Aeroelastic Analysis of High-Aspect-Ratio Wings Using a Coupled CFD-CSD Method

Yong Su JUNG, Dong Ok YU, and Oh Joon KWON†

Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-338, Republic of Korea

In the present study, aeroelastic stability and the response of high-aspect ratio wings are numerically investigated using a coupled CFD-CSD method. The wing aerodynamic loads are calculated using a CFD flow solver based on unstructured meshes. The elastic deformation is evaluated using a FEM-based CSD solver employing a nonlinear flap-lag-torsion beam theory. The CSD solver also includes a built-in aerodynamics module based on a two-dimensional strip theory, coupled with a dynamic stall model, which is used for comparison with the coupled CFD-CSD method. Coupling of the CFD and CSD solvers is accomplished by adopting a conventional serial staggered method. At first, validation of the present coupled CFD-CSD method is made for an NACA0012 wing, and the predicted static deformation and dynamic response are compared with other predictions. The coupled method is then applied to an electric aerial vehicle wing, and the dynamic aeroelastic stability and response are investigated. It is found that the geometrical nonlinearity of the structure is responsible for degrading the dynamic stability of the wings. It is also found that the aeroelastic behaviors obtained using the coupled CFD-CSD method show higher aerodynamic damping than those of the strip theory-based analyses.

Key Words: Aeroelasticity, Computational Fluid Dynamics (CFD), Computational Structural Dynamics (CSD), Coupled CFD-CSD Method, High-aspect-ratio Wing, Strip Theory

Nomenclature

$C_p$: surface pressure coefficient  
$c$: wing chord length  
$\mu$: spanwise deflection  
$\nu$: lead-lag deflection  
$\omega$: flap bending deflection  
$\omega_n$: natural frequency  
$\phi$: torsional deformation at elastic axis

1. Introduction

High-altitude-long-endurance (HALE) aircraft are usually designed to have lightweight, high-aspect-ratio wings with thick airfoils to maximize the aerodynamic efficiency. High-aspect-ratio wings tend to be very flexible, and thus they can undergo large structural deflection, even during normal flight operations. Because large deflection can significantly alter the flight performance and the system stability of the wing, the wing aeroelastic characteristics are directly related to aircraft reliability and survivability. Therefore, the aeroelastic behavior of high-aspect-ratio wings should be accurately analyzed for designing more efficient and reliable HALE aircraft.

In the late 1990s, aeroelastic behaviors of high-aspect-ratio wings were extensively studied by several researchers. The studies were particularly focused on investigating the effect of geometrical structural nonlinearity. It was found that the geometrical nonlinearity, such as large deformation and nonlinear coupling between the deflection modes, should be considered for the structural analysis of high-aspect-ratio wings. In the research conducted by Patil et al.,1–3) aeroelastic analyses were conducted for a high-aspect-ratio NACA0012 wing. In their study, a geometrically-exact nonlinear beam model was used to calculate the dynamic response of the wing, and a finite-state aerodynamic theory, coupled with the ONERA dynamic stall model,4) was used to predict the aerodynamic loads on the wing. The results showed that large deflection can change the natural frequencies of the wing, which in turn, can produce noticeable changes in its aeroelastic behavior. The limit cycle oscillation (LCO) was observed below the linear flutter speed when the nonlinear beam model was used for the structural analyses. In their study, however, relatively simple aerodynamic models were adopted to determine the aerodynamic loads, whereas sophisticated computational structural dynamics (CSD) models were utilized for wing structural modeling. Simple aerodynamic models, such as the finite-state aerodynamic theory, have an inherent limitation for accurately predicting realistic flow features involving three-dimensional unsteady, viscous flow characteristics.

For performing missions such as surveillance and reconnaissance, HALE aircraft are designed to operate at high altitudes where the air density is relatively low, compared to that at sea level. To produce enough lift in this low Reynolds number regime, HALE aircraft usually fly at high angles of attack, and as a result, the wing is easily exposed to highly nonlinear aerodynamic phenomena, such as flow separation and dynamic stall. Therefore, accurate prediction of the nonlinear aerodynamic characteristics for the wing is very im-

© 2016 The Japan Society for Aeronautical and Space Sciences  
†Received 25 February 2015; final revision received 28 October 2015; accepted for publication 18 January 2016.  
*Corresponding author, ojkwon@kaist.ac.kr
important for investigating the aeroelastic behavior of HALE aircraft.

