A numerical analysis of aerofoil flutter in ground effects

T. Kawahara*, M. Kikuchi**, and K. Hirano**

* Graduate School, University of Miyazaki,
** Dept. of Mech. Systems Eng., University of Miyazaki

ABSTRACT

The "Aero-train" flies in the close field above the ground using ground effects. It is important for Aero-train that making known the relationship between the Ground Effects and "Flutter". So we simulated Aerofoil Flutter in Ground Effects. We made wing models having arbitrary oscillations and they were analyzed both situations with or without ground. After the phenomena of the flow around the oscillating wing were considered, we calculated the Aerodynamic works that the oscillating wing gets from the flowing fluids during one-period of its oscillation.

Key Words: Wing in ground effect, aero-train, aerofoil flutter, unsteady flow, unsteady aerodynamic force

1. Introduction

Researches of a new rapid transport system with an environmental affinity "*Aero-train*" are conducted mainly in Tohoku University and University of Miyazaki. The Aero-train has wings and it glides in the close-field above the ground using ground effects. Until now, although researches for improvements of lift and drag in the ground effects have been held a lot, there has been little research for the dynamic stability of the wing in the ground effects. So it is thought that making known the mechanism how the ground effects affect to dynamic stability of the wing is very important. To elucidate the effects of ground on aerofoil flutter, we calculated the aerodynamic work on the aerofoil oscillating in two-freedom of heaving and pitching oscillations.

2. Flutter analysis

There is a phenomenon called "*Flutter*" which relates to the stability of wing. It is self-induced oscillation with two-degree-of-freedom: heaving and pitching, which occurs when wing get energy from fluids flowing around it. In this paper, we simulated the flutter in the ground effects using a numerical analysis method. We made wing models having arbitrary oscillations and they were calculated for both situations with or without the ground using a thermo-fluid analysis software FLUENT. After the phenomena of the flow around the wing were considered, the aerodynamic works that the wing gets from the flowing fluids during one-period of its oscillation were calculated.

The oscillation modes are given by

$$h = h_0 \sin(2\pi f t) \quad \text{for heaving motion} \qquad (1)$$

$$\alpha = \alpha_0 \sin(2\pi f t - \phi) \quad \text{for pitching motion} \qquad (2)$$

where ϕ is the phase difference between the heaving and the pitching oscillations. The numerical parameters used in calculation are listed in Table 1, where $A_g = \alpha_0 b' / h_0$: amplitude ratio of the pitching and heaving oscillation at the leading edge of the aerofoil and b' is 1/4 chord length. H is the trailing edge time average height above the ground. The aerofoil section used in the calculation is NACA0012.

Table 1 Numerical parameter in the calculations

U[m/s]	5 , 10 , 15
ϕ [rad]	0 , $\pi/6$, $\pi/3$, $\pi/2$, $2\pi/3$, $5\pi/6$, π
H/b	inf , 4 , 1 , 0.75 , 0.5
h_0 [m]	2×10^{-3}
α_0 [rad]	0.08
A_g	1
f [Hz]	10
ρ [kg/m^3]	1.225
μ [Pa·s]	1.7894×10^{-5}

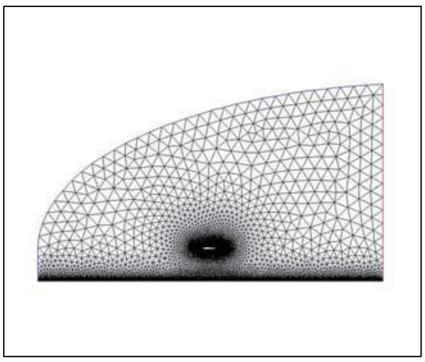

Fig. 1 Element breakup in the calculating area above the ground.

