress in the fluid; $q_i$ is the volume heat of unit mass in the $x, y$ and $z$ directions; $\gamma$ is the ratio of specific heat capacities, and for an ideal gas its value is 1.4; $\mu$ is the molecular viscosity coefficient, which generally is obtained from the Sutherland equation; $\mu_i$ is turbulence viscosity, determined by the turbulence model or sub-grid model; and $\Pr$ and $\Pr_i$ donate the laminar and turbulence Prandtl numbers, respectively.

The discrete Equation (2) on control volume $\Omega_m$ and Equation (1) are rewritten in the following form:

$$V_{\Omega_m} \frac{dQ_{\Omega_m}}{dt} = - \left[ r(Q_{\Omega_m}, V_{\text{grid}}) - r^V(Q_{\Omega_m}) \right] \tag{5}$$

where $V_{\Omega_m}$ is the volume $\Omega_m$; and $r(Q_{\Omega_m}, V_{\text{grid}})$ and $r^V(Q_{\Omega_m})$ are the residual vectors of the inviscid and viscous flux, respectively.

The advection upstream splitting method (AUSM) $+$ up scheme is adopted for spatial discretization. To calculate the turbulence viscosity coefficient $\mu_i$, the turbulence model employs the $k - \omega$ shear stress transport (SST) model. The pseudo-time marching adopts the implicit lower–upper symmetric Gauss–Seidel scheme (LU-SGS). More details on CFD numerical methods are presented in Jiang (2013).

### 2.3. Static aeroelastic equations

In the static aeroelastic problem, the CSD technique was employed to acquire structural displacement coupled...
with the CFD method. However, the iterative process of CSD is quite expensive in terms of time consumption. One of most practical structural dynamics analysis approaches is the modal method, which can be applied to small elastic deformation (compared to the reference length of the aircraft) problems when the model has good linear structural characteristics. Therefore, a modal decomposition is introduced to reduce the basis of the modal coordinates to a discrete finite element structure, which leads the aeroelastic system to be linear. The modal approach reduces the complexity of building the aeroelastic equations. It also increases the computational efficiency and decreases the computation time significantly compared with the common finite element method.

The modal method (Neumann & Ritter, 2009; Thomson & Dahleh, 1998) is applied to obtain the structural displacement, since deformations due to elasticity in this research are quite small compared with the reference length of the FSW. The structural elastic deformation is generally described using $N$ order structural modes, which can be written as:

$$w(t) = \sum_{i=1}^{N} \Phi_i q_i(t) \quad (6)$$

where $w$ is the structural displacement due to elasticity; $\Phi_i$ is the mass-orthogonally scaled modal basis of the $i$th mode by modal analysis or modal experiments; and $q_i$ is the generalized displacement of the $i$th order mode.

The general form of the structural dynamic equation (Ye, Ye, Feng, Pan, & Wang, 2019; Ye, Ye, Li, & Wu, 2019) in a flow field can be written as

$$M \ddot{q} + G \dot{q} + K q = Q \quad (7)$$

where $M$, $G$ and $K$ are the matrix of generalized mass, structural damping and stiffness, respectively. To solve the static aeroelastic problem by a modal approach, $M = 0$ and $G = 0$ should be applied. Therefore, Equation (7) will be reduced to a general system of $N$ linear equations, which can be written as:

$$K q = Q \quad (8)$$

3. Validation case

3.1. Verification of forward swept wing

Breitsamter and Laschka (2001) conducted a series of FSW wind-tunnel experiments in 2001 in the low-speed wind-tunnel at the Technical University of Munich, Germany. The wing-body configuration shown in Figure 2 is used to validate the adaptability and precision of the CFD solver on the FSW configuration. Simulations are conducted at a far-field velocity of 40 m/s with a corresponding Reynolds number of $0.46 \times 10^6$. Figure 3 plots the aerodynamic force at different AOA values. The simulations acquire highly consistent results with the wind-tunnel test outcomes, which illustrates the adaptability of the CFD solver on the FSW.