Recently, computational fluid dynamics (CFD) techniques have been utilized to overcome the limitation of using a simple finite-state aerodynamic model and to improve the prediction accuracy for the aeroelasticity studies of high-aspect-ratio wings. First, coupled CFD-CSD analyses for the static aeroelasticity of a high-aspect-ratio NACA0012 wing were made by Smith et al. In their study, it was shown that the aerodynamic force and moment predictions provided by the nonlinear solution of the Euler equations are lower than the predictions of a vortex panel method. This indicates that the divergence, and possibly the flutter speeds, predicted by lower-order aerodynamics may be overly conservative. Bendiksen performed a study about limit cycle flutter of a high-aspect-ratio swept wing at transonic Mach numbers using a nonlinear structural model (CSD) based on plate finite element and Euler flow solver (CFD) based on Galerkin finite element discretization. It was observed that the structural washout effect from aeroelastic deformations plays a fundamental role to generate low-amplitude LCOs in the case of a high-aspect-ratio swept wing. Hallissy and Cesnik investigated the static and dynamic aeroelasticities of a high-aspect-ratio wing using a loosely coupled method between a quasi-3D structure solver (CSD) and Euler/Navier-Stokes flow solver (CFD) capable of mesh deformation. The static deflections and dynamic transient behaviors of the wing were calculated using both the coupled CFD-CSD method and an in-house aeroelastic solver based on finite-state aerodynamics. A comparison of the results indicated that the coupled CFD-CSD results generally agreed well with the response of the in-house solver, but the coupled CFD-CSD solver provides higher aerodynamic damping than the finite-state aerodynamics. However, in their study, the time-accurate CFD-CSD coupled analyses were made only for a short period of time after the excitation. Therefore, fully developed dynamic behaviors such as LCO, and detailed aeroelastic analyses were not presented.

In the present study, a coupled CFD-CSD method has been developed to predict the aerodynamic loads and elastic deformation of high-aspect-ratio wings. The wing aerodynamic loads were calculated using a Navier-Stokes CFD solver based on unstructured meshes. The wing elastic deflection was calculated using a FEM-based CSD solver adopting a nonlinear coupled flap-lag-torsion beam theory. The CFD and CSD solvers were coupled by exchanging the information based on a partitioned solution method. First, static CFD-CSD coupled analyses were conducted for predicting the mean aeroelastic deflection of the high-aspect-ratio wings under various flight conditions. Then, unsteady time-accurate, coupled CFD-CSD analyses were made for investigating the dynamic aeroelastic response and post-flutter behaviors. Calculations were also made utilizing the aerodynamic model based on a strip theory, and the results were compared with those of the CFD-CSD method. Validation of the present coupled method was made for an NACA0012 flexible wing configuration for which abundant predicted results are available for comparison. The coupled method was then applied to the high-aspect-ratio wing configuration of an electric aerial vehicle developed by the Korea Aerospace Research Institute (KARI), and the aeroelastic characteristics of a realistic HALE wing was studied by including varying structural properties along the wing span.

2. Numerical Method

2.1. CFD flow solver

For the assessment of aerodynamic loads, a three-dimensional incompressible Navier-Stokes CFD solver based on unstructured meshes was utilized. The equations can be written in an integral form for arbitrary computational domain $V$ with boundary $\partial V$ as

$$\frac{\partial}{\partial t} \int_V \vec{Q} \, dV + K \frac{\partial}{\partial \vec{n}} \int_V \vec{Q} \, dV + \int_{\partial V} \vec{F}(\vec{Q}) \cdot \vec{n} \, dS = \int_{\partial V} \vec{G}(\vec{Q}) \cdot \vec{n} \, dS$$  \hspace{1cm} (1)

where $\vec{Q}$ is the vector of the primitive variables, and $\vec{F}(\vec{Q})$ and $\vec{G}(\vec{Q})$ denote the inviscid and viscous fluxes of these variables, respectively. $K$ is the preconditioning matrix introduced to accommodate the artificial compressibility into the governing equations. In the present flow solver, the governing equations were discretized using a vertex-centered finite-volume method. The flow domain was divided into a finite number of control volumes surrounding each vertex. The inviscid fluxes were evaluated using second-order Roe’s flux-difference splitting scheme, while the viscous flux terms were computed based on central differencing. A dual-time implicit time integration algorithm based on linearized Euler backward differencing was utilized to advance the solution in time. To consider the turbulence effect, the Spalart-Allmaras one-equation model was adopted. The additional equation was solved separately from the mean flow equations in a loosely coupled manner.

The mesh movement due to wing elastic deformation was taken care of using mesh deformation techniques. To handle the deformation of prismatic elements near the solid surface, an algebraic approach was adopted, whereas a spring analogy was applied to the tetrahedral elements away from the body.

On the solid surface of the wing, the no-slip condition was applied. The characteristic inlet/outlet boundary condition with Riemann invariants was applied at the far boundaries. The symmetric boundary condition was imposed at the boundary containing the wing root.

To reduce the large computational time involved in the three-dimensional flow calculations, the flow solver was parallelized using MeTis and MPI libraries.