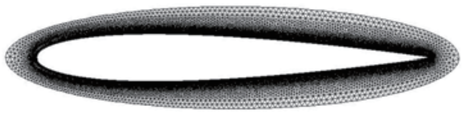

Fig. 2 Dynamic mesh zone

Fig.1 shows the element breakup in the calculating area above the ground and fig.2 shows the dynamic mesh zone around oscillating aerofoil. The number of mesh is 61,260~132,624, it depends on the oscillating modes and the height of the aerofoil.

As the boundary condition, the uniform flow velocity and a turbulent intensity are given at the inlet, the pressure is given at the outlet. In this problem there is a strong interference of the aerofoil and the ground through the fluid, we gave the moving ground with the same velocity as the inlet velocity.

The aerodynamic work in a period W is given by

$$W = \frac{1}{T}\int_0^T \left(L\left(-\dot{h}\right)\mathrm{d}t + M\dot{\alpha}\mathrm{d}t\right) \tag{3}$$

where L is lift, M is nose up moment. When it is positive, the oscillation of the aerofoil is encouraged by the air flow.

3. Numerical results and consideration

We created the meshes close to the aerofoil surface instead of using the wall function in the calculation. We confirmed the non-dimensional parameter $y^+ = \rho u_\tau y / \mu$ was less than unity in all cases, where u_τ the friction velocity and y the distance between the closest mesh point and the aerofoil surface.

Fig. 3 and 4 show the lift force and the moment for five periods respectively, in the heaving and the pitching oscillations, where the phase lag ϕ is $5\pi/6$, average height H/b is 0.5, the reduced frequency $k_f = 2\pi fb/U$ is 0.31. The time average of lift is negative and the nose up moment is positive. Fig. 5 shows the time average lift for the fifth period. The reason is that the lift is exerted at near the maximum thickness of the aerofoil 30% chord, on the other hand the pitching axis is 25% chord. It is supposed to work the Venturi effect in the oscillating case.

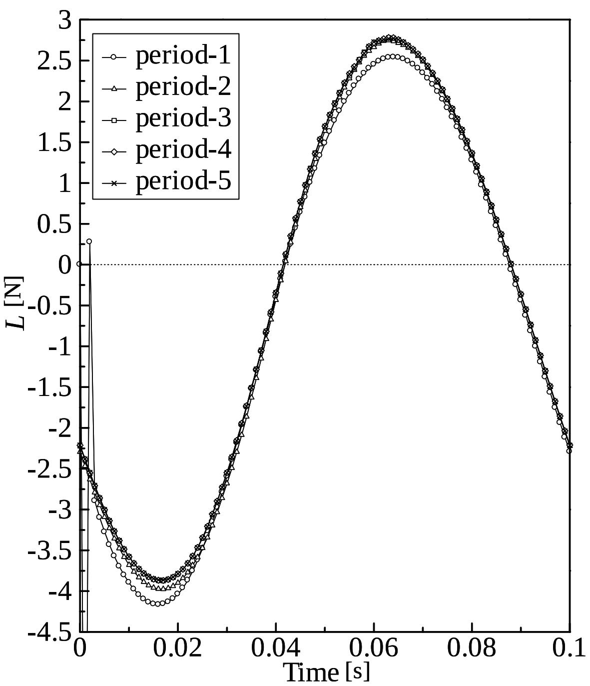

Fig.3 Comparison of lifts by periods (U = 10 [m/s] , $\phi = 5\pi/6$, H/b = 0.5 , $\mathrm{Re} = 3.4 \times 10^4$)

