Improvement of Aerodynamic Performance of the Aero-Train by Controlling Wing-Wing Interaction Using Single-Slotted Flap

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Aero-train is a new driving concept using aerodynamic technology under development by the Kohama Laboratory, Institute of Fluid Science, Tohoku University. It employs the wing-in-ground effect to enable travel at high speeds over land. Aero-train makes use of the ground effects of lift and side force between the wings and a U-shaped guideway for stability. The main wings have vertical wings at the tips, which are arranged in tandem to regulate the roll and yaw stability in the U-shaped guideway. However, the vertical wings deteriorate the lift-to-drag ratio of the Aero-train by aerodynamic interaction with the main wings. The present study was performed to improve the aerodynamic performance of the Aero-train by controlling wing-wing interaction. Installation of a single-slotted flap on the wings considerably improved the aerodynamic performance of the wings.

Key Words: Computational Fluid Dynamics, Finite Element Method (FEM), Flow Control, Flow Visualization, Separation, Single-Slotted Flap, Wing-Wing Interaction

1. Introduction

Recently, due to the increase in environmental problems, research and development of transport systems cannot be carried out without considering energy efficiency and environmental impact. The Aero-train is a new concept of a super high-speed ground transportation system using natural energy resources(1). As envisioned, it will be able to reduce the energy consumption to a minimum by aggressively using the ground effect.

The ground effect is the effect of the rise of pressure under the wing and weakening of the wing tip vortices as the wing approaches the ground. Hence, the ground effect increases the lift-to-drag ratio (L/D).

The Aero-train makes use of a U-shaped guideway, in which stability is enhanced by the ground effects of lift and side force. The main wings have vertical wings at the tips. These vertical wings are arranged in tandem to automatically regulate the lateral position of the Aero-train in the U-shaped guideway by utilizing the wing-in-ground effect between the vertical wings and the side walls. However, the vertical wings deteriorate the L/D of the Aero-train due to aerodynamic interaction with the main wings, as experienced in the flight testing of the Aero-train. In the current design of the Aero-train, there is a large separation region at the juncture of the main wing and the vertical wing. A picture of the separated flow is shown in Fig. 1. The size of the Aero-train is 8.5 m in length, 3.4 m in width, and 1.2 m in height. The propellers are driven by electric motors. The total distance of the guideway is about 2 km. Flight test is carried out at the velocity of about 100 km/h and it is controlled automatically by a personal computer. The L/D of the current model is about 13.

The objective of this study was thus to increase the L/D of the Aero-train by controlling the separated flow at the juncture of the main wing and the vertical wing by means of a single-slotted flap(2), (3). Also, an attempt was made to maintain the ground-effect characteristics (the slope of the C_L curve plotted to the height of the wing from the ground) of the wings by installing a single-slotted flap because the ground effect works as a restoring force to maintain the suspension-height of the Aero-train. Since separation is closely related to the energy dissipation in the boundary layer, it can be delayed by controlling the boundary layer. If air flows through the slot from the lower surface to the upper surface, a new boundary layer is developed on the upper surface of the flap. This prevents separation of the flow. In addition, the energy of the flow, which has become exhausted while passing over the upper surface of the main wing, is enhanced by the slot.

To increase the L/D, wind tunnel experiments were...
carried out using wing models with the slotted flap. The shape of the slot of the wing models was decided by preliminary computation. In the wind tunnel experiments, the controllability of separated flow and the change of the ground effect characteristics of the wings resulting from installation of a single-slotted flap were evaluated.

Nomenclature

\[ bm \] : semispan of main wing [mm]
\[ bs \] : span of vertical wing [mm]
\[ CD \] : drag coefficient \([D/\{1/2 \rho U^2_\infty (S_m+S_s)\}]\)
\[ CL \] : lift coefficient \([L/\{1/2 \rho U^2_\infty S_m\}]\)
\[ CSF \] : side force coefficient \([L_s/\{1/2 \rho U^2_\infty S_s\}]\)
\[ cm \] : chord of main wing [mm]
\[ cs \] : chord of vertical wing [mm]
\[ D \] : drag [N]
\[ hm \] : trailing edge height of main wing over ground plate [mm]
\[ hs \] : trailing edge height of vertical wing over side plate [mm]
\[ hm/cm \] : trailing edge height over chord of main wing
\[ hs/cs \] : trailing edge height over chord of vertical wing
\[ L \] : lift of main wing [N]
\[ L/D \] : lift-to-drag ratio
\[ LS \] : side force (lift of vertical wing) [N]