2.2. CSD structure solver

The high-aspect-ratio wing structure was modeled as a nonlinear Euler-Bernoulli cantilever beam undergoing spanwise deflection, lead-lag bending, flap bending, and torsional deformation by following the formulation described by
Hodges and Dowell.15) The equations of motion were derived based on Hamilton’s principle. In Fig. 1, the wing coordinate system and wing deformation kinematics are presented. The Cartesian coordinate system \( x, y, z \) is attached to the undeformed wing. The \( x \)-axis coincides with the elastic axis, and the \( y \)-axis, which points toward the leading-edge, is parallel to the extension of the chord line. When the wing is deformed, a point \( p \) on the undeformed elastic axis is moved to point \( p' \) by spanwise deflection \( (u) \), lead-lag bending \( (v) \), and flap bending \( (w) \) in the \( x, y, z \) directions, respectively. Then the wing cross section containing \( p' \) undergoes rotation of elastic torsion \( (\phi) \) about the deformed elastic axis \( (\xi) \). To obtain the discretized equations governing the wing elastic motion, a finite-element method was adopted. The wing is divided into a number of finite elements, and each element involves 15 nodal degrees of freedom as shown in Fig. 2.

The distribution of deformation over each element can be represented by appropriate interpolating polynomial shape functions. In the present study, the third-order Hermite polynomial, which allows continuities of both displacement and slope between the elements, was used for the lead-lag and flap bending deflections. For each spanwise and elastic torsion deformation, the third-order and second-order Lagrangian polynomials were utilized, such that the continuity of displacement is guaranteed. The discretized form of the model can be written as

\[
\int_{t_1}^{t_2} \left[ \sum_{i=1}^{N_e} \delta U_i - \delta T_i - \delta W_i \right] dt = 0 \quad (2)
\]

where the subscript \( i \) denotes the \( i \)-th beam element, and \( N_e \) is the total number of finite elements on the wing. \( \delta U_i, \delta T_i, \) and \( \delta W_i \) are the variation of strain energy, variation of kinetic energy, and virtual work done by the aerodynamic forces, respectively. After applying the interpolating polynomials, the above elemental energy variations can be expressed in the following matrix form in terms of the nodal displacement, \( q_i \), as

\[
M_i \ddot{q}_i + K_i q_i = F_{NL,i} + F_{\text{aero},i}
\]

\[
q_i^T = \begin{bmatrix} u_1, v_1, w_1, \phi_1, v'_1, \phi'_1, u_2, \phi_2, u_3, u_4, v_2, w_2, \phi_3, v'_2, w'_2 \end{bmatrix}_i
\]

Here, \( M_i \) and \( K_i \) are the elemental mass and stiffness matrices, respectively, and \( F_{NL,i} \) and \( F_{\text{aero},i} \) represent the elemental nonlinear vectors and the external aerodynamic loads on the \( i \)-th element of the wing. The global nonlinear equations of motion of the wing can be obtained by assembling the elemental matrices and the vectors over \( N_e \) beam elements as

\[
M \ddot{q} + Kq = F_{NL} + F_{\text{aero}}
\]

This dynamic system of equations is solved using the generalized-\( \alpha \) time integration method.16) The dynamic system of equations can be reduced to static equilibrium equations by neglecting the time derivative terms as

\[
Kq = F_{NL} + F_{\text{aero}}
\]

In Eq. (5), the aerodynamic load \( F_{\text{aero}} \) is determined using the CFD calculation in the coupled CFD-CSD method. In the case of comprehensive CSD solver calculations, the built-in strip theory aerodynamic model can also be utilized. In this case with the strip theory, the unsteady effect was considered by adopting an indicial step response method developed by Leishman et al.17,18) The strip theory was further extended to the nonlinear flow regime to include the effect of the nonlinearities in lift, pitching moment and drag behaviors due to airfoil stall by adopting a dynamic stall model described by Leishman and Beddoes.17,19)

2.3. Coupled CFD-CSD method

In the present study, the CFD and CSD solvers were coupled using a partitioned solution method. In this coupling methodology, the fluid and structural equations are solved separately in each module, but the information is properly exchanged. The CFD solver transfers sectional aerodynamic loads to the CSD solver by integrating surface pressure and skin friction along the chordwise direction at a number of cross sections of the wing. The CSD solver also transfers the wing deformation data as a function of spanwise location to the CFD solver.

