Characteristics of Unsteady Aerodynamics and Pressure Fields of Wings Flying with Heave Motion in the Ground Effect

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Summary

The WIG (Wing-In-Ground effect) is an unconventional aircraft and for a ship which is operated in a seaway utilizing the high lift-to-drag ratio. When the WIG flies over the waves, unsteady aerodynamic forces induced by the waves act on the airframe and cause the unsteady change of the pitching moment with the movement of the center of pressure. They have a possibility to cause the instability of the motion of the airframe. Therefore, the characteristics of unsteady aerodynamic forces become an important topic related to WIG’s flight stability. This paper takes up the WIG flying with heave motion in the ground effect and makes clear the property of unsteady aerodynamic forces and moment. The Time-domain boundary element method is employed for analyzing the problem and the validation of the obtained results are also carried out by comparing with experimental results. In the experiment, not only the measurement of unsteady forces and moment but also the measurement of the unsteady pressure field over the ground are attempted by applying the technique to measure the unsteady waves of ships. The later one is the first trial in this research field and obtained experimental data itself is valuable from the academic point of view.

1. Introduction

When the wings fly in the vicinity of the ground or sea surface, the lift increases and the drag decreases. This phenomenon is well known as the ground effect. WIG (Wing-In-Ground effect) is an unconventional aircraft and/or a ship which utilizes this phenomenon, and is expected to make fast-mass transportation possible in a seaway.

For the conventional aircrafts which fly at high altitude, the center of pressure $x_{cp}$ is a function of the angle of attack of the wing provided that the Reynolds number is constant and the air flow is uniform. On the other hand, when the wing flies in the ground effect, the changes of the angle of attack and the flight altitude affect the shift of $x_{cp}$. The fluctuation of $x_{cp}$ due to the unsteady aerodynamic forces induces the change of the pitching moment. It has one of the possibilities to cause the instability of the airframe motion. Therefore, it is important especially for the WIG to understand the property of unsteady aerodynamics.

The early studies on unsteady aerodynamics can be found in the literatures for the 2-D airfoils in the field of the aerodynamics and numerous papers have been presented so far. Most of them, however, are for the airfoils out of the ground effect. The studies on the properties of unsteady hydrodynamics have been carried out similarly in the field of naval architecture. For example, Kyoizuka analyzed unsteady lift for heaving 3-D hydrofoils and also investigated the unsteady lift acting on oscillating 2-D hydrofoils beneath the free-surface. Some studies applied CFD to the hydrofoils acting beneath the free-surface. Tanaka simulated unsteady hydrodynamics of 2-D and 3-D hydrofoils with a moving aileron, which are equipped to the catamaran. Videv and Doi investigated the thrust produced by oscillating 2-D hydrofoils and clarified the flow field around it. All of them focus on the free-surface effect on the unsteady hydrodynamics acting on hydrofoils.

Theoretical and experimental studies of the WIG including unsteady aerodynamic properties can be seen in Iwashita et al. They studied both steady and unsteady problems of a canard-configuration WIG flying over the calm water and progressive wave. Another studies focused on the unsteady aerodynamic properties of 2-D and 3-D wings flying over incident wave can be seen in Liang et al. and Yang et al. Most of these studies discuss the integrate values as represented by unsteady forces and moments, and there are no experimental results which clarify the local physical value such as unsteady pressure distribution.

In this study, the 3-D wings flying with heave motion in the ground effect are focused upon and investigate not only on the unsteady aerodynamic properties but also on the unsteady pressure field over the ground. The time-domain boundary element method (T-D BEM) is employed and calculation results are validated by the towing tank experiment in which the unsteady aerodynamic properties and the pressure field are simultaneously measured.

2. Numerical Calculation

The Time-Domain boundary element method (T-D BEM) is employed in the present study in order to estimate precise characteristics of unsteady aerodynamics and pressure field taking the nonlinear effect into account.

2.1 Outline of the mathematical formulation

The wings flying at constant speed $U$ with heave motion of $\dot{z}(t)$ (t:time) in an incompressible and inviscid air domain are considered, and the space-fixed coordinate system as illustrated in Fig. 1 is taken. The flow is assumed to be irrotational.

In the figure, $S_{\rho}(t), S_{\tau}(t),$ and $S_{n}(t)$ respectively represent the wing surface, free-surface and wake-sheet surface at an arbitrary
time $t$. The normal vector $n$ is taken inward the air-domain. It is assumed that the deformation of the wake sheet such as the roll-up at the wing tip does not affect the aerodynamic properties and the free surface is treated as a rigid flat surface. In the previous study by the authors, these assumptions have been confirmed to be adequate for the calculation of WIGs\cite{14}.