2. Numerical Analysis

Numerical analysis was carried out using a finite element analysis program (ANSYS). The flow field was analyzed using the CFD of ANSYS. This flow model uses the transport equation derived from the 3-D Navier-Stokes equation. It uses the incompressible energy equation and the standard \(k-\varepsilon\) model for a turbulence model. The numerical analysis was performed to determine the flow at the juncture of the main wing and the vertical wing, and the slot shape.

2.1 Mesh and boundary condition

Figure 2 shows the computational mesh around the wing model with single-slotted flaps.
wings. It contains 729,580 nodes and 709,766 elements. An element consists of a 3-D fluid element with an eight-node brick. As for the coordinate system, the $x$-axis is streamwise and the $z$-axis is spanwise, the $y$-axis being perpendicular to the $x$-axis and $z$-axis. As for the size of the model of the wings, the main wing has a chord of 150 mm and a span of 160 mm, and the vertical wing has a chord and span of 100 mm.

For the boundary conditions in this analysis, the no-slip condition was applied to the flow on the wing surface and symmetric boundary condition was used at the root of the wing. Freestream velocity was 35 m/s and the velocity of the ground and that of the side wall were equal to the freestream velocity. The freestream velocity $U_\infty$ was 35 m/s, yielding a Reynolds number of $Re = 3.5 \times 10^5$ based on the chord length of the main wing. The whole domain was assumed to be turbulent.

2.2 Results

Figure 3 shows models with and without the single-slotted flap on the main and vertical wings. The velocity vectors shown here are 1 mm above the surface of the wing. The slot gaps increase from the 3-mm entrance on the low surface to the 8-mm exit on the upper surface, such as in Fig. 2. This shape and location of the slot showed the best results in controlling the boundary layer and the separated flow at the juncture. The location of the slot of the main wing is 31% chord from the trailing edge and the location of the slot of vertical wing is 30% chord from the trailing edge. This result shows that the separated flow due to wing-wing interaction can be controlled by a slotted flap.

3. Wind Tunnel Experiment

This experiment was carried out based on the data obtained from numerical analysis. Here, the locations of the slot were determined to allow good ground-effect characteristics of the lift and the side force.

3.1 Experimental set-up and procedure

Figure 4 shows the experimental set-up and the coordinate system that was used. As for the coordinate system, the $x$-axis is streamwise and $z$-axis is spanwise of the main wing, and the $y$-axis is perpendicular to the $x$-axis and $z$-axis.

Figure 5 shows the shape and layout of the wing model. $\alpha_m$ was defined as the angle of the lower surface of the main wing and the ground plate, and $\alpha_s$ was defined as the angle of the lower surface of the vertical wing and the side plate. The U-shaped guideway is imitated by the ground plate and the side plate. These plates were made of aluminum, and the side plate was vertically installed on the ground plate. There is an extension wall installed on the right side wall of the wind tunnel to maintain constant...
flow in the guideway, and a 3-component force load cell is attached to the extension wall. On the other side, a support for connecting the wing and the load cell is fixed at 1/4 chord of the main wing. In Fig. 4, αm is changed by rotating the support. hm is changed by moving the load cell and the extension wall. Similarly, h is changed by moving the side plate. The model with αs = 2° is installed perpendicular to the main wing, which has a value αm = 0°. The main wing has a span of 160 mm and a chord of 150 mm, and the vertical wing has a span and chord of 100 mm. The airfoil of the main wing is NACA6412m and CLARK Y60 for the vertical wing. NACA6412m of the main wing is a modification of NACA6412, with its lower surface being improved by making it a flat plate in consideration of ground-effect characteristics. There is a dummy wing, with a span of 50 mm, between the main wing and the extension wall. This dummy wing has the same airfoil as the main wing. The purpose of this wing is to eliminate the effect of the extension wall and to reduce the aerodynamic forces acting on the support. The main wing is fixed 0.3 mm away from the dummy wing to eliminate the effect of the dummy wing. A slotted flap is installed on both the main and vertical wings. The flap is fixed at the same angle of attack for both the main and vertical wings. Here, in order to remove the difference of the root airfoil of the main wing and the tip airfoil of the dummy wing, the slot only extends 25 mm from the root of the main wing.