The overall procedures for the present coupled CFD-CSD method are presented in Fig. 3. For static aeroelastic analyses, shown in Fig. 3(a), steady CFD calculation is conducted for the undeformed wing on the initial mesh. Once a steady-state flow solution is obtained, the sectional aerodynamic loads are transferred to the CSD solver, and the wing elastic deformation is calculated as in Eq. (5). To consider the calculated wing deflection in the CFD calculation, the mesh deformation technique is applied, and the mesh points are moved by following the wing deflection. Then, the flow simulation is conducted on the deformed wing configuration. The above procedure is repeated until a converged static equilibrium wing deformation is obtained. For the dynamic aeroelastic analysis presented in Fig. 3(b), the CFD and
CSD solvers are coupled tightly in a time-accurate manner, and information about the unsteady aerodynamic loads and aeroelastic deformation is exchanged at every time step. The converged steady-state solution is used as the initial condition for the unsteady coupled CFD-CSD simulations. Advancement of the solution in time is achieved by adopting the conventional serial staggered (CSS) method of Farhat et al.20)

3. Results and Discussion

3.1. NACA0012 wing

Initially, validation of the present coupled CFD-CSD method was made by calculating the aeroelastic behaviours of a flexible NACA0012 wing configuration. The wing has a rectangular planform shape without twist or sweep, and is made of an NACA0012 airfoil section from root to tip. The information about the wing configuration and its structural properties are summarized in Table 1.

In Fig. 4, the computational mesh used for the CFD calculations is presented. To capture the boundary layer on the wing surface more accurately, a hybrid mesh topology containing both prismatic and tetrahedral cells was used. A total of 25 layers of prismatic cells were packed normal to the wing surface with an initial grid spacing of $4 \times 10^{-5}$ chord and a stretching ratio of 1.25, and the remaining flow domain was filled with tetrahedral cells. The unstructured mesh used for both static and dynamic aeroelastic solutions consists of 1,462,427 nodes, 1,632,020 prismatic cells, and 3,597,144 tetrahedral cells.

3.1.1. Static aeroelastic analysis

First, static coupled CFD-CSD simulations were performed. The calculations were made for a flight speed of 25 m/s with an angle of attack of 2° at an altitude of 20 km. Figure 5 shows the spanwise distributions of the static wing deformation. The solution converged within approximately six coupled iterations where the tip deflection and twist changed less than 1% between iterations. The flap-up deflection and the nose-up torsion are predicted to be about 20% of span length and 1.5° at the wing tip, respectively. The chord-wise deformation is relatively small which is about 0.0025% of span length at the wing tip due to the large edgewise stiffness. The negative sign means the deformation occurred in a downwind direction. Overall, the present results compare well with other CFD-CSD results conducted by Hallissy and Cesnik,8) demonstrating that the performance of the coupled solver is proven, and the present static aeroelastic coupling has been validated.

3.1.2. Dynamic aeroelastic analysis

To investigate the aeroelastic behavior and stability, the wing was perturbed from the converged static deflection state, and then the aeroelastic response was observed over time. In the present study, an initial tip flapwise displacement was imposed as the disturbance, and the dynamic response of the wing was examined, similar to the study by Patil et al.3) The dynamic aeroelastic responses using the strip theory were also calculated to assess the effect of using a different aerodynamics model, in comparison to the present coupled CFD-CSD method.

In Fig. 6, comparison of the time history of wing tip flapwise deflection is shown for the initial tip displacements of 1, 2, and 4 m at a flight speed of 30 m/s with an angle of attack of 0°. It was observed that a critical magnitude of disturbance of 2 m is required to excite LCO at the specific speed of

| Table 1. NACA0012 wing geometry and structural properties. |
|---------------------------------|------|
| Semi-span (m)                   | 16   |
| Chord (m)                       | 1    |
| Elastic axis                    | Mid-chord |
| Center of gravity               | Mid-chord |
| Mass/span (kg/m)                | 0.75 |
| Inertia about mid-chord (kgm)   | 0.1  |
| Torsional stiffness (Nm²)       | $1.0 \times 10^4$ |
| Bending stiffness (Nm²)         | $2.0 \times 10^4$ |
| Edgewise stiffness (Nm²)        | $5.0 \times 10^6$ |
The amplitude and frequency of the motions during LCO do not change above the critical disturbance of 4 m. In Fig. 7, the time history of the wing tip flapwise deflection is presented for various flight speeds of 25, 28 and 30 m/s with an angle of attack of 0°. It is shown that a critical speed of 28 m/s is required to excite LCO (ω = 18.84 rad/s) for a specific disturbance with an initial tip displacement of 4 m, and above the critical speed of 30 m/s, a different LCO (ω = 15.7 rad/s) with higher amplitudes is observed. In the figures, the system tries to come back to a zero deflection steady-state with positive damping ratio below the critical point. However, above the critical point, the system absorbs more than the critical amount of energy before it reaches the zero steady-state, and it jumps to an unstable state and maintains the deformed state, providing the forces required to sustain the deformation.

