Fundamental Study on Adaptive Wing Structure for Control of Wing Load Distribution*

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(Received February 8th, 2017)

When damage occurs on a wing during flight, the stress at the damage site becomes large and the risk of catastrophic failure increases. In order to deal with this problem, Objective Stress Reduction (OSR) is considered by controlling the wing load distribution using an adaptive wing. The purpose of OSR is to reduce all or part of the stress acting on the wing. OSR also helps to adjust the extent of reduction depending on the condition in order to avoid increasing drag as much as possible. Static aeroelastic analysis is conducted for an adaptive wing model that has plain flaps at its leading- and trailing-edges using MSC/NASTRAN. From the results of a parametric study, it is revealed that the bending moment and drag are in a trade-off, and that OSR can adjust the extent of stress reduction depending on the various flight conditions by controlling the set of flap deflection angles.

Key Words: Adaptive Wing, Aeroelasticity, Structural Analysis

Nomenclature

\( \delta \) : flap deflection angle
\( \delta' \) : value calculated from lift distribution
\( AR \) : aspect ratio of wing
\( b' \) : semispan length
\( C \) : coefficient
\( L' \) : lift per unit span
\( L \) : lift
\( LEF \) : leading-edge flap
\( M \) : bending moment
\( TEF \) : trailing-edge flap
\( x \) : chordwise direction
\( y, \eta \) : spanwise direction
\( z \) : direction forming right-handed coordinate system with \( x \) and \( y \)

Subscripts

\( 0 \) : without flap deflection
\( D_i \) : induced drag
\( i \) : flap number counting from inboard wing
\( \text{max} \) : maximum
\( r \) : wing root
\( \text{total} \) : total

1. Introduction

With the recent emphasis on economy and environmental feasibility, the demand for fuel-efficient aircraft is increasing. These aircraft use different features and techniques to reduce fuel consumption and improve fuel efficiency. One of the effective ways to reduce the weight of the aircraft is to introduce lightweight materials, such as carbon fiber reinforced plastics (CFRP). Another remarkable feature is to introduce a high aspect ratio wing to reduce the induced drag. In addition, an adaptive wing is also considered as an approach from the perspective of functionalized structure.

The adaptive wing is a wing that can change its form and aerodynamic force during flight. The typical constitution of this wing has variable camber surfaces at its leading- and trailing-edges.1) Today’s aircraft wings equipped with flaps and ailerons are also adaptive wings in a broad sense. Conventionally, these wings are deformed as a high-lift device at the time of take-off and landing, or as a control surface at the time of maneuvering, and are never used under other flight conditions. On the other hand, in the case of an adaptive wing, they are deformed more aggressively to control wing load distribution under other flight conditions, such as when cruising. To control wing load distribution, the adaptive wing in this study refers to the wings introducing some control surfaces in the spanwise direction.

Generally, aircraft wings are designed to be either optimal for a single cruise flight condition or near-optimal for multiple flight conditions. That is, the wings are less optimal for any other flight conditions. The adaptive wing can modify the spanwise load distribution during flight to be more suitable for a wider range of conditions in the flight profile.

Several previous studies have been conducted to investigate the potential performance of adaptive wings, and their purposes are mainly divided into two categories: drag reduction2-4) and load alleviation.5-7) Rodriguez et al. conducted an aeroelastic analysis for a wing of the Generic Transport Model (GTM) aircraft with the adaptive wing that is known as the Variable Camber Continuous Trailing-Edge Flap (VCCTEF) system, and showed the wave drag reduction by deflecting the VCCTEF.2) Lebofsky et al. showed a large reduction in the
maximum bending moment of the Truss-Braced Wing (TBW) by deflecting VCCTEF. Tamayama et al. also applied an adaptive wing to the High-Altitude Long Endurance Aerial Vehicle (HALE), as a wing aspect ratio of about 20, and significant amount of the wing root bending moment was reduced. In such a wide variety of applications, Objective Stress Reduction (OSR) is considered as a new usage of the adaptive wing in this study. Although OSR is a type of load alleviation, its purpose is not only to reduce the maximum load acting on the wing when the aircraft is in a high-g maneuver or under the condition of encountering wind gusts. The purpose is to reduce all or part of the load by changing the extent of reduction depending on the various flight conditions without increasing the drag as much as possible. In the future, CFRPs will be used extensively to make aircraft parts, including wings, to achieve the desired weight saving. In that case, a significant reduction in strength due to damage is one of the concerns. Therefore, researches have been actively carried out on Structural Health Monitoring (SHM), which rapidly evaluates the damage conditions during flight. In addition, research on the strain measurement method related to SHM has been conducted. With these technologies, it is possible to conduct damage detection and inverse estimation of load distribution. On the basis of the information, it is possible to reduce the stress at the damage site by controlling the aerodynamic load distribution using an adaptive wing.