3.2. Verification of static aeroelasticity

The high Reynolds number aerostructural dynamics (HIRENASD) (Ballmann et al., 2008) wing-body was developed by Aachen University as a CAE code validation in the First Aeroelastic Prediction Workshop (AePW), held in Honolulu, Hawaii, USA. A HIRENASD wing model with an LE sweep of $34^\circ$ has an aspect ratio of 9 and a span of 2.75 m. The wing geometric details are shown in Figure 4. The wing is built by supercritical airfoil BAC3-11/RES/30/21 and the planform refers to a similar transport aircraft, the SFB 401 configuration. The wing model was constructed by connecting two solid components with an upper and lower shell. Maraging steel was used to define the material of the model, with elastic modulus 181.3 GPa and Poisson’s ratio 0.264. Modal analysis was then carried out with the unstructured finite element models of 100,931 tetrahedral volume elements and 169,808 nodes by ANSYS workbench to obtain natural frequencies and modal shapes. The coarse hybrid-unstructured CFD volume mesh provided by the AePW was used in the aeroelastic simulation, with 83,893 faces, 2,932,525 nodes and 7,851,519 volume elements. The grid includes 26-layer boundary layer prism cells, whose first layer spacing, perpendicular to the wing surface, was $5.0 \times 10^{-6}$ times the...
wing’s reference chord length. For a total of 51 experimental static conditions, the simulation was conducted at $Ma = 0.8$, $Re = 7 \times 10^6$ and $AOA = 1.5^\circ$. $q/E$ is $0.22 \times 10^6$, where $E$ is the material elastic modulus and $q$ is the free stream dynamic pressure. The $k-\omega$ SST turbulence model was adopted for fully turbulent flow field simulation. After CFD/CSD coupling 25 times, the final results were converged. Figure 5 illustrates the pressure coefficient comparison between the experimental data and computational results at seven different span stations, $\eta = y/b/2 = 0.15, 0.32, 0.46, 0.59, 0.66, 0.80, 0.95$. It can be seen that the lower surface pressure agrees perfectly with the experimental data, while the pressure obtained from the computation on the upper surface is slightly larger than in the experiment. Figure 6 compares the elastic displacements from simulations and experiments at the LE and TE. Wingtip deformations are relatively well probed in the calculation and agree closely with the experimental results. Both the pressure coefficients and the elastic deformation illustrate positive consequences of the precision of the numerical calculations.

4. Active aeroelastic wing technique on forward swept wing

4.1. Computational model

An FSW configuration with LE and TE is designed and displayed in top view (units: mm) in Figure 7. The untapered wing model has both the LE sweep and TE sweep of 45° with a full-span aspect ratio of 4. The lengths of the LE and TE surfaces along the spanwise direction are both 1200 mm. In Figure 7, the spanwise guideline of control surfaces should be $1200/\sqrt{2} = 1697$ mm. The size of the control surfaces along the chord length is 200 mm. The perpendicular distances between the control surfaces and the main wing are both 10 mm. The symmetric NACA0012 airfoil section without twist is incorporated along the wing span. For the purpose of analysis and to reduce simulation time, we built a half-span model. The wing model was constructed by connecting two control surface parts and the main wing. The whole model, including the main wing, control surfaces and connecting parts, was made of an aluminum alloy of elastic modulus 71 GPa and Poisson’s ratio 0.33.

The CFD computation mesh is illustrated in Figure 8, including the surface mesh of the far field, LE, TE and slice at half span. The far-field boundary is defined as a Riemann non-reflecting boundary. The walls, including the main wing, LE and TE, are treated as adiabatic no-slip boundary conditions. For the symmetry, the non-penetrating condition is satisfied. The far-field boundary is a half-spherical face with a radius of 50 m. The surface grid numbers of the LE surface, main wing and TE surface are 23,391, 109,039 and 26,189, respectively. The inviscid hybrid grid generated by POINTWISE is used to ensure the volume grid quality in the mesh deformation process. The total cell number is 3,020,845. For the definition of control surface direction, we usually consider the deflection direction causing increasing lift as the positive direction. In the subsequent simulations, the LE and TE surfaces deflect from $-20^\circ$ to $20^\circ$ with an interval of $5^\circ$, as shown in Figure 9, defining the LE and TE downward deflection (–$z$ direction) as positive and upward (+$z$ direction) as negative.