![Fig. 1 Space-fixed coordinate system.](image)

The velocity potential $\Phi(x; t)$ of the air, which is governed by the Laplace equation $\nabla^2 \Phi(x; t) = 0$, must satisfy the following boundary conditions:

$$
[H] \frac{\partial \Phi(x; t)}{\partial n} = V(t) \cdot n \quad \text{on } S_H(t)
$$

$$
[F] \frac{\partial \Phi(x; t)}{\partial n} = 0 \quad \text{on } S_F(t)
$$

$$
[K] \Phi^+(x; t) - \Phi^-(x; t) = 0 \quad \text{on } S_k(t)
$$

where $x = (x, y, z)$ is a position vector and $V(t) = (U, 0, \dot{\xi}(t))$ is a velocity of the wing surface. Equation (3) represents the Kutta condition, where $\Phi^+(x; t)$ and $\Phi^-(x; t)$ indicate the pressures on upper and lower surface of the wake sheet. By applying the Green’s second identity, the following integral equation with respect to $\Phi$ can be obtained:

$$
\frac{\Phi(P; t)}{2} = \int_{S_H(t)+S_F(t)} \frac{\partial G(P, Q)}{\partial n_Q} \Phi(Q; t) dS - \int_0^\tau \{ \int_{S_H(t)} G(Q; \tau) \frac{\partial \Phi(Q; \tau)}{\partial n_Q} dS \} d\tau - \int_{S_H(t)+S_F(t)} \frac{\partial \Phi(Q; t)}{\partial n_Q} G(P, Q) dS
$$

for $P \in S_H(t)+S_F(t)$ (4)

where $G(P, Q) = 1/4\pi|PQ|$, $P = (x, y, z)$, $Q = (\xi', \eta', z')$ and $\Gamma(Q; \tau) = \Phi(Q_1^+; \tau) - \Phi(Q_1^-; \tau)$, $\Phi(Q_2^+; \tau)$ and $\Phi(Q_2^-; \tau)$ are the velocity potentials of upper point $Q_1^+$ and lower point $Q_2^-$ at the trailing edge.

Equation (4) can be solved by means of the time marching method by the time step $\Delta t$. At each time step, equation (4) can be solved with respect to $\Phi(P; t)$ on $S_H(t)$ and $S_F(t)$ by discretizing the surface $S_H(t)$ and $S_F(t)$ into a finite number of elements and assuming physical quantities to be constant in each panel.

The pressure on $S_H(t)$ and $S_F(t)$ is calculated by the following Bernoulli’s pressure equation:

$$
p(x; t) - p_0 = -\rho_0 \frac{\partial \Phi(x; t)}{\partial t} - \frac{\rho_0}{2} \nabla \Phi(x; t) \cdot \nabla \Phi(x; t)
$$

where $p_0$ is the atmospheric pressure and $\rho_0$ is the density of air. The velocity field $\nabla \Phi(x; t)$ in equation (5) is calculated by the 2-D spline interpolation method. Kutta condition (3), which contains the nonlinear term shown in equation (5), is numerically satisfied by the Newton-Raphson method\cite{15}.

Unsteady aerodynamic forces and moment, $F_i(t)$, acting in $i$-th direction are obtained by integrating the pressure (5) over $S_H(t)$ as follows:

$$
F_i(t) = -\int_{S_H(t)} \{ p(x; t) - p_0 \} n_i dS \quad (i = 1 \sim 6)
$$

where $(n_1, n_2, n_3) = n, (n_4, n_5, n_6) = x \times n$. Applying the Fourier series expansion to obtained time histories of $F_i(t)$, the forces and moment are decomposed into the steady and the unsteady terms. In this study, the unsteady terms are calculated up to 2nd-order term in order to investigate the nonlinear effect.

2.2 Numerical calculation method

In the first step, the boundary value problem explained in the previous section is solved at $t = 0 \equiv t_0$ assuming the wake sheet to flow out from the trailing edge along the uniform flow. After $t = t_0$, the wing moves at velocity $V(t_0)$ with adding wake sheet element of length $V(t_0)\Delta t$ behind the trailing edge, and the boundary value problem is solved at an updated time $t = t_0 + \Delta t \equiv t_1$. This process is repeatedly updated by the increment time $\Delta t$ (see Fig. 1). When the wing surface is discretized into a finite number of panels of $N_H$, the discretized form of equation (4) at $n$-th time step ($t = t_n$) can be expressed in the form

$$
- \sum_{j=1}^{N_H} \frac{\partial G_{ij}}{\partial n} \Phi^n_j - \sum_{n_{i+1}}^{N_H} \int_{\Gamma_{ij}} G_{ij} \frac{\partial \Phi^n_j}{\partial n} dS = - \sum_{j=1}^{N_H} \frac{\partial G_{ij}}{\partial n} \Phi^n_j \quad (i = 1 \sim N_H)
$$

where $\Phi^n_j$ indicates the velocity potential of $j$-th panel at $n$-th time step (hereafter, the superscript indicates the number of the time step). $N_i$ indicates a number of trailing-edge panels and $i = mN_i + k$ shows the wake-sheet panel number which is numbered along the trailing edge adding $N_i$ panels at every step time behind the trailing edge. $\Gamma_{ij}^n$ is a potential jump at the trailing edge and calculated by $\Gamma_{ij}^n = \Phi^n_j - \Phi^n_i$, where $\Phi^n_i$ shows the potentials at upper and lower side of $k$-th panel of the trailing edge. $G_{ij}$ and its normal derivatives are defined as

$$
\frac{\partial G_{ij}}{\partial n} = \int_{\Gamma_{ij}} \frac{\partial G^n_P}{\partial n} dS
$$