The purpose of the present study is to investigate the potential feasibility of using OSR by conducting a static aeroelastic analysis of an adaptive wing model using MSC/NASTRAN. The wing model has four plain flaps that can be deflected independently at each of its leading and trailing edges. By conducting a parametric study of the flap deflection angles, it is ascertained whether or not the adaptive wing can correspond to some flight conditions.

2. Aeroelastic Analysis

For this study, an aeroelastic analysis is conducted to consider the change in aerodynamic force generated by the wing deformation. The solver used is the SOL144, the aeroelastic solver in MSC/NASTRAN. The wing model has four plain flaps that can be deflected independently at each of its leading and trailing edges. By conducting a parametric study of the flap deflection angles, it is ascertained whether or not the adaptive wing can correspond to some flight conditions.

2.1. Analysis models

The semispan wing model used in this study is based on the JAXA Technology Reference Aircraft (TRA) 2012A, a 120-passenger commercial transport aircraft. The specifications for the JAXA TRA2012A are shown in Table 1. Using the values in Table 1, the semispan wing model is generated and its two-view drawing is shown in Fig. 1. Here, the swept-back angle at the 25% chord line and dihedral angle are assumed to be 0°, and the taper ratio is set to be 0.3. The root and tip chord length are 5,102mm and 1,656mm, respectively. The semispan length is 15,200mm. The wing thickness at the root and tip are 559mm and 181mm, respectively. The chord length and the wing thickness vary linearly along the spanwise direction. The wing section has a super-critical airfoil, the “NASA/Langley whitcomb integral supercritical airfoil.” There are four flaps with equal spanwise lengths of 3,800mm at each of the wing leading- and trailing-edges as devices to modify the spanwise load distribution. The leading-edge and trailing-edge flaps are named as “LEF i” and “TEF i” respectively, where i = 1~4 and “i” is the flap number counting from the most inboard one.

As mentioned above, two analysis models are required to perform an aeroelastic analysis. The structural model is shown in Fig. 2. The model is composed of spars, ribs and skins in order to investigate the stress of each member to improve fidelity. In Fig. 2, the skins at the 3rd and 4th flap sections are removed so that it is easy to see the inner structure. The front and rear spars are placed at the 15% and 60% chord lines, and each flap section has seven ribs. The structural model is divided into 15 elements in the chordwise direction and 96 elements in the spanwise direction, and shell elements are used. The material is assumed to be ultra-duralumin. The thicknesses of each member at the root and tip are shown in Table 2. These Fig. 1. Two-view drawing of wing model [mm].

![Fig. 1. Two-view drawing of wing model [mm].](image1)

![Fig. 2. Structural model.](image2)

![Table 1. Specifications of the JAXA TRA2012A.](table1)

<table>
<thead>
<tr>
<th>Cruise Mach number</th>
<th>0.78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing area</td>
<td>1.224 * 10^4 [mm^2]</td>
</tr>
<tr>
<td>Fuselage diameter</td>
<td>3,700mm</td>
</tr>
<tr>
<td>Lift coefficient at cruising</td>
<td>0.5194</td>
</tr>
<tr>
<td>Cruise altitude</td>
<td>35,000ft (same as A319)</td>
</tr>
</tbody>
</table>

![Table 2. Thickness of spars, ribs and skins [mm].](table2)

<table>
<thead>
<tr>
<th>Member</th>
<th>Root</th>
<th>Tip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spur</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Rib</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Skin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wing box</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Flap</td>
<td>4.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
values vary linearly along the wing span. The flaps are attached to the wing box, with rigid bar elements placed at the 2nd, 4th and 6th ribs of each flap counting from the most inner position. A rigid boundary constraint is applied to the node placed at the center of the wing root: this node is connected to other nodes on the wing box with the constraint having six degrees of freedom.