The modal analysis module of ANSYS workbench is adopted to acquire the first four order modes including natural frequencies and elastic shapes, illustrating the main dynamic characteristics of the LE surface,
Figure 4. (a) HIRENASD wing configuration; (b) tetrahedral computational structural dynamics (CSD) mesh; (c) hybrid computational fluid dynamics (CFD) mesh: surface grid and slice grid at mid-wing.
Figure 5. Comparison of the pressure coefficient between experimental and computational aeroelastic results ($\alpha = 1.5^\circ$).

Figure 6. Comparison of the spanwise displacement between experimental and computational aeroelastic results ($\alpha = 1.5^\circ$). LE = leading edge; TE = trailing edge.

For the purpose of verifying the aeroelastic effects of the elastic control surfaces on the FSW, the aeroelastic computations are first employed at $Ma = 0.3$ and $Ma = 0.8$, at sea level conditions. The Reynolds number is about $6.98 \times 10^6$ and $1.86 \times 10^7$, respectively, based on the model’s aerodynamic mean chord length of 1 m.

The aerodynamic lifts, drags and moments obtained from CAE simulations are illustrated in Figures 11–15.
It can be seen that the lift, drag and bending moment of FSW are slightly shifted up owing to the elasticity effect. A proportional correlation is found between the lift and deflections of the TE surface. As the LE surface deflects
Figure 10. First four order structural mode shapes.

Table 1. Natural frequencies of the first four order structural modes.

| Mode | Frequency/Hz |
|------|--------------|
| 1    | 6.00         |
| 2    | 35.16        |
| 3    | 36.49        |
| 4    | 58.03        |

Figure 11. Lift coefficient versus control surfaces deflection angle. LE = leading edge; TE = trailing edge.

from $-20^\circ$ to $10^\circ$, the lift of the FSW increases and as it deflects from $10^\circ$ to $-20^\circ$ the lift decreases when the TE surface deflection was set by $0^\circ$. With the deflection of

Figure 12. Drag coefficient versus control surfaces deflection angle. LE = leading edge; TE = trailing edge.

the control surfaces drag of the FSW increases dramatically, except in the situation of upward deflection of the TE surface.

The bending moment of the half-span wing about the wing root is illustrated in Figure 13, which shows a similar tendency to the lift curves. From Figure 14, we can see that the root bending moment of the FSW is generally proportional to the wing's lift. With the upward deflection of the LE and downward deflection of the TE, less root bending moment is generated under uniform
lift conditions. The maximum root bending moment decreases of 2.55% and 20.136% are obtained at $-15^\circ$ and $20^\circ$ deflections. Therefore, the control surface deflection could effectively reduce the root bending moment by utilizing the active deformation produced by the control surface twist.

Figure 16 presents the generalized displacements of the first four order structural modes. This shows that the generalized displacements of the first bending mode are more significant than for the other three modes. The first bending mode dominantly determines the structural deformation on the FSW. The wingtip displacement versus lift coefficient curves are plotted in Figure 17, illustrating the influence of the control surfaces on structural displacements. These curves demonstrate that the downward deflection of LE and TE will increase the structural effectiveness; that is, the displacement at the wingtip decreases under the same lift circumstances. In detail, 10.79% and 15.16% reductions in the LE and TE wingtip displacement are obtained when $-20^\circ$ LE deflection is set. On the other hand, 36.53% and 39.87% reductions in the LE and TE wingtip displacement are obtained when TE deflection is $+20^\circ$.

Downward deflections of LE and TE directly bring about a reduction in aerodynamic lift, resulting in decreased aeroelastic deformations. This demonstrates
that the occurrence of FSW torsion divergence can be delayed by deforming the control surface positions without the loss of flight lift. In other words, if the divergence is about to happen, the pilot or on-board computer can prevent the structural failure from happening by active control of the LE or TE surfaces when lift can be maintained.

In contrast, the opposite influence on wingtip displacement and torsion will take place when the LE deflects beyond +10°. A 'reverse bending' appears in the results of transonic simulations, but not in subsonic simulations. This implies the loss of lift coefficient and increase in FSW displacement and torsion caused by the elasticity effect. Large positive deflections of the LE should be forbidden when the FSW encounters the aeroelastic problem.

Generally speaking, TE positive deflection and LE negative deflection can effectively reduce the wingtip displacement at the LE and TE and the wing torsion. Although complete elimination of the divergence seems impossible, the active aeroelastic control of LE and TE surfaces can greatly reduce the FSW torsion problem and delay the divergence. TE deflection is more effective than LE deflection in improving the aeroelastic deformation performance on the FSW.