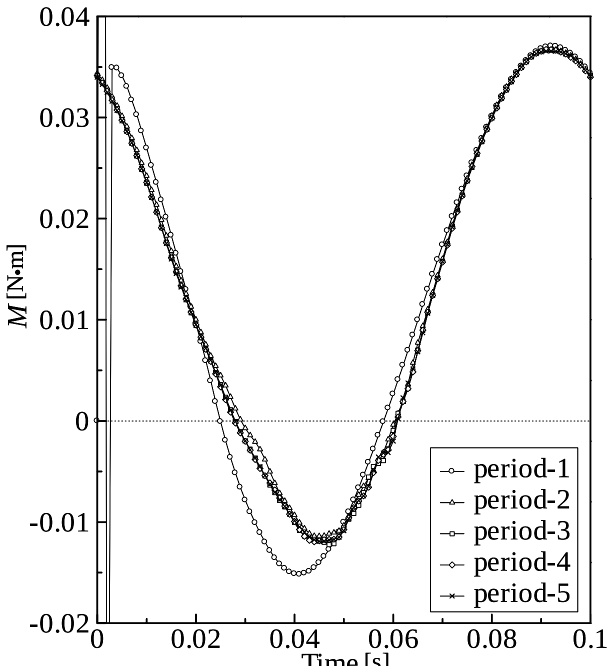

Fig.4 Comparison of lifts by periods (U = 10 [m/s] , $\phi = 5\pi/6$, H/b = 0.5 , $\mathrm{Re} = 3.4 \times 10^4$)

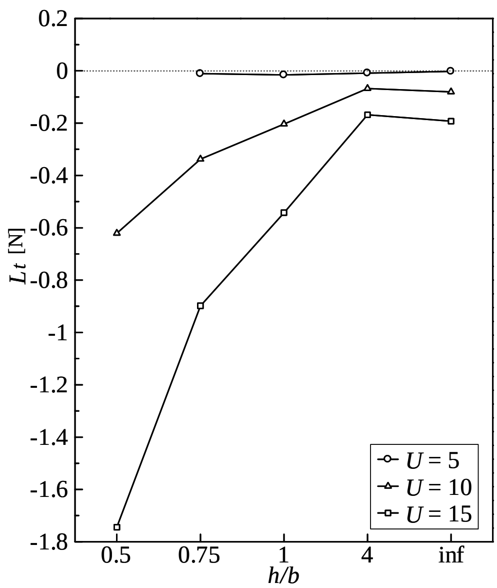

Fig. 5 Time average of lifts in the fifth period ($\phi = \pi/6$)

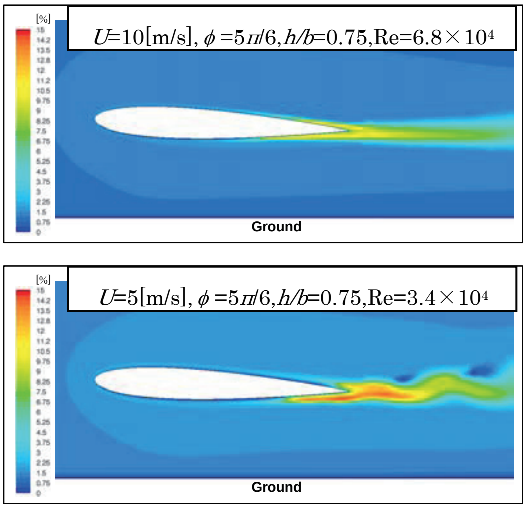

Fig.6 Turbulent intensity distribution

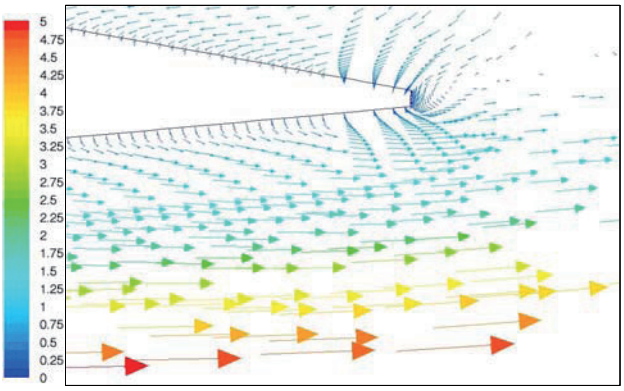

Fig.7 Velocity vector around the trailing edge
(U=5[m/s], ϕ =5π/6,h/b=0.75, Re=3.4×10^4.)

