Static and Dynamic Aeroelastic Analysis of a High Aspect Ratio Wing through CFD-CSD Coupled Method

Jong-Hwan Kim
Aerospace and Mechanical Engineering, Korea Aerospace University
Goyang, Republic of Korea
purenbit@nate.com

Jae-Sung Bae
School of Aerospace and Mechanical Engineering, Korea Aerospace University
Goyang, Republic of Korea
jsbae@kau.ac.kr

Jai-Hyuk Hwang
School of Aerospace and Mechanical Engineering, Korea Aerospace University
Goyang, Republic of Korea
jhhwang@kau.ac.kr

Abstract—The Solar powered unmanned aircraft have a high-aspect-ratio wings because SPUAV must satisfy the requirement of long endurance and high lift-drag ratio. Therefore, the structure of SPUAV’s wings are structurally very flexible. The very high flexible wing might have large deformation and many aeroelastic problems. In this paper have a static/dynamic aeroelastic analysis through CFD-CSD coupled method. A Computational Fluid Dynamic is used to compute the aerodynamics and Finite Element Method is used for structural analysis.

Keywords—High Aspect Ratio Wing; SPUAV; CFD; CSD; Aeroelastic; Flutter

I. INTRODUCTION

During flight, aeroelastic phenomenon can happen due to interaction between elastic, inertial, and aerodynamic forces. Such aeroelastic phenomenon can be categorized into two groups; static and dynamic problems. One of the typical examples of dynamic aeroelastic phenomenon is flutter, which happens on certain flow conditions. It leads to unexpected increase on the size of the fluid-induced vibration, and it might result in the destruction of the structure within a few seconds. For the static aeroelastic phenomenon, there are the redistribution of the aerodynamic load due to wing transformation, control surface reversal, and divergence.

Recently, to solve such aeroelastic problems, the research using CFD-CSD coupled method or Fluid-Structure Interaction (FSI) has been actively conducted. Carnie and Qin [1] performed a static aeroelastic analysis of the Helios HP03 model developed by NASA using common CFD models, computerized structural analysis code, and self-developed deforming mesh code. LEE et al. [2] conducted a study on a high altitude solar aircraft that could fly 24 hours continuously by optimizing the wing. In their study FSI was used to analyze the static aeroelastic of the wing and NSGA-2 was optimized using multi-objective genetic algorithm. KIM and Lee [3] performed the analysis of load redistribution problem for a 3-D aircraft wings with control surfaces. Ye et al. [4] conducted the time-domain flutter analysis of AGARD Wing 445.6 model using Ansys CFX module. The AGARD model was used for flutter experiment at 1960's.

An aircraft wing has various configurations to have the best aerodynamic efficiency depending on the operation purpose and flight conditions. It is because aerodynamic performance is varied by the angle of incidence, the aspect ratio of the wing, the shape of the wing tip, etc. And it causes the difference on payload, fuel efficiency, range, endurance, and so on. The unmanned solar aircraft with High-Altitude Long-Endurance (HALE), which is expected to be able to replace of the satellite, has a high aspect ratio (AR) to achieve high aerodynamic efficiency by minimizing the drag force. However, the high AR wing could cause problems like large elastic deformation and aeroservoelastic instability because it is very flexible.

In the present study, a CFD-CSD coupled analysis of high AR wing is performed to verify its static and dynamic instability. CFX and Ansys were used to perform Aerodynamic analysis and structural analysis respectively. The method is by applying the generated aerodynamic force of CFD results as the load condition on structural analysis and once more using the displacement result of structural analysis to perform CFD analysis. The iterations go on until...
the results converge. In the case of the flutter analysis, it was conducted by passing each other's information of pressure, velocity, and displacement between the aerodynamic grid and structural grid.

II. ANALYSIS MODEL

Fig. 1 shows the solar-powered for the present study. Fig. 2 shows the CATIA model of its wing whose AR is about 14. The base materials of the wing are balsa wood and plywood which are commonly used in model aircrafts. In addition, composite materials was partially used for reinforcement on the wing. Aircraft specifications are presented in Table 1.

III. ANALYSIS

A. CFD analysis

Fig. 3 shows the flow field and grid of the wing used for the CFD calculations. The size of the flow field was modeled 20 times larger based on the chord length so that the flow could be stabilized. And the rear side was set three times the length of the front to stable the wake. Inlet conditions were set in the airspeed conditions of 11m/s and 37.5m/s for static aeroelastic analysis and flutter analysis, respectively. Outlet conditions were set in pressure 1atm. Even though un-structure grid is slower in calculation compared to the structure grid, it is easy to create the mesh of complex shapes and it is used in the present study. SST model was used to model the turbulence and boundary layer was built 20-ply up with 5mm thickness. Node points of flow field are 353,964 and the number of total elements is 1,070,665. About 50,000 grids are used for the wing surface to increase the accuracy of results. The Reynolds number at this time was about 220,000. The above conditions are applied the same for each and every repeated flow analysis.