The results using the present time-accurate coupled solvers show very similar trends with other results based on a geometrically-exact nonlinear beam model and a finite-state aerodynamic theory by Patil et al.3) From these dynamic stability analyses, the present coupled solvers were well validated by applying structural nonlinearity and unsteady viscous aerodynamics.

Although these dynamic behaviors and characteristics using both CFD and strip theory are similar to each other, slightly different characteristics of LCO are observed between the two results. Especially, at the flight speed of 30 m/s, a more simple periodic motion is observed in the CFD results compared to the strip theory. To examine the difference in more detail, phase-plane diagrams of LCO are

![Comparison of flapwise deflection](image1)

![Comparison of torsional deflection](image2)

![Chordwise deflection](image3)

Fig. 5. Static aeroelastic deformation at a flight speed of 25 m/s.

![Strip theory-CSD](image4)

![CFD-CSD](image5)

Fig. 6. Time history of flapwise tip deflection with various initial tip disturbances at a flight speed of 30 m/s.

![Strip theory-CSD](image6)

![CFD-CSD](image7)

Fig. 7. Time history of flapwise tip deflection for various flight speeds.
compared at the flight speed of 30 m/s in Fig. 8. When the strip theory is utilized, the complexity of the phase-plane diagrams is enlarged, and periodic doublings appear more clearly than the CFD-based results. This tendency indicates that utilization of the strip theory may cause earlier predictions in divergence and flutter speeds, because the complexity of LCO generally increases with flight speed. This also implies that the coupled CFD-CSD method provides more aerodynamic damping than the strip theory-CSD approach.

To analyze the effect of the structural nonlinearity on the dynamic stability of the wing, the dynamic behaviors of the wing were examined using the time-accurate coupled CFD-CSD method. Initially, a linear structural beam model, in which geometrically nonlinear terms were neglected, was utilized as the structure module. With an initial tip displacement of 4 m, the wing structure was released, and the aeroelastic responses were observed for various flight speeds of 25, 30, 31.67, and 35 m/s. In Fig. 9, the results of the time-domain damping ratios of torsional tip motions are presented. Here, the damping ratios were calculated by adopting a moving-block method. The figure shows that the linear flutter speed based on the damping ratios was predicted at 32.39 m/s, and the linear flutter frequency at the flutter speed was identified as 23.87 rad/s. These results are good in agreement with those of other predictions showing the linear flutter speed of 32.21 m/s and the flutter frequency of 22.61 rad/s.

When the geometric structural nonlinearity was disregarded, the dynamic responses were more stable and the point of flight velocity where LCO starts was delayed compared to the results using the nonlinear structural beam model. To be specific, the flutter speed of 32.39 m/s predicted using the linear structural beam model is faster than the flight speed where LCO starts using the nonlinear structural beam model, which is expected to be between 25 m/s and 28 m/s as shown in Fig. 7. This demonstrates that the structure nonlinearities reduce the wing stiffness and stability, as Tang and Dowell also indicated.

In Fig. 10, the dynamic aeroelastic response of the wing tip motion, including the nonlinear structural beam model, is presented for the two flight speeds. The wing structure was released from a flapwise tip displacement of 4 m; same as the previous linear structure analysis. When compared with the aeroelastic responses of the wing using the linear structure beam model, the overall dynamic stability was decreased. The amplitude of LCO, which was initially excited at 28 m/s as shown in Fig. 7, increased further at 30 m/s. When the flight speed was further increased to 33 m/s, the oscillations became aperiodic and showed a quite chaotic behavior because of the strong geometric nonlinearity.

Figure 11 shows the dynamic behavior of the wing and the pressure distributions on the wing surface during the LCO at the flight speed of 30 m/s. It was observed that a flap-up motion exists, along with the nose-down and lead motions. At the same time, a flap-down motion was also shown, accompanied by the nose-up and lag motions. An instantaneous high-pressure region appeared on the upper and lower surfaces of the wing during the flap-up and flap-down motions, respectively. In addition, the dynamic motion of the wing induced high-order vibration mode shapes, meaning that a large amount of energy is activated on the wing during the LCO.

In Fig. 12, the results of the Fast Fourier Transform for the torsional tip motion during the LCO are presented for the flight speed of 30 m/s. It was observed that a flap-up motion exists, along with the nose-down and lead motions. At the same time, a flap-down motion was also shown, accompanied by the nose-up and lag motions. An instantaneous high-pressure region appeared on the upper and lower surfaces of the wing during the flap-up and flap-down motions, respectively. In addition, the dynamic motion of the wing induced high-order vibration mode shapes, meaning that a large amount of energy is activated on the wing during the LCO.