Fig.6 shows the turbulent intensity I in the flow fields, where

$$I = \sqrt{(2/3)k}\,/U \tag{4}$$

$$k = \frac{1}{2}\overline{u_i' v_j'} \tag{5}$$

k is the turbulent energy. The turbulent intensity for $U = 10\mathrm{m/s}$ is stronger near the trailing edge of the aerofoil than for $U = 5\mathrm{m/s}$. In the calculation, the frequency was fixed at 10Hz, then the former reduced frequency is 0.31, the latter is 0.62. The difference of the turbulent intensity is due to unsteadiness. Fig.7 shows velocity vector near the trailing edge for $k_f = 0.62$, the reverse flow is seen in the upper side of the near trailing edge. It may be the cause of the increase of the turbulent intensity. Fig 8 shows the velocity profile which is colored by the turbulent intensity. The velocity gradient becomes smaller traveling towards the trailing edge.

In the calculation of aerodynamic work, we used the aerodynamic force in the fifth period, because the both of lift and moment have same value after the third period. Fig.9 shows the dependence of aerodynamic works on the phase lag between the heaving oscillation and the pitching oscillation. It is well known that the maximum work id done near $\phi = \pi/2$, fig.9 shows that the ground increases the work.

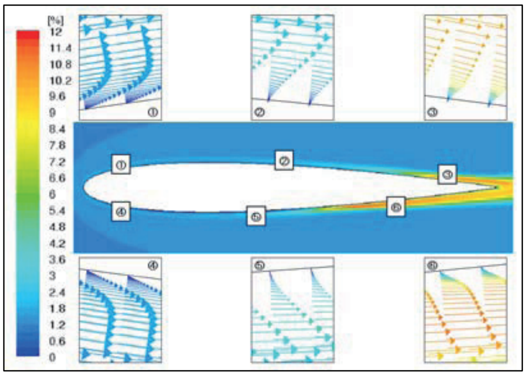

Fig.8 Velocity gradient on the oscillating aerofoil colored by the turbulent intensity.

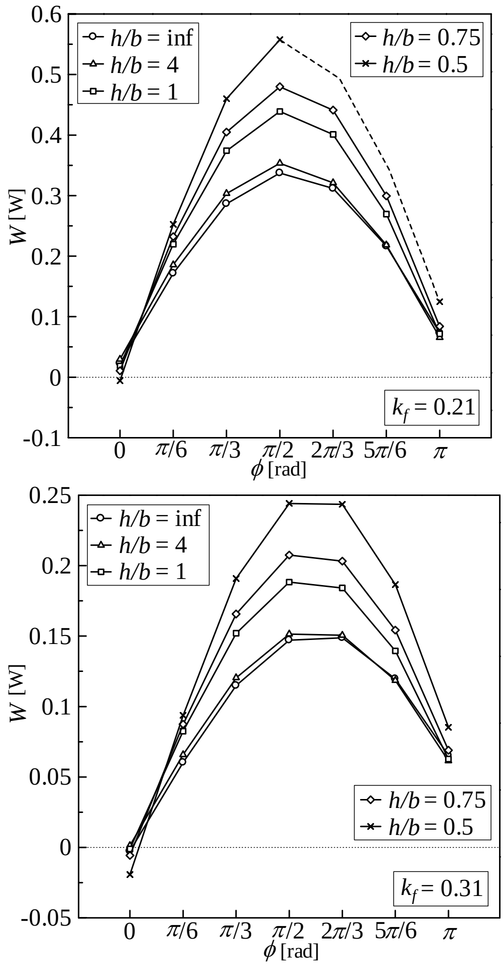

Fig.9 The dependence of aerodynamic work on phase for $U = 15\mathrm{m/s}$ (upper) and $10\mathrm{m/s}$ (lower)

4. Summary

The relation between the flutter phenomena and the aerodynamic works was considered. As a result, we came out the tendency of relation between the flutter phenomena and aerodynamic works.