The velocities on $S_H(t)$ is obtained by using the 2-D Spline interpolation scheme. A local curvilinear coordinate $(\xi, \eta)$ is taken on $S_H(t)$, where $\xi$ and $\eta$ are taken in the directions of chord and span respectively. A dataset of position vector at $n$-th time step $[P^n_x]_{i=1-N_H}$ and corresponding velocity potential $[\Phi^n_x]_{i=1-N_H}$ are now expressed by $x(\xi, \eta)$ and $\Phi(\xi, \eta)$ for simplification. They are expressed by using the 2-D Spline function in the form

$$
x(\xi, \eta) = \sum_{k=1}^{N_x} \sum_{l=1}^{n_x} A_{kl} B_k(\xi) B_l(\eta)
$$

$$
\Phi(\xi, \eta) = \sum_{k=1}^{N_x} \sum_{l=1}^{n_x} \alpha_{kl} B_k(\xi) B_l(\eta)
$$
where \( B_0(\xi) \) and \( B_1(\eta) \) are B-Spline functions. Coefficients \( \lambda_k \) and \( \alpha_{kl} \) are determined by substituting the distributions of \( x \) and \( \Phi \) in the left hand side. The unit fundamental vectors in \( \xi, \eta \) and \( \zeta \) axis, where \( \zeta \) is orthogonal to \( \xi \) and \( \eta \), are calculated by equation (9) as

\[
e_k = \frac{\partial x}{\partial \xi} \frac{\partial \Phi}{\partial \xi} \quad e_\eta = \frac{\partial x}{\partial \eta} \frac{\partial \Phi}{\partial \eta} \quad e_\zeta = \frac{\partial x}{\partial \zeta} \frac{\partial \Phi}{\partial \zeta}
\]

Then the velocities on \( S_{SH}(t) \) are calculated by

\[
\begin{bmatrix}
\frac{\partial \Phi}{\partial \xi} \\
\frac{\partial \Phi}{\partial \eta} \\
\frac{\partial \Phi}{\partial \zeta}
\end{bmatrix}
= \begin{bmatrix}
e_k & e_\eta & e_\zeta
\end{bmatrix}
\begin{bmatrix}
\frac{\partial \Phi}{\partial \xi} \\
\frac{\partial \Phi}{\partial \eta} \\
\frac{\partial \Phi}{\partial \zeta}
\end{bmatrix}
\]

The boundary condition on \( S_{SH}(t) \) can be used with the relation \( \partial \Phi/\partial \zeta = [e_k \times e_\zeta] \partial \Phi/\partial n \).

As already noted at the beginning in this section, the steady problem is solved in the first step and set the obtained solution as a solution of \( t = t_0 \). The steady problem is solved for the coordinate advancing together with the wing. Then, the velocity potential and the body boundary condition lead to

\[
\Phi = -UX + \phi, \quad \frac{\partial \Phi}{\partial n} = Un_x
\]

And the pressure \( p^0 \) at \( t = t_0 \) is calculated by

\[
p^0 = \frac{1}{U^2} \left[ 2U \frac{\partial \Phi}{\partial x} - \nabla \phi \cdot \nabla \phi \right]
\]

The obtained velocity potential is stored as a solution of \( t = 0 \) as

\[
\Phi_j^0 = -UX_j^0 + \phi_j^0
\]

where \( x_j^0 \) and \( \phi_j^0 \) means the \( x \)-coordinate and the velocity potential \( \phi \) for \( j \)-th panel on \( S_{SH}(t) \). From the second time step, the boundary value problem with respect to \( \Phi \) is directly solved with the earth-fixed coordinate system. So, the advection term must be taken into account in the calculation of the partial derivative of \( \Phi \) with respect to \( t \) which appears in equation (5). For \( t = t_1 \), equation (5) is calculated as

\[
\frac{p_j^1}{\rho a U^2/2} = -\frac{2}{U^2} \left[ \frac{\phi_j^0 - \Phi_j^0}{\Delta t} - (x_j^0 - x_j^1) \nabla \phi_j^0 \right] - \frac{1}{U^2} \nabla \phi_j^0 \cdot \nabla \phi_j^0
\]

where \( p_j^1 \) and \( x_j^1 \) denote the pressure and the position vector of \( j \)-th panel at \( t = t_1 \). The 1st-order backward difference is applied to the partial derivative of \( \Phi \) with respect to \( t \). For \( t \geq t_1 \), 2nd-order backward difference can be applied and the corresponding form of equation (16) becomes as

\[
\frac{p_j^n}{\rho a U^2/2} = -\frac{2}{U^2} \left[ \frac{3\phi_j^n - 4\phi_j^{n-1} + \phi_j^{n-2}}{2\Delta t} - (x_j^n - x_j^{n-1}) \cdot \nabla \phi_j^n \right] - \frac{1}{U^2} \nabla \phi_j^n \cdot \nabla \phi_j^n \quad (n \geq 2)
\]

\( p_j^n, x_j^n \) and \( \phi_j^n \) are the pressure, the position vector and the velocity potential of \( j \)-th panel at \( t = t_n \), respectively.

In the present calculation, the heave motion \( \xi_j(t) \) of the wing is given by

\[
\xi_j(t) = \begin{cases} 0 & (0 \leq t \leq 2\Delta t) \\ A \sin \omega (t - 2\Delta t) & (t > 2\Delta t) \end{cases}
\]

where \( A \) is an amplitude of heave motion and \( \omega \) is a circular frequency. The calculation is carried out up to 3.57, where \( T \) is a period of heave motion defined by \( T = 2\pi/\omega \), and the time step is set to \( \Delta t = T/30 \).