Figure 6 and Table 1 show pictures of the models used in determining the position of the slot. The shape of the slot used in this model is that obtained from the numerical analyses, i.e., the width of the main wing slot is 3 mm, that of the chord of the flap is 47 mm, that of the vertical wing slot is 3 mm and that of the chord of the flap is 30 mm. As shown in Fig. 6 and Table 1, three more models were constructed with the chord of the flap on the main wing being 67 mm for A, 57 mm for B, and 37 mm for D. The slot was at the same position in percent chord on the vertical wing models. In this experiment, the aerodynamic performance
of combinations of the four models of the main wing and 4 models of the vertical wing were used.

Using these models, $L$ and $D$ were measured, the $h_m$ and $\alpha_m$ being changed when $h_s$ was fixed at 9 mm. The $h_s$ was changed when measuring the side force. $\alpha_s$ was fixed at 2 degrees. The experimental conditions and the parameters are shown in Table 2.

### 3.2 Results

#### 3.2.1 Variation of aerodynamic performance by single-slotted flap

The flow over the upper surface observed in the experiments was first compared with that predicted in the numerical analysis. Figure 7 shows the visualization of the upper surface of the C-c wing model.

This photograph indicates that the slotted flap removed the separated region. This result agrees well with the velocity vector in Fig. 3.

To find the optimum position of the slot, aerodynamic performance measurements were carried out for a total of 16 models by combining the main and vertical wings shown in Fig. 6. Among all the models, only some models with outstanding ground-effect characteristics were examined in detail in comparison with the baseline model.

Figure 8 shows the aerodynamic characteristics of the models at $\alpha_m = 2^\circ$. The $C_L$ of the models with single-slotted flaps is lower by 0.045 in comparison with the baseline model, but the ground-effect characteristics of the models are similar to that of the baseline model. Also, the $C_D$ values decrease as the main wing approaches the ground plate. This is because the pressure leakage from the slot increases as the main wing approaches the ground plate, resulting in an increase of the outflow of the air from the slot with consequent suppression of the separation by the wing-wing interaction. The $L/D$ of the models increases rapidly as $h_m/c_m$ decreases, in comparison with that of the baseline model. On the other hand, the $L/D$ of the B-a and B-d models are the most prominent in com-

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Table 2  Experimental condition and parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Main wing</th>
<th>Vertical wing</th>
</tr>
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<tbody>
<tr>
<td>Freestream velocity $U_\infty$ [m/s]</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Reynolds number $Re$</td>
<td>$3.5 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>Angle of attack $\alpha$ (deg)</td>
<td>2, 4, 6</td>
<td>2</td>
</tr>
<tr>
<td>Distance between trailing edge of wing and plate $h$ [mm]</td>
<td>6–30</td>
<td>6–25</td>
</tr>
<tr>
<td>($h_m/c_m = 0.04 \pm 0.2$)</td>
<td>($h_s/c_s = 0.06 \pm 0.25$)</td>
<td></td>
</tr>
</tbody>
</table>

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Fig. 7 Oil flow visualization over the upper surfaces of the C-c wing model and the baseline model ($\alpha_m = 4^\circ$, $\alpha_s = 2^\circ$, $h_m/c_m = 0.04$, $h_s/c_s = 0.09$, $U_\infty = 35$ m/s)
Fig. 9 Aerodynamic characteristics of the models at \( \alpha = 4^\circ \). In comparison with those of the other models and the ground-effect characteristics of the baseline model are the most prominent in comparison with those of the other models. The ground effect works as the restoring force in the pitch direction of the Aero-train. At the target suspension height of the Aero-train (i.e., \( h_m/c_m = 0.067 \)), the \( L/D \) of the \( B-d \) model will increase by about 17.1% and \( C_D \) will decrease by about 20% compared with the baseline model.