The aerodynamic model is shown in Fig. 3. Aerodynamic force acting on the object in a subsonic flow is calculated according to the lifting surface theory in MSC/NASTRAN. Thus, the model is a plate, and divided into 20 elements in the chordwise direction and 40 elements in the spanwise direction. The effects of the airfoil camber and flap deflection are considered as downwash acting on each panel. Then, the inputs of the calculation are Mach number, dynamic pressure, angle of attack, and downwash acting on each aerodynamic panel, and the output is aerodynamic force acting on each aerodynamic panel. However as mentioned later, the Mach number, dynamic pressure and angle of attack are constant. By summing the aerodynamic force acting on each panel along the 25% chord line, the lift and bending moment distributions can be calculated.

2.2. Analytical conditions

The particular flight conditions used for this study are cruise flight conditions. According to the specification for the JAXA TRA2012A in Table 1, the cruise Mach number 0.78 and cruise altitude 35,000 ft. are used. To generate enough lift for cruise flight conditions, the cruise Mach number 0.78 and cruise altitude 35,000 ft. are used. To generate enough lift for cruise flight without any flap deflection, the angle of attack is set to 1.1°. The case without any flap deflection is taken as the baseline in this study and is called the “base flight condition.” The total lift, wing root bending moment and maximum von-Mises stress of the spars, ribs and skins of the base flight condition are presented in Table 3.

3. Parametric Study

The purpose of OSR is to reduce all or part of stress acting on the wing and to adjust the extent of reduction depending on the conditions in order to avoid increasing drag as much as possible. The stress is mainly determined by the bending moment and torsional moment. However, the absolute value of torsional moment is much smaller than that of bending moment (see Fig. 7 and Fig. 10). Then, only the bending moment is discussed in this paper. Here, it is noted that buckling criterion should be considered for the static and aeroelastic structural design. However, the present study does not take buckling into account and evaluates the bending moment distributions using the aerodynamic loads and resulting stress distributions. The feasibility of controlling of wing load distribution using flaps (i.e., OSR) is investigated without determining the dimensions of detailed structures of the wings. Structural design considering buckling is to be conducted in future work.

In order to make the bending moment small, it is generally required to increase the lift generated on the inboard wing and to decrease that generated on the outboard wing. However, this means that the lift deviation becomes larger from elliptic lift distribution, for which the induced drag is minimum. Therefore, OSR results an issue of trade-off between bending moment and drag. In this section, the parametric study on OSR is conducted to discuss the trade-off issue.

3.1. Parameters

The parameters of this study are flap deflection angles δ as shown in Eq. (1).

\[ \delta = \{ \delta_{LEF1}, \ldots, \delta_{LEF4}, \delta_{TEF1}, \ldots, \delta_{TEF4} \} \]  

Figure 4 shows the definition of the flap angles sign. Nose-up is positive for the LEFs and nose-down is positive for the TEFs.

3.2. Constraints

In this study, two constraints are considered for the parameters, shown in Eq. (2) and Eq. (3).

\[ -10^\circ \leq \delta \leq +10^\circ \]  

\[ \frac{L_{total}(\delta) - L_{total,0}}{L_{total,0}} \leq 0.01 \]  

First of all, the upper and lower limits, 10° is applied to flap angles δ (δ_{LEFs} and δ_{TEFs}), as shown in Eq. (2). This limitation is required to avoid impractical large angle values, which cause an unfavorable large drag under cruise condition.

Next, in order to maintain the cruise flight conditions, the total lift \( L_{total}(\delta) \) is made to be equal to that of the condition without flap deflection, \( L_{total,0} \). Thus the error from \( L_{total,0} \) is accepted up to 1%, as shown in Eq. (3).

3.3. Evaluation parameters

As described above, the purpose of OSR is to reduce all or part of stress acting on the wing and to adjust the extent of reduction depending on the conditions in order to avoid increasing drag as much as possible. Accordingly, one of the evaluation parameters is the bending moment distribution \( M(\gamma) \), which is a major factor in determining the wing stress. \( M(\gamma) \) is calculated from the lift distribution \( L(\gamma) \) obtained from MSC/NASTRAN using Eq. (4).

\[ M(\gamma) = \int_{y}^{b'} L'(\eta)(\eta - y) \, d\eta \]  

Another parameter is coefficient of induced drag, \( C_{D\iota} \).