2.3 Computation panels

Figure 2 shows the computation panels of the rectangular wing and the main wing with end-plates respectively. By using the symmetric property of the problem, only the region of \( y > 0 \) is necessary in the calculation. The upper side of each figure shows the computation panels at \( t = 0 \) sec. The wing surface of the rectangular wing and the main wing with end-plates are discretized into the finite number of the panels of \( N_H = 695 \) and \( N_H = 1675 \) respectively. The length of wake sheet in the \( x \)-direction is \( 3 \times c (m) \) behind the trailing edge, which is used in the calculation in the 1st step.

The calm free-surface/ground region in the \( x \)-direction is \( 2 \times c (m) \) behind the trailing edge and \( 3.5 \times U \times T + 3 \times c (m) \) ahead of the trailing edge, and the region in the \( y \)-direction is \( 3 \times c (m) \). The
panel size in the x-direction, $\Delta x$, is determined so that $\Delta x = U \times \Delta t$ is satisfied referring the previous studies. The numbers of divisions in the y-direction are 14 and 18 for the rectangular wing and the main wing with end-plates respectively.

2.4 Estimation of the friction drag

The friction drag acting on the heaving wing is estimated by the same manner as used in the author’s previous paper. For example, for the main wing of dimensions shown in Table 1, friction drag coefficient is evaluated by the graph as seen in Fig. 3. Figure 3 is the representation of the database obtained by analysis of NACA3409 wing section through commercial software ANSYS Fluent. The friction drag coefficient $C_{df}$ is illustrated as the function of the Reynolds number $Re$ and the lift coefficient $C_L$.

![Fig. 3 Estimation method of the friction drag coefficient with 'ANSYS Fluent'.](image)

The chord length $c(y)$ of the wing strip is defined as the left side of Fig. 3 and $Re = \sqrt{V(t)c(y)} / \nu$ is calculated, where $\nu$ is the kinematic viscosity of the air. Using this $Re$, $C_d(y)$ obtained by the T-D BEM and the replacement $C_d(y) \rightarrow C_{df}$, $C_d(y)$ is interpolated from the right side of Fig. 3 provided that the viscous drag is almost free from the ground effect. The friction drag acting on the whole wing surface, $C_{df}$, is estimated by integrating $C_{df}(y)$ of each wing strip along the span direction. Similarly, the database for the NACA0006 wing section is used for the end-plates of the main wing.

3. Experiment

The towing tank experiment is carried out at Research Institute for Applied Mechanics (RIAM), in Kyushu University. The dimension of the tank is 65 m long, 5 m wide and 7 m water depth.

3.1 Experimental models

The experimental models are a rectangular wing of aspect ratio 3.0 and a main wing with end-plates which is a part of the canard-configuration WIG designed by authors taking over the concept of Kubo & Akimoto. These models are shown in Fig. 4 and the principal particulars are listed in Table 1. The wing section of two wings is NACA3409 and the main wing equips the end-plates with NACA0006 section. The main wing with end-plates has a taper ratio of 0.40, a sweepback angle of 4.0 degs. and a cathedral angle of 8.0 degs..

![Fig. 4 Perspective views of two wing models.](image)

### Table 1 Principal particulars of experimental models.

<table>
<thead>
<tr>
<th>Root chord length (m)</th>
<th>Tip chord length (m)</th>
<th>Span (m)</th>
<th>Project area (m²)</th>
<th>Airfoil section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular wing</td>
<td>0.240</td>
<td>0.120</td>
<td>0.170</td>
<td>NACA3409, NACA0006</td>
</tr>
<tr>
<td>Main wing with end-plates</td>
<td>0.300</td>
<td>0.720</td>
<td>0.150</td>
<td>(End-plates)</td>
</tr>
</tbody>
</table>

3.2 Towing test in the water

Figure 5 shows the experimental setup of the towing tank test. The wings are set in the water through the strut (breadth is 17 mm) and two load cells, and towed with heave motion forced by the motion excitation device.

A ground plate ($L = 5$ m, $B = 2$ m) is set in the water. The submergence depth of the ground plate is determined by the numerical simulation with BEM including the free-surface effects, so that the influence of the free-surface on steady hydrodynamics becomes less than 1.0%. As a result, it has been confirmed that the submergence depth of the ground plate should be set at least 900 mm (3.5× chord length) below the free-surface.

The twelve pressure sensors (Kyowa electric Instruments Co., Ltd., PS-05KD) are embedded in the ground plate along longitudinal lines under the midspan and the wing tip in order to measure the unsteady pressure distribution on the ground plate.

The flight altitude is defined as a non-dimensional parameter $h/c$, where $h$ is the height from the ground plate to the trailing edge and $c$ is the chord length at midspan. The experiment is conducted by changing the flight altitude $h$ and the period of heave motion $T$. The amplitude of heave motion, $A$, of both models is 10 mm. In case of the main wing with end-plates, the amplitude of 5 mm is also conducted to investigate the nonlinear effect. And the non-dimensional amplitude of heave motion divided by chord length $A/c$ is used in this paper. The period is replaced by the wave number $K = \omega^2 / g$ and a non-dimensional value $KC$ is used in the analysis. The angle of attack of both wings is fixed at 3.0 degs in all of the present experiments. The towing speeds of the rectangular wing and the main wing with end-plates are 2.213 m/s and 2.500 m/s, which corresponds to Reynolds number of $5.3 \times 10^5$.
and 7.5 \times 10^5\) respectively. The experimental conditions are summarized in Table 2.

The values of \(Kc\) in the present experiments are determined within the framework of the restricted performance of the motion excitation device. Since the lowest period of the motion excitation device is 0.50 sec., the period of 0.549 sec. is selected so that \(Kc = 4.0\) is satisfied. And the period of 1.099 sec., which is almost twice of 0.549 sec., is selected so that \(Kc = 1.0\) is satisfied. The wave-length to airframe-length ratios, \(\lambda/L\), for two cases are 8.84 and 19.64 respectively provided that the real airframe with the length \(L = 35\) m (the root chord length of the main wing is 10 m) is cruising at \(U = 75.59\) m/s (=270 km/h) over the regular head waves with the wave length \(\lambda\).

<table>
<thead>
<tr>
<th>(\lambda/L)</th>
<th>(8.84)</th>
<th>(19.64)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda) (m)</td>
<td>35</td>
<td>69.6</td>
</tr>
<tr>
<td>(L) (m)</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

The angle of attack \(\alpha\) is adjusted by rotating a shaft from a towing carriage. This adjustment is done in the calm water before towing the model and \(\alpha\) is measured up to four decimal places.

Table 2 Experimental conditions of towing tank test.

<table>
<thead>
<tr>
<th>(\alpha) (deg)</th>
<th>Rectangular wing</th>
<th>Main wing with end-plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed, (U) m/s</td>
<td>2.213</td>
<td>2.500</td>
</tr>
<tr>
<td>Reynolds number, (Re)</td>
<td>5.3 \times 10^6</td>
<td>7.5 \times 10^7</td>
</tr>
<tr>
<td>Flight altitude, (h/c)</td>
<td>0.20, 0.30, 0.40, 0.50, 1.00</td>
<td>0.35</td>
</tr>
<tr>
<td>Wave number, (k)</td>
<td>1.0 \sim 4.0 ((A = 0.5))</td>
<td></td>
</tr>
<tr>
<td>Angle of attack, (\alpha)</td>
<td>3.0 degs.</td>
<td></td>
</tr>
<tr>
<td>Amplitude, (A)</td>
<td>10 mm, ((A/c = 0.042))</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 is a sample of the time history of \(\alpha\) measured in the experiment of the main wing with end-plates, in which \(\alpha\) is adjusted to 3.0 degs. in the calm water and towed at 2.500 m/s (\(Re = 7.5 \times 10^7\)) with heave motion of the period \(T = 0.549\) sec. \((Kc = 4.0\)). In the figure, the time range of \(1.2 < t < 3.48\) sec. shows that the model is towed just over the ground plate. Although the noise-like vibration with high frequency due to the vibration of the total system including towing carriage can be seen in the figure, the average value in \(0 < t < 5.0\) sec. is 2.98 degs. It can be confirmed that the angle of attack \(\alpha\) set in the calm water is almost maintained while the wing is towed with heave motion.

3. 3 Multifold method for the unsteady pressure measurement

In this study, the multifold method\(^{21,22}\), which was developed by Ohkusu for measuring the unsteady wave around the ship, is
applied in order to measure the unsteady pressure distribution on the ground plate. According to the past studies\(^{22}\), an appropriate number of wave probes to measure the 1st-order unsteady term is six. By using this knowledge, the measurements are carried out by using totally twelve pressure sensors which are set along two longitudinal lines under the midspan and the wing tip (see Fig. 5).

The space-fixed coordinate system \(O-XY\) and the body-fixed coordinate system \(o-xy\) defined in Fig. 7 are used in the analysis. The wing is advancing with constant forward speed \(U\) with heave motion along positive \(X\)-direction. The relationship between the space-fixed and the body-fixed coordinate system is as follows:

\[
X = x + Ut, \quad Y = y
\]

(19)

When the wing is advancing with heave motion of circular frequency \(\omega\), the pressure \(P(x, y, t)\) acting on the ground plate is expressed by the summation of the steady and the unsteady terms;

\[
P(x, y, t) = P_s(x, y) + P_r(x, y) \cos \omega t + P_u(x, y) \sin \omega t
\]

(20)

where \(P_s(x, y)\) is the steady term and \(P_r(x, y)\) and \(P_u(x, y)\) are cosine and sine components of the 1st-order unsteady term respectively. By substituting equation (19) into equation (20), equation (20) can be written as follows;

\[
P(X - Ut, Y) = P_s(X - Ut, Y) + P_r(X - Ut, Y) \cos \omega t + P_u(X - Ut, Y) \sin \omega t
\]

(21)

The data acquisition by each pressure sensor starts at \(t = t_i\), \((i = 1 \sim 6)\), when the leading edge of wing reaches each pressure sensor. Hence, \(t\) can be written as \(t = t_i + t_i' + x_i/U\), \((i = 1 \sim 6)\), where \(x_i\) is the \(X\)-coordinate of pressure sensors embedded in the ground plate. Therefore, equation (21) is expressed in the form;

\[
P(-Ut_i, Y) = P_s(-Ut_i, Y) + P_r(-Ut_i, Y) \cos \omega t_i + X_i/U
\]

(22)

Rewriting \(P(-Ut_i, Y)\) to \(P_i\) simply, and using the relation \(x = -Ut\) and \(Y = y\), equation (22) can be rewritten finally as

\[
P_i(x, y) = P_s(x, y) + P_r(x, y) \cos \omega(t + X_i/U)
\]

(23)

Equation (23) contains three unknowns \(P_s(x, y), P_r(x, y)\) and \(P_u(x, y)\). When the wing is towed with heave motion in the water, six time-histories of the unsteady pressures \(P_i(x, y)\) with different phases of \(\omega X_i/U\), \((i = 1 \sim 6)\) are measured. In other words, the pressures \(P_s(x, y), P_r(x, y)\) and \(P_u(x, y)\) are measured six times at different time. In order to obtain accurate results, \(\Delta X = X_{i+1} - X_i\) should be determined so that \(n\omega \Delta X/U = 2\pi\) is satisfied, where \(n = 6\) is a total number of pressure sensors. The longitudinal positions of twelve pressure sensors in Fig. 5 are determined by considering that the present experiment is carried out for \(Kc = 1.0, 4.0\) and for two wings with different chord length and different towed speed. By applying the least square analysis to the six time-histories, three unknowns in equation (23) can be determined.

3.4 Fourier analysis

Figure 8 is the time history of the unsteady lift measured by the front load cell when the rectangular wing is towed at \(\alpha = 3.0\) degs., \(h/c = 0.30, Kc = 4.0, Re = 5.3 \times 10^4\) and \(A/c = 0.042\). The lift increases temporary during the period in which the wing is passes over the ground plate. Considering this period, the Fourier series expansion is applied to a part of this time range, that is, two periods 27 as illustrated in the figure by the solid line.

4. Results & Discussions

4.1 Time histories of unsteady aerodynamic properties

(1) Influence of the flight altitude

Figure 9 shows the time histories of the unsteady aerodynamic forces and moment acting on the rectangular wing at \(\alpha = 3.0\) degs.,
$Kc = 4.0, \ Re = 5.3 \times 10^4$ and $A/c = 0.042$. The time histories of forced heave motion of the wing are shown in a lower-right figure. Upper three figures show the drag coefficient, the lift coefficient and the moment coefficient (around the steady center of pressure) defined by

$$C_D(t) = \frac{-F_x(t)}{\rho S U^2/2}, \ C_L(t) = \frac{F_y(t)}{\rho S U^2/2}, \ C_M(t) = \frac{F_z(t)}{\rho S U^2 c/2} (24)$$

where $S$ is the project area of the wing and $\rho$ is the density of the air. $F_x(t)$ is the pitching moment around steady center of pressure. The solid circle and the white circle are the experimental results at $h/c = 0.30$ and 1.00. And the solid lines and the dotted lines show the calculation results of the T-D BEM at $h/c = 0.30$ and 1.00 respectively. Horizontal axis is an elapsed time divided by the period $T$ and time histories of two periods of oscillation are shown. The steady aerodynamic coefficients, which are measured by towing the wing without heave motion, are also shown in each figure. In the following explanation, the coefficients in (24) are described by $C_D$, $C_L$ and $C_M$ for simplification.

The calculation results of $C_L$ agree well with the experimental results for $h/c = 1.0$. The difference appears around $t/T = 0.7, 1.7$ for $h/c = 0.30$, and the calculation overestimates measured $C_L$. The similar results are also observed in Fig. 10. However, there is no such difference for the main wing with end-plates shown in Fig. 11 later. One of the reason of this difference may be the wake-sheet model used in the present calculation. The rectangular wing is straight cut at wing tips. Therefore, the real wake sheet will flow out not only from the trailing edge but also from the wing side. In the present calculation, however, the wake sheet is assumed to flow out only from the trailing edge as already shown in Fig. 2 (a). On the other hand, the wing tip of the main wing with end-plates is closed at the bottom of the end-plates (chord length converges to zero). So, the wake-sheet model will be appropriate and such
difference as observed for the rectangular wing will not appear.

The discrepancy can be also observed in the drag coefficient $C_D$ in Fig. 9 especially at low flight altitude $h/c = 0.3$. This may be caused by the effect of the flight altitude on the friction drag. In the present calculations, the friction drag is assumed to be free from the flight altitude as explained in section 2.4. In addition, nonlinearity can be clearly observed in the drag coefficient $C_D$ of both experiment and calculation. This nonlinearity seems to become small as increasing the flight altitude and the tendency of fluctuation gets close to the calculation results.

The center of pressure coefficient $C_p$ denotes a nondimensional distance from the leading edge to the center of pressure $x_{cp}$. The distance is nondimensionalized by the chord length. It can be calculated by using $C_D, C_L$ and $C_M$, at each time step. The lower-left and lower-middle figures in Fig. 9 respectively show the time history of $C_p$ and its fluctuation amount $|\Delta C_p|$ at different flight altitude $h/c$, which is simply obtained by taking the difference between the maximum value and the minimum value of the time history $C_p$. The $C_p$ nonlinearily oscillates around the steady position during the periodic change of the forces and moment as seen in the lower-left figure. The fluctuation amount $|\Delta C_p|$ shown in the lower-middle figure is converging as the flight altitude $h/c$ increases. From the figure, it is found that the value of $|\Delta C_p|$ is about 0.2 at $h/c = 1.0$. This means that $C_p$ fluctuates around the mean position with the oscillation range of 0.2 at $A/c = 0.042$. This is caused by the fluctuation of the relative angle of attack $\alpha_r$ due to the heave motion shown in Fig. 15, later. It is also found from the figure that $|\Delta C_p|$ becomes larger as $h/c$ decreases. Consequently, $|\Delta C_p|$ reaches 0.27 at $h/c = 0.2$, while $|\Delta C_p|$ = 0.2 at $h/c = 1.0$. This means that $|\Delta C_p|$ is increased by 0.07 c due to the ground effect. Therefore, it is confirmed that the amplitude of heave motion affects the fluctuation amount $|\Delta C_p|$ more remark-

Fig. 9  Effect of flight altitude on the unsteady aerodynamic forces and moment for the rectangular wing at $\alpha = 3.0$ degs., $Kc = 4.0$, $A/c = 0.042$ ($Re = 5.3 \times 10^4$ in towing tank experiment).
The pitching moment coefficient around the steady center of pressure $C_{m_p}$ is shown in upper-right figure. The $C_{m_p}$ non-linearly oscillates as the flight altitude decreases. The $C_{m_p}$ of nose up direction become large when the wing is in the down stroke motion at $h/c = 0.30$.

(2) Influence of the amplitude of heave motion

In light of the agreement of computed results with measured results, the influence of the amplitude of the heave motion on the unsteady aerodynamic coefficients $C_D$, $C_L$, and especially $C_p$ is numerically investigated by changing the amplitude of heave motion.

Figure 10 shows obtained results for the rectangular wing flying at $h/c = 0.30$, $\alpha = 3.0$ degs. $Re = 5.3 \times 10^5$ with heave motion of different amplitude $A/c$ at $Kc = 4.0$. According to the linear theory, the unsteady forces and moment are proportional to the amplitude of heave motion, $A$. The results of $C_L$ and $C_P$ show this tendency well, although it can not be seen in the result of $C_D$ because of the strong nonlinearity.

The lower-left figure in Fig. 10 shows that $C_p$ also oscillates with strong nonlinearity as the amplitude of $A/c$ increases. The rearward shift of $C_p$ from its steady position ('Steady center of pressure coef. (Exp.)' in the figure) becomes larger than that of forward shift with the increase of heave amplitude $A/c$. And the fluctuation amount $|\Delta C_p|$ shown in the lower-middle figure reduces drastically with decreasing the amplitude of motion. Although the large shift of $C_p$ doesn’t affect the pitching moment $C_{m_p}$ remarkably, non-linearity shown in pitching moment seems to increase with the increase of $A/c$. This phenomenon is one of the important features for considering flight stability in the ground effect.

Corresponding results of the main wing with end-plates are shown in Fig. 11. The flight altitude and the angle of attack of the main wing with end-plates is fixed at $h/c = 0.35$ and $\alpha = 3.0$ degs., respectively. The angle of attack $\alpha$ is equivalent to the mounting angle of the main wing with end-plates to the airframe and makes the lift-to-drag ratio maximum at such flight altitude $h/c = 0.35$. The experimental amplitude of heave motion are $A/c = 0.017$ and $0.033$. Similar results to the rectangular wing are obtained also for the main wing with end-plates. The fluctuation amount $|\Delta C_p|$ is drastically reduced as decreasing the amplitude of heave motion. The pitching moment coefficient $C_{m_p}$ seems to linearly oscillate at $A/c = 0.033$ and $h/c = 0.35$. Non-linearity appears in the pithing moment especially when the wing is in the ground effect.

Through the comparison between computed and measured results, overall calculation results for both rectangular wing and main wing with end-plates agree well with experiments. The estimation accuracy of these values improve, if the wing has closed wing tips like a main wing with end-plates.

4.2 Characteristics of unsteady aerodynamics

4.2.1 Rectangular wing

Figures. 12 and 13 are the results of the unsteady aerodynamic forces and moment acting on the rectangular wing. The horizontal axis on each graph in Fig. 12 is $h/c$ and $Kc$ in Fig. 13. In both Fig. 12 and 13, the vertical axis show $C_D$, $C_L$ and $C_{m_p}$ (moment around trailing edge) from left to right. The phases of the 1st-order unsteady forces and moment are illustrated at the bottom part in both figures. In all the analyses in this paper, a reference time $t = 0$ sec. is defined as the moment when the heave motion reaches to the maximum position of the amplitude $A$.

(1) Steady terms of forces and moment

At first, the steady forces and moment illustrated at the top part in Fig. 12 are highlighted. In each figure, Delta symbols show the steady aerodynamic forces and moment obtained by the steady experiment [4] in which the wing is towed at constant forward speed.
$U$ without heave motion. Filled circles and open circles are obtained in the present experiments in which the wing is towed at constant forward speed $U$ with heave motions of \( Kc = 1.0 \) and 4.0, respectively. The amplitude of heave motions is fixed at \( A/c = 0.042 \). The steady forces and moment shown by filled circles and open circles are obtained as the 0-th order term of the Fourier series expansion for measured time-histories. No difference is observed between filled circles and open circles of \( C_L \) and \( C_{MTL} \), and this implies that the frequency of heave motions does not affect the steady term of lift and moment. On the other hand, \( C_D \) of \( Kc = 4.0 \) is slightly smaller than that of \( Kc = 1.0 \). The difference between delta symbols and filled/open circles shows the influence of heave motions in the steady forces and moment. No difference can be seen in \( C_L \) and \( C_{MTL} \). The difference, however, can be clearly observed in \( C_D \). Filled/open circles in the figure of \( C_D \) are slightly smaller than delta symbols. This indicates that the thrust is generated by heave motions of the wing as already reported by some researches.\(^{\text{7)(8)}}\). The present result additionally shows that the thrust becomes larger in the ground effect and also becomes slightly larger as the frequency of heave motion increases. These phenomena observed in the measured results can be seen more clearly in the results of numerical calculation. Small effect of the frequency on the steady drag coefficient \( C_D \) can be seen by comparing the solid line with the dashed line. The effect is slightly emphasized by the ground effect as \( h/c \) becomes small. The thrust by heave motions can be also seen by comparing dashed/solid line and two-dots-chain line which shows the computed result for the wing towed without heave motion. The effect of the frequency of heave motion is confirmed in Fig. 13, in which \( Kc \) is taken as the horizontal axis. The effect becomes remarkable as the frequency becomes high.

(2) Unsteady terms of forces and moment

Next, the 1st-order unsteady forces and moment are highlighted. As easily noticed in Fig. 12, the amplitude of the unsteady forces and moment increase as the flight altitude becomes smaller. This can be also observed in the time history of Fig. 9. Both results show that the unsteady aerodynamic properties are also affected by the ground effect remarkably. The magnitude of the unsteady lift at \( Kc = 4.0 \) and \( h/c = 0.20 \) reaches about 50% of the steady lift even when the \( A/c = 0.042 \). The figure also shows that the effect of heave motion on the magnitude of the 1st-order unsteady aerodynamics becomes remarkable as the frequency becomes high. This can be also confirmed in Fig. 13. The 1st-order unsteady aerodynamic forces and moment are gradually increasing from \( Kc = 1.0 \) to 4.0.

The 2nd-order unsteady forces and moment are also shown in Fig. 12. The 2nd-order terms remarkably appear in the lower flight altitude and the higher frequency. The magnitude of the 2nd-order unsteady lift and moment at \( h/c = 0.2 \) and \( Kc = 4.0 \) is less than 5% of the 1st-order unsteady term. On the other hand, the 2nd-order unsteady drag reaches about 25% of the 1st-order unsteady terms. However, the 2nd-order unsteady aerodynamic forces and moment drastically decreases as the flight altitude increases. Therefore, the nonlinear calculation by the T-D BEM may not necessary if the flight altitude is sufficiently high.

Through these calculations and experiments, the influence of the ground effect in the unsteady aerodynamics due to the heave motion seems to be large and not to be negligible in magnitude. However, the phase difference of the unsteady lift to the heave motion is about 90 degs. as shown in the figures. This implies that the unsteady lift acts as a damping force. It is suspected that the unsteady aerodynamic forces and moment suppress the growth of airframe motions when the WIG flies over the waves.

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**Fig. 11** Effect of amplitude of heave motion on the unsteady aerodynamic forces and moment for the main wing with end-plates at \( \alpha = 3.0 \text{ degs.}, h/c = 0.35, Kc = 4.0 (Re = 7.5 \times 10^5 \text{ in towing tank experiment}).**
Fig. 12 Flight altitude dependency of unsteady aerodynamic properties of the rectangular wing at $\alpha = 3.0$ degs., $Kc = 1.0$ and 4.0, $A/c = 0.042$ ($Re = 5.3 \times 10^5$ in towing tank experiment).

Fig. 13 Period of heave motion dependency of unsteady aerodynamic properties of the rectangular wing at $\alpha = 3.0$ degs., $h/c$ = 0.20, 1.00, $A/c = 0.042$ ($Re = 5.3 \times 10^5$ in towing tank experiment).
4.2.2 Main wing with end-plates

Figure 14 shows the unsteady aerodynamic forces and moment acting on the main wing with and without end-plates at \( \alpha = 3.0 \) degs., \( h/c = 0.35 \), \( Re = 7.5 \times 10^5 \) and \( A/c = 0.033 \) where the horizontal axis of each figure is \( Kc \). The dashed line shows the calculation results of the main wing without end-plates. The tendency of the unsteady aerodynamic characteristics shown by the dashed line is almost the same as that observed for the rectangular wing model.

The solid line and filled circles respectively show the computed and measured results for the main wing with end-plates. The comparison between the solid line and the dashed line indicates that the end-plates scarcely affect the 1st-order unsteady lift although they improve the steady lift by about 20%. On the other hand, the amplitude of the unsteady drag of the main wing with end-plates at \( Kc = 4.0 \) is about 29% larger than that without end-plates.

The reason will be explained as follows. Figure 15 is a schematic diagram illustrating the side view and the bottom view of the wing in the downstroke of heave motion. Composition of the uniform flow velocity \( U \) and the relative velocity \( U_r \) due to the downstroke of the wing yields the incoming flow velocity \( U^w \) as illustrated in the figure. Then, the \( x \) component of the lift \( F_w^x \) caused by the flow \( U^w \) becomes the lift \( F_w^x \) acting on the wing instantaneously. \( F_w^z \), which is the \( z \) component of \( F_w \), acts on the wing as the thrust. In the same way, the thrust \( F^o \) and the side force \( F^s \) are generated by the end-plates as the effect of the induced flow velocity \( U^e \). In the downstroke, the clearance between the wing tip and the ground becomes narrow and the ground effect is promoted especially when the wing equips the end-plates. This can be also confirmed in