Another problem, i.e. aeroelastic torsion, which is one of the most critical limitations in the development of the FSW, should be taken into serious consideration. Figure 18 shows the torsion distribution on the FSW under the condition of LE and TE deflection. The torsion increases from the root to the tip of the wing for both situations. Another important aspect that we noticed is that torsion angles are shifted upward when deflection increases from −20° to 20°, which means that the torsion increases with the increment in FSW lift. However, from the perspective of efficiency, important results about the reduction in FSW torsion can be obtained from Figure 19. In aeroelasticity computation, LE negative deflection and TE positive deflection can depress the FSW torsion angle greatly. When LE deflects −20°, the torsion angle at the FSW wingtip can be reduced up to 24.34%. A bigger surprise is that the torsion angle is reduced to 78.97% at most when TE deflection is 20°. The improvement in torsion performance of this level could provide a solution to the existing torsion problem of the FSW to some extent. However, the same reverse bending is obtained when the LE rolls upward beyond 10°.
Figure 19. Wingtip torsion angle versus lift coefficient. LE = leading edge; TE = trailing edge.

4.3. Simulations for different dynamic pressures

Calculations conducted at a Mach number of 0.9 from dynamic pressure of 46,818–112,363 Pa are employed to investigate the rolling maneuver performance of a parameter called control surface effectiveness.

Control surface effectiveness (Andersen, Kolonay, & Eastep, 1998) is defined as the ratio of the rolling moment stability derivatives of flexible and rigid wings, which are produced by control surfaces' rotation $\delta$ at a given flight condition. It can be denoted as $\varepsilon$ and calculated by the following expression:

$$\varepsilon = \frac{C_{M_{3,\text{flexible}}}}{C_{M_{3,\text{rigid}}}}$$ (9)

In this research, control surfaces of the LE and TE deflect from $-10^\circ$ to $10^\circ$ with an interval of $5^\circ$.

The results in Figures 20–22 demonstrate that the lift, drag coefficient, torsion angle and root bending moment of the FSW generally increase as the dynamic pressure increases. The lift coefficient induced by the TE control surface deflection is distributed more widely than for the LE over all dynamic pressure points in Figure 20. At the downward deflection of $20^\circ$, the TE brings a lift drop at high dynamic pressure. Another phenomenon found in the drag curves is that LE upward deflection slightly changes the drag. At low dynamic pressure, the TE downward deflection generates far more lift than the LE, while at high dynamic pressure both drag values become very close. Figure 21 shows that LE negative and TE positive deflections induce smaller torsion angles at low dynamic pressure, while LE positive and TE negative deflections produce smaller torsion angles at high dynamic pressure.

Figure 20. (a) Lift coefficient and (b) drag coefficient versus dynamic pressure. le = leading edge; te = trailing edge.

Figure 21. Torsion angle versus dynamic pressure. le = leading edge; te = trailing edge.
Figures 23 and 24 illustrate, respectively, the torsion angle and root bending moment versus lift coefficient at different dynamic pressures. The torsion curves have a similar tendency to those in Figure 19. As the dynamic pressure increases, the reverse bending effect appears earlier. At high dynamic pressure, positive rolling of the LE is prohibited since it will directly cause a loss of lift and an increase in torsion. The LE and TE downward deflections are certainly still effective in deceasing the torsion and deformation of the FSW. The slopes of the curves are slightly raised as dynamic pressure increases. In other words, the FSW structural availability becomes more effective as the flexibility increases. The TE and LE effectiveness calculated by Equation (9), as shown in Figure 25, is always beyond 1 and increases as the dynamic pressure increases. This demonstrates the effective functionality of LE and TE control surfaces over a large range of dynamic pressures. Among all those calculation points, no control reversal is observed.

4.4. Aerodynamic analysis

As analyzed in Sections 4.2 and 4.3, while the active upward deflection of the LE and TE control surfaces will bring negative effects, the downward deflection brings several benefits to the FSW, as follows:

1. smaller root bending moment in the same lift condition
2. smaller LE and TE displacement in the same lift condition
(3) smaller torsion angle generated by deflection in the same lift condition
(4) better aeroelasticity performance as the dynamic pressure increases
(5) better rolling effectiveness as the dynamic pressure increases.