<table>
<thead>
<tr>
<th>Table 3. Total lift, maximum bending moment and maximum von-Mises stress of the base flight condition.</th>
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<tbody>
<tr>
<td>Total lift, ( L_{total} ) [N]</td>
</tr>
<tr>
<td>Maximum bending moment, ( M_{max} ) [Nmm]</td>
</tr>
<tr>
<td>Spat</td>
</tr>
<tr>
<td>Rib</td>
</tr>
<tr>
<td>Skin</td>
</tr>
</tbody>
</table>

Fig. 3. Aerodynamics model.

Fig. 4. Definition of flap angle sign (i=1–4).
Although, the total drag is the sum of parasite drag and induced drag in incompressible flow, the increase in parasite drag due to flap deflection is assumed to be small because the flap angles are limited to small values, as described above. Therefore, considering the induced drag is sufficient. The $C_{D,i}$ is calculated according to the lifting line theory and expressed as Eq. (5).

$$C_{D,i} = \frac{C_L^2}{\pi AR} (1 + \delta')$$  \hspace{1cm} (5)

Here, $\delta'$ is calculated from the lift distribution $L'(y)$.

### 3.4. Sets of flap deflection angles

Many sets of flap deflection angles should be calculated using MSC/NASTRAN. The sets of flap deflection angles are determined according to the following steps:

**Step 1:** Total lift $L_{total}$ is approximately expressed as a function of eight flap deflection angles. The approximate function is created as a second-degree polynomial model. In order to determine the coefficients of the function, 100 analyses are carried out. The 100 analyses are determined using a central composite design, the experimental design that is usually used for second-degree modeling, using the “ccdesign” function of MATLAB.

**Step 2:** The sets of flap deflection angles are shown in Table 4. Table 4 reveals that each LEF has five values and each TEF has seven values, and that a total of 1,500,625 sets of flap deflection are considered. All of the flap deflection angles are discrete values in order to reduce the analysis cost. The number of LEF values is less than that of TEF values because the effects of LEFs on total lift are relatively smaller than those of TEFs. The values of TEF1 and TEF2 are different from those of TEF3 and TEF4 because there is no need to drastically decrease the lift of inboard wing or drastically increase the lift of outboard wing.

Although the sets of flap deflection angles are discrete, the number of the sets is too many to analyze using MSC/NASTRAN. Then, the number is reduced using the approximate function created in Step 1. Only the sets of flap deflection angles whose approximate total lift fulfill Eq. (3) are calculated using MSC/NASTRAN. Finally, the number of sets becomes 3,436.

### 4. Results & Discussions

The sets of flap deflection angles are calculated using MSC/NASTRAN, and the relationship between wing root bending moment $M_r$ and the coefficient of induced drag $C_{D,i}$ of each case are plotted in Fig. 5. Here, all cases fulfill Eq. (2) and Eq. (3). Figure 5 shows that the lower the $M_r$, the higher the $C_{D,i}$, meaning that $M_r$ and $C_{D,i}$ are in a trade-off as mentioned above. The closed square shows the base flight condition in Fig. 5. Here, let us consider four other cases and the flap deflections shown in Fig. 5: Case A (solid rhombus), Case B (left solid triangle), Case C (right solid triangle) and Case D (solid circle). Case A has the minimum $C_{D,i}$ and Case D has the minimum $M_r$. Case B and Case C are discussed in Section 4.2. The values of $M_r$ and $C_{D,i}$ for the base flight condition, Case A and Case D are shown in Table 5. The $C_{D,i}$ of Case A is reduced by 3.82% and the increase in $M_r$ is small. On the other hand, the $M_r$ of Case D is reduced by 52.0% and there is a significant increase in $C_{D,i}$.

The lift distribution of each case and elliptic lift distribution are shown in Fig. 6. For Case A, compared to the base flight condition, the lift generated on the inboard wing decreases and that generated on the outboard wing increases, so that the lift distribution becomes close to the elliptic distribution, for which the induced drag is minimum. The flap deflection of Case A in Fig. 5 shows that TEF1 deflects to decrease the lift and TEF3 deflects to increase the lift. On the other hand, LEFs have no noticeable tendency. This is because the effects of LEFs on lift are small and the values of LEFs are discrete.