<table>
<thead>
<tr>
<th>Categorize</th>
<th>Wing span</th>
<th>Wing area</th>
<th>Chord length</th>
<th>Aspect ratio</th>
<th>Flight weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.2m</td>
<td>1.25m²</td>
<td>0.3m</td>
<td>14</td>
<td>5.5kg</td>
</tr>
</tbody>
</table>

Fig. 3. Flow field

B. Verification of CFD Results

The present CFD results are verified for each boundary conditions, grid, and turbulence models in computational fluid dynamics. The calculation of steady-state aerodynamics was done by XFL5 which is a Vortex Lattice Method (VLM) widely used in the aerodynamic analysis of subsonic region. The present chordwise and spanwise pressure coefficient distributions of a rectangular wing are compared with those of XFL5 as shown in Fig. 4 and Fig. 5, respectively. The present results are good agreement with those of XFL5.

C. FEM analysis

ANSYS v.13 which is commonly utilized commercial computational analysis code was used for the structural analysis. In the case of load case, pressures around the wing are transformed directly on the surface mesh. For the contact conditions of each component, bonded conditions...
were used to share the node point. The number of nodes and elements used in the transformation between structural grids and aerodynamic grids are about 50,000 and 48,000 respectively.

**TABLE 2. Deformation of experiment & analysis**

<table>
<thead>
<tr>
<th>Load</th>
<th>Experiment</th>
<th>Analysis</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement(mm)</td>
<td>9.8N</td>
<td>40mm</td>
<td>37.5mm</td>
</tr>
<tr>
<td></td>
<td>19.6N</td>
<td>92mm</td>
<td>86.88mm</td>
</tr>
</tbody>
</table>

**TABLE 3. SPUAV wing Natural frequency**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.09</td>
</tr>
<tr>
<td>2</td>
<td>13.5</td>
</tr>
<tr>
<td>3</td>
<td>30.5</td>
</tr>
<tr>
<td>4</td>
<td>37.8</td>
</tr>
<tr>
<td>5</td>
<td>59.2</td>
</tr>
<tr>
<td>6</td>
<td>80.5</td>
</tr>
</tbody>
</table>

D. Static result verification

The static test of the present FEM model was performed for its verification. Table 2 shows the static deformation when the concentrated force is applied. The results show that the errors between the present analysis and experiment are under about 6%.

E. Free vibration analysis

For the flutter analysis the free vibration analysis of the present model was performed. The results are shown in Table 3. The natural frequency of the fundamental mode is 6.09 Hz. These results in Table 3 and its mode shapes are used in the following flutter analysis.

F. MSC.Nastran flutter analysis

Prior to the CFD-CSD coupled analysis The flutter analysis was performed by MSC.Nastran and its p-k method was used. From the flutter analysis the flutter speed and flutter frequency are 35m/s and 13.45Hz, respectively, for sea-level condition. This flutter speed will be verified in the preceding section.

**TABLE 4. Yield stress versus maximum stress**

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield stress(MPa)</th>
<th>Maximum stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>3900</td>
<td>378.13</td>
</tr>
<tr>
<td>Plywood</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Balsa</td>
<td>12.7</td>
<td></td>
</tr>
</tbody>
</table>

IV. RESULT

A. Static aeroelastic analysis

The computation condition for the static aeroelastic analysis is the airspeed of 11m/s at the sea level. The aerodynamic forces on the wing surface calculated from CFD are transformed to the structural loads applied for FEM analysis. The deformations of the wing from FEM are re-transformed to the CFD grid. These transformations were performed iteratively until converged. The number of iteration for convergence was 7 as shown in Fig. 6. When converged the stress distributions and pressure distributions of the wing are presented in Fig. 7 and Fig. 8, respectively. From the static aeroelastic results it can be concluded that divergence does not occur since the cruise air speed of the present wing is about 9 m/s.
B. Dynamic aeroelastic analysis

Finally the present study performed the dynamic aeroelastic analysis of the high AR wing using ANSYS’s CFX and transient structural analysis modules. The computational condition is determined by the airspeed of 37.5 m/s from MSC.Nastran’s results. From the present coupled analysis the vertical displacements of trailing edge (TE) and leading edge (LE) of the wing tip are monitored whether the flutter occurs or not. Fig. 9 shows the time history of TE displacement of the wing tip. It is known that the response is neutrally stable and the present coupled results are in a good agreement with those of MSC.Nastran. The flutter results shows that the present wing is aeroelastically stable at the cruise speed.

V. CONCLUSION

In the present study, the CFD-CSD coupled analysis for static and dynamic analysis were performed for the high AR wing of the solar-powered UAV. FEM model and CFD model of the present high AR wing are established and they are verified. Static and dynamic aeroelastic analyses of the wing using CFD-CSD coupled method are performed. The results show that the present wing is aeroelastically stable for both static and dynamic cases.

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