In Fig. 12, the results of the Fast Fourier Transform for the torsional tip motion during the LCO were presented for the flight speed of 30 m/s. It was observed that there are three dominant fre-
frequency components exist: 15.7 rad/s, which corresponds to the nonlinear flutter frequency, 30.97 rad/s for the 1st torsional natural frequency, and 46.5 rad/s close to the second harmonic of the flutter frequency. Because of the nonlinear structural coupling between bending and torsion, the torsional and chordwise natural frequencies change as the tip displacement is increased. The nonlinear flutter frequency and second harmonic of the flutter frequency coincide with the cross-points between the 2nd flapwise (14.1 rad/s) and 1st torsional natural frequencies (30.97 rad/s), and the 3rd flapwise (39.36 rad/s) and 1st chordwise (31.73 rad/s) natural frequencies, respectively.\(^1\),\(^2\) The predicted nonlinear flutter frequency was much lower than the linear flutter frequency, and this tendency is very similar to the prediction of 15.83 rad/s by Patil et al.\(^3\).

### 3.2. Electric aerial vehicle wing

Next, the validated coupled CFD-CSD method was applied to the aeroelastic analyses of the wing of an electric aerial vehicle developed by the Korea Aerospace Research Institute. The full span length of the wing is 10.74 m, and the wing aspect ratio is approximately 21. The wing is untwisted, and is made of a SG6043 cambered airfoil section. The wing has an incidence angle of 1.65°/C\(^1\). The center of mass is located about 0.4\(c\), and the elastic axis is located at the quarter chord of the wing section along the wingspan. To reflect the realistic configuration of the wing into the aeroelastic analyses, the winglet was also considered for the CFD calculations, as well as the mass center offset from the elastic axis in the flap-torsional inertia coupling.

In Fig. 13, the structural properties and the sectional mass of the EAV wing are presented along the wingspan. The structural properties are not constant, but vary along the wingspan. In general, for high-aspect-ratio wings, a stiffer structure is required at the wing root to endure the bending moments invoked by the spanwise aerodynamic loading. Similarly, the wing of the electric aerial vehicle also possesses a structural stiffness distribution, which becomes more flexible toward the outward region. The first several natural vibration modes and the corresponding frequencies of the EAV wing were predicted as shown in Table 2.

The computational mesh and the boundary conditions for the CFD calculations are presented in Fig. 14. The unstructured mesh contains 1,390,259 nodes, 2,001,500 prismatic cells, and 2,108,863 tetrahedral cells. A total of 20 layers of prismatic cells are packed normal to the wing surface with an initial grid spacing of 8.0 \times 10^{-5} chord and a stretching ratio of 1.3 to capture the boundary layer on the wing surface accurately. The far-field configuration and the imposed
boundary conditions are similar to those of the previous NACA0012 wing case.

Unlike the NACA0012 wing case, the strip theory-based method could not be applied for dynamic stability of the EAV wing because the many empirical constants used for the NACA0012 wing in the dynamics stall model are not universal. Thus, a tuning process is required whenever the wing configuration changes. Although the strip theory-CSD method is much cheaper than the CFD-CSD method in terms of computational cost, the CFD-CSD method can be thought of as a valuable tool since it is free from not only the limitation of configuration, but also flow environment.

### Table 2. Predicted EAV wing natural frequency (Hz).

| Vibration mode | Vibration frequency |
|----------------|---------------------|
| 1st Eigenvalue | Flapwise 1.92       |
| 2nd Eigenvalue | Edgewise 5.09       |
| 3rd Eigenvalue | Flapwise 8.38       |
| 4th Eigenvalue | Torsional 10.45     |
| 5th Eigenvalue | Edgewise 19.85      |

### 3.2.1. Static aeroelastic analysis

The static aeroelastic analyses were first conducted at the operational flight speeds of 7.6 m/s and 10 m/s using both coupled CFD-CSD and strip theory-CSD methods. The converged spanwise wing deformations are shown in Fig. 15. At both flight speeds, the lag, flap-up bending and nose-down torsional deflections reached static equilibrium states, and the wing deflections increased in magnitude with the flight speed. Bigger torsional deflections are observed especially at the outward region of the wing because of the relatively small torsional stiffness. The strip theory results show bigger flap-up deflection and smaller lag deflection than the CFD-based results, although the overall behaviors are similar between the two approaches. The tendency of over-predicted flap-up deflection using the strip theory has also been previously observed using the low-order aerodynamics model.5)

### 3.2.2. Dynamic aeroelastic analysis

Using the converged static aeroelastic deflections as the initial condition, the wing was perturbed by applying a single-period sinusoidal force in the chordwise direction to the wing tip and the transient aeroelastic response was examined. The transient responses were observed at flight speeds of 7.6 m/s and 10 m/s.
of 7.6, 17, 18 and 20 m/s. For all flight speeds, the perturbation from the steady-state aeroelastic equilibrium was forced with an identical magnitude of 50 N. The applied sinusoidal frequency was 5 Hz, which corresponds to the first chordwise natural frequency.