Special attention should be paid to LE upward deflection, which could cause reverse bending, resulting in the deterioration of deformation and torsion performance. To further analyze how the deflection works on the aeroelastic performance of the FSW, we divided the whole FSW into 13 parts using the simulation result at Ma = 0.8 from Section 4.2. In general, the root bending moment and torsion moment, which are directly connected with spanwise bending deformation and torsion deformation in this study, are determined by both the position where the lift is generated and the magnitude of the force.

First, the lift, which is the source producing the aeroelastic deformation along the wing span, is extracted, as shown in Figure 26. With the deflection of the control surfaces, the lift distribution shape along the span changes noticeably. In the condition without any control surface deflection, the lift distribution is quite close to the ‘elliptical lift distribution’, which means that less drag will be generated by the FSW. As the deflection of the LE grows, the lift coefficient increases at the mid-wing, where the LE control surface is located, and at the inner wing part. When $\delta_{LE}$ is above $+5^\circ$, lift at the inner wing part starts to drop heavily, and the lift is barely produced when $\delta_{LE}$ is up to $+20^\circ$ along the inner 30% of the FSW. For the TE deflection, lift generated by the inner and mid-wing also increases. While TE downward deflection produces more lift, upward deflection causes the lift to decrease or even generates negative lift. From the lift distribution analysis, the control surface deflection mainly influences lift induced by the inner and middle wing parts.
Then, we calculate the AC position for different deflection configurations, as shown in Figure 27. The AC position in the X direction mainly determines the torsion of the FSW, which is the major roadblock to bringing FSWs into numerous application. The AC position in the X direction is illustrated with the deflection of the control surfaces. With the deflection of the FSW LE control surface, the AC position moves toward the LE, while TE deflection leads the AC position toward the TE. Relatively small changes in the AC position in both the X and Y directions are found with the deflection of the TE. This is because the suction and pressure areas move greatly from the middle wing to forward the LE control surface when rolling the LE, as shown in Figure 28. While deflecting the TE, the suction area of the main wing expands just around the AC position. When the lift loss of the inner wing caused by LE deflection occurs, the AC position in the Y direction translates greatly toward the wingtip. In particular, when the LE control surface undergoes a large positive deflection, the AC position in the Y direction moves more strongly than the other deflection (Figure 29). Although the lift obtained from Figure 11 drops, the root bending moment continues to increase, which results in the increment of displacement and torsion. That is why reverse bending exists in Figures 17, 19, 23 and 24.

5. Conclusion

A computational aeroelastic method was built by coupling the RANS CFD method and modal method with the IDW method used for grid deformation. Two validation cases, i.e. an FSW-body and a HIRENASD aeroelasticity wing-body, were successfully employed to verify the adaptability, effectiveness and accuracy of the methodology.
An untapered FSW model with LE and TE control surfaces was designed to conduct active aeroelasticity simulation. Two scenarios of transonic aeroelasticity simulations were performed at different control surface deflections and at different dynamic pressures. The conclusions obtained from the simulations are as follows:

1. LE and TE downward deflections on the FSW effectively decrease the torsion angles, displacements and root bending moments at the same lift coefficient.
2. FSW flexibility enhances the depression of deformation as dynamic pressure increases.
3. Better rolling performance of the FSW is obtained at higher dynamic pressure. 'Aileron reversal' did not happen throughout the simulation of dynamic pressure, since LE and TE control effectiveness was always beyond 1.
4. FSW control surfaces' deflection greatly changes the AC position, resulting in the improvement of the wing's torsional deformation.
5. 'Reverse bending' in the torsion and displacement curves is mainly caused by the lift loss at the wing root and the AC position moving towards the wingtip owing to LE upward deflection.

In this article, two control surfaces were added to conduct the static aeroelasticity simulation to investigate the possibility and effectiveness of AAW application on the FSW. A more complicated FSW model with more control surfaces will be designed to perform the dynamic aeroelastic simulations, since the control system has not yet been taken into consideration. A system combining aerodynamics, structural behavior and dynamic control of flaperons and ailerons will be built in a future study. Then, flight dynamic equations will be built with the addition of closed-loop control. An optimization strategy could be introduced to build a control law of control surfaces to acquire better results on the depression of FSW torsion.

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