The bending moment distribution of each case is shown in Fig. 7. Although the bending moment of Case A increases along the wing span compared to that of the base flight condition, the
amount of increase is very small. For Case D, compared to base flight condition, the lift generated on the inboard wing increases and that generated on the outboard wing decreases so that the wing root bending moment becomes minimum. The flap deflection of Case D in Fig. 5 shows that the flaps deflect to increase the lift of the inboard wing and to decrease that of the outboard wing. Then, the bending moment is reduced significantly along the wing span as compared to the base flight condition.

The torsional moment distribution of each case is also plotted in Fig. 7. The torsional center is on the 25% chord line. As mentioned above, the absolute values of the torsional moments are smaller than those of the bending moments.

Based on the distributions mentioned above, cruise flight conditions of the following two cases are considered: one is the condition without any damage on the wing and the other is that with some damage on the wing.

4.1. Cruise flight conditions without any damage

When the aircraft is under cruise flight conditions and it does not have any damage, there is no reason to reduce the stress and the requirement on the wing is to minimize the drag. Therefore, Case A is the best at this time. The stress distributions of the base flight condition and Case A are shown in Fig. 8 (a) and (b), respectively. Compared with the stress of the base condition in Fig. 8 (a), those of Case A in Fig. 8 (b) do not change nor do they increase significantly. It can also be said that the penalty due to the increase of bending moment is sufficiently small.

4.2. Cruise flight conditions with some damage

When the aircraft has one or more points of damage on the wing, the stress at the damage site increases and the risk of damage growth that can result in failure also increases. In order to avoid such a risk, the requirement for OSR is to reduce the load acting on the wing. Here, it should be noted that the requirement is not to minimize the load, but to reduce the load by some extent. Of course, it is possible to reduce the stress along the wing span with Case D, where the amount of stress reduction is the largest. However, there is no need to minimize the load or stress because it is sufficient to reduce the load by the extent that the damage does not progress. Therefore, it is important to consider how much and where to reduce the stress. Here, let us consider Case D and the remaining two cases in Fig. 5: Case B, where $M_r$ is reduced by about 20%, and Case C, where $M_r$ is reduced by about 40%.

The lift distributions and bending moment distributions of the base flight condition, Case B, Case C and Case D are plotted in Fig. 9 and Fig. 10, respectively. As shown in Fig. 9 and Fig. 10, the lift generated on the inboard wing increases and that generated on the outboard wing decreases in all cases. Additionally, the larger the lift deviation from that of the base flight condition, the larger the extent bending moment reduction along the wing span. The flap deflections of the three cases in Fig. 5 show that TEFs deflect to decrease the lift of the inboard wing and increase that of the outboard wing. In addition, the absolute values of the flap angles become larger as the lift deviations increase. However, LEFs have no noticeable tendency because of the same reason as Case A.
The torsional moment distribution of each case is also plotted in Fig. 10. As mentioned above, the absolute values of the torsional moments are smaller than those of the bending moments.

In Fig. 10, the bending moment distributions on the outboard wing for Case B, Case C and Case D are close to each other, especially when $y$ is more than 10,000mm. This means that if damage exists only around the wing tip, the best flap deflection is Case B, where the lift deviation and drag are the smallest of all three cases. On the other hand, if damage also exists on the inboard wing, Case C and Case D are more effective in terms of stress reduction. Of course, which to use depends on the required extent of stress reduction and it is decided according to the structure and materials used.

5. Conclusions

In order to reduce all or part of stress acting on the wing without increasing the drag as much as possible, Objective Stress Reduction (OSR) was considered as a new means of using an adaptive wing. Static aeroelastic analysis was conducted for an adaptive wing model with four plain flaps at using an adaptive wing. Static aeroelastic analysis was conducted for an adaptive wing model with four plain flaps at using an adaptive wing. From the results of a parametric study, it was revealed that there is a trade-off between bending moment and drag, and that OSR is capable of adjusting the extent of stress reduction depending on the various flight conditions. For future research, the set of flap deflection angles need to be optimized while assuming specific damage.

Acknowledgments

This study was conducted under the financial support of Grant-in-Aid for Scientific Research (No.15K06598) from the Japan Society for the Promotion of Science.

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