\[ F_{\text{sin}}, = \begin{cases} 0 & t < 0 \\ 50 \sin(\omega_n t) & 0 \leq t \leq \frac{2\pi}{\omega_n} \\ 0 & t > \frac{2\pi}{\omega_n} \end{cases} \tag{6} \]

The time history of each deflection mode after the perturbation is shown in Fig. 16. It is observed that the flapwise and torsional modes are also excited, in addition to the chordwise direction, due to the nonlinear structural coupling between the three modes. Below the flight speed of 18 m/s, the amplitude of vibration decreases for all modes, and the wing shows a stable dynamic response. At the higher flight speeds of 18 m/s and 20 m/s, the amplitudes of vibration increase after the initial perturbation, and the wing experiences unstable behaviors. At the flight speed of 20 m/s, the rate of amplitude growth is pretty rapid, and the wing enters a LCO in a short period of time. The dynamic behavior of the unstable wing during the LCO is presented in Fig. 17. The results show that the behavior is similar to that of the NACA0012 wing described previously, with the flap-up motion coinciding with the nose-down and lead motions, and the flap-down motion with the nose-up and lag motions. The wing outward region was deflected much larger in magnitude than the inward region because of the relatively more flexible structure.

In Fig. 18, FFT analyses were performed for the chordwise and torsional tip motions, and the results are presented for the flight speeds of 17 m/s and 20 m/s. These two flight speeds were selected because they exhibit stable and unstable responses, respectively. It is observed that an excitation frequency of 4.8 Hz dominantly appears for both chordwise and torsional modes at the flight speed of 17 m/s. At the higher flight speed of 20 m/s, the dominant frequency component was 9 Hz, which corresponds to the nonlinear flutter frequency. The results indicate that the nonlinear flutter frequency is again caused by the nonlinear structural coupling between flapwise and torsional modes. This is presumably because the first torsional natural frequency of 10.45 Hz and the second flapwise natural frequency of 8.38 Hz are changed, becoming closer to each other at the nonlinear flutter frequency as the wing tip static deflection was increased at the flight speed of 20 m/s. A frequency of 18 Hz, which is close to the second chordwise natural frequency, is also observed with the chordwise motion, demonstrating that a large amount of energy with a high-order vibration mode shape is activated on the wing during the LCO.

4. Conclusions

In the present study, a coupled CFD-CSD method has been developed for predicting static aeroelastic deflections and dynamic aeroelastic behaviors of high-aspect-ratio wings. The wing aerodynamic loads were calculated using a Navier-Stokes CFD solver and unstructured meshes. The wing elastic deformations were obtained using a FEM-based CSD solver based on a nonlinear coupled flap-lag-torsion beam theory. The CFD and CSD solvers were coupled by adopting a conventional serial staggered (CSS) procedure.

Initially, the coupled calculations were conducted for a flexible NACA0012 wing for validation. It was found that the present CFD-CSD results are in good agreement with
other predictions for both static deformation and dynamic behavior. It was shown that the CFD-based loads provide more aerodynamic damping compared to the two-dimensional strip theory, which may cause earlier predictions in divergence and flutter speeds. It was also shown that geometrical nonlinearity is responsible for degrading the system stiffness and stability. Below the linear flutter speed, LCO occurred over a relatively wide range of flight speeds when structural nonlinearity is considered. The structural nonlinearity also influences wing dynamic stability more than the difference in the aerodynamic damping between CFD and strip theory.

The coupled CFD-CSD method was then applied to the high-aspect-ratio wing of an existing electric aerial vehicle. The static aeroelastic analyses showed that the strip theory tends to predict larger flap-up deflection compared to the CFD calculation. Time-accurate coupled CFD-CSD simulations were performed for various flight speeds. It was found that, above a critical flight speed, the wing motion becomes unstable and enters a LCO. During the LCO, the dominant frequency of the chordwise and torsional motions corresponds to the nonlinear flutter frequency, whereas the excitation frequency is observed dominantly at a stable flight speed.

Acknowledgments

This work was supported by the New & Renewable Energy Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20153030023880). This research was also supported by the Climate Change Research Hub of KAIST (Grant No. N01150026).

References

1) Patil, M. J., Hodges, D. H., and Cesnik, C. E. S.: Nonlinear Aeroelasticity and Flight Dynamics of High-altitude Long-endurance Aircraft, Proceedings of the 40th Structures, Structural Dynamics and Materials Conference, St. Louis, Missouri, USA, 1999.
2) Patil, M. J., Hodges, D. H., and Cesnik, C. E. S.: Characterizing the Effects of Geometrical Nonlinearities on Aeroelastic Behavior of High-aspect-ratio Wings, Proceeding of the International Forum on Aeroelasticity and Structural Dynamics, Williamsburg, Virginia, USA, 1999.
3) Patil, M. J., Hodges, D. H., and Cesnik, C. E. S.: Limit Cycle Oscillations in High-aspect-ratio Wings, Proceeding of the 40th Structures, Structural Dynamics and Materials Conference, St. Louis, Missouri, USA, 1999.
4) Petot, D.: Differential Equation Modeling of Dynamic Stall, No. 1989-5, La Recherche Aerospatiale, 1989.
5) Smith, M. J., Patil, M. J., and Hodges, D. H.: CFD-based Analysis of Nonlinear Aeroelastic Behavior of High-aspect Ratio Wings, Proceeding of the 41st Structures, Structural Dynamics and Materials Conference, Seattle, WA, USA, 2001.
6) Bendiksen, O. O.: Transonic Limit Cycle Flutter of High-Aspect-Ratio Swept Wings, J. Aircraft, 45 (2008), pp. 1522–1533.
7) Bendiksen, O. O.: High-Altitude Limit Cycle Flutter of Transonic Wings, J. Aircraft, 46 (2009), pp. 123–136.
8) Hallissy, B. P. and Cesnik, C. E. S.: High-fidelity Aeroelastic Analysis of Very Flexible Aircraft, Proceeding of the 52nd Structures, Structural Dynamics and Materials Conference, Colorado, Denver, USA, 2011.
9) Chorin, A. J.: A Numerical Method for Solving Incompressible Viscous Flow Problems, J. Comput. Phys., 135 (1997), pp. 118–125.
10) Roe, P. L.: Approximate Riemann Solvers, Parameter Vectors and Difference Schemes, J. Comput. Phys., 43 (1981), pp. 357–372.
11) Spalart, P. R. and Allmaras, S. R.: A One-Equation Turbulent Model for Aerodynamic Flows, Proceedings of the 30th Aerospace Sciences Meeting and Exhibit, Reno, NV, USA, 1992.
12) Kholodar, D. B., Mortan, S. A., and Cummings, R. M.: Deformation of Unstructured Viscous Grids, Proceeding of the 43rd AIAA Aerospace Science Meeting and Exhibit, Reno, NV, USA, 2005.
13) Bottasso, C. L., Detomi, D., and Serra, R.: The Ball-vertex Method: A New Simple Spring Analogy Method for Unstructured Dynamic Meshes, Comput. Meth. Appl. Mech. Eng., 194 (2005), pp. 4244–4264.
14) Acikgoz, N. and Bottasso, C. L.: A Unified Approach to the Deformation of Simplicial and Non-simplicial Meshes in Two and Three Dimensions with Guaranteed Validity, *J. Comput. Struct.*, 85 (2007), pp. 944–954.

15) Hodges, D. H. and Dowell, E. H.: Nonlinear Equations of Motion for the Elastic Bending and Torsion of Twisted Nonuniform Rotor Blades, NASA TN D-7818, National Aeronautics and Space Administration, 1974.

16) Chung, J. and Hulbert, G. M.: A Time Integration Algorithm for Structural Dynamics with Improved Numerical Dissipation: The Generalized-α Method, *J. Appl. Mech.*, 60 (1993), pp. 371–375.

17) Leishman, J. G. and Beddoes, T. S.: A Generalized Model for Unsteady Aerodynamic Behavior and Dynamic Stall using the Indicial Method, Proceeding of the 42nd Annual Forum of the American Helicopter Society International, Washington, DC, USA, 1986.

18) Leishman, J. G., Jose, A. I., and Baeder, J. D.: Unsteady Aerodynamic Modeling with Time-varying Free-stream Mach Numbers, Proceeding of the 61st Annual Forum of the American Helicopter Society International, Grapevine, TX, USA, 2006.

19) Leishman, J. G. and Beddoes, T. S.: A Semi-empirical Model for Dynamic Stall, *J. Am. Helicopter Soc.*, 34 (1989), pp. 3–17.

20) Farhat, C., Zee, K. G., and Geuzaine, P.: Provably Second-order Time-accurate Loosely-coupled Solution Algorithms for Transient Nonlinear Computational Aeroelasticity, *J. Comput. Meth. Appl. Mech. Eng.*, 195 (2006), pp. 1973–2001.

21) McNamara, J. I. and Friedmann, P. P.: Flutter-Boundary Identification for Time-Domain Computational Aeroelasticity, *AIAA J.*, 45 (2007), pp. 1546–1555.

22) Tang, D. M. and Dowell, E. H.: Effect of Geometric Structural Nonlinearity on Flutter and Limit Cycle Oscillations of High-aspect-ratio Wings, *J. Fluids Struct.*, 19 (2004), pp. 291–306.

S. Saito
Associate Editor