Figure 9 shows the aerodynamic characteristics at \( \alpha = 4^\circ \). The ground-effect characteristics of \( C_L \) of the \( B-d \) and \( C-d \) models are similar to that of the baseline model, but the ground-effect characteristics of the \( B-a \) model deteriorate in comparison with that of the baseline model. The \( C_L \) values of the models are similar to that of the baseline model. The \( C_D \) curves of the models with single-slotted flaps are lower by more than 0.005 in comparison with that of the baseline model when \( h_m/c_m \leq 0.1 \). The \( L/D \)s of the models with single-slotted flaps are higher than that of the baseline model due to the decrease of \( C_D \). On the other hand, the ground-effect characteristics of the \( B-d \) model are the most prominent. Also, the \( L/D \) of the \( B-a \) model is the most prominent. Thus, at \( h_m/c_m = 0.067 \), the \( L/D \) will increase by about 40% and \( C_D \) will decrease by about 26.8% compared with the value of the baseline model.

Figure 10 shows the aerodynamic characteristics at \( \alpha = 6^\circ \). The ground-effect characteristics of \( C_L \) of the \( B-d \) and \( C-d \) models are similar to that of the baseline model, but the ground-effect characteristics of the \( B-a \) model deteriorate in comparison with that of the baseline model. The \( C_D \) of the models with single-slotted flaps are lower by more than 0.01 in comparison with the \( C_D \) of the baseline model, when \( h_m/c_m \leq 0.1 \). The \( L/D \)s of the models with single-slotted flaps are higher than that of the baseline model due to the decrease of \( C_D \). On the other hand, the ground-effect characteristics of the \( B-d \) model are the most prominent. Also, the \( L/D \) of the \( B-a \) model is the most prominent. Thus, at \( h_m/c_m = 0.067 \), the \( L/D \) will increase by about 71.7% and \( C_D \) will decrease by about 37.8% compared with value of the baseline model.

The above-mentioned results demonstrated that the \( L/D \) of the wing models dramatically increased with the installation of the single-slotted flap. Among the wing models with a single-slotted flap, the \( L/D \) of the \( B-d \) model was the most prominent, although the ground-effect characteristics of the \( B-a \) model was somewhat less than that of the baseline model. On the other hand, among the wing models with a single-slotted flap, the ground-effect characteristics of the \( B-d \) model were the most prominent. Thus, at \( h_m/c_m = 0.067 \), the \( L/D \) of the \( B-d \) model increased by about 17%.
at $\alpha_m = 2^\circ$, by about 22.3% at $\alpha_m = 4^\circ$ and by about 31.6% at $\alpha_m = 6^\circ$.

3.2.2 Change of side force by single-slotted flap

In the experiment of side-force measurement, the height of the main wing was fixed at $h_m/c_m = 0.067$ and $h_s$ was changed from 4 mm to 20 mm. Figure 11 shows the ground-effect characteristics of the side-force coefficient $C_{SF}$. This graph is plotted using the distance between the vertical wing and the side plate on the $x$-axis, and the side-force coefficient on the $y$-axis. The figure shows that the $C_{SF}$ of the models with single-slotted flaps decreases somewhat in comparison with that of the baseline model. Also, the ground-effect characteristics of the models with single-slotted flaps tend to be lower in comparison with that of the baseline model. This ground effect works as the restoring force in the yaw and roll directions on the Aero-train, and thus using a single-slotted flap tends to lower the yaw stability of the Aero-train.

4. Conclusion

As an attempt to improve the aerodynamic performance of the wing configuration, numerical analysis and wind tunnel experiments were performed with installation of a single-slotted flap. From these results, the following conclusions were reached.

(1) By the installation of a single-slotted flap on the wings, when $\alpha_m = 2^\circ$ to $6^\circ$, the $L/D$ increased sharply.

- The increase in $L/D$ of the $B-a$ model was the most prominent in comparison with values for the other models. The location of the slot of the $B-a$ model in percent chord of the main wing was 38% and that of the vertical wing was 50%.

- The increase in the ground-effect characteristics of the $B-d$ model in percent chord of the main wing was 38% and that of the vertical wing was 20%.

(2) The ground-effect characteristics of $C_{SF}$ of the models with single-slotted flaps tended to be lower in comparison with that of the baseline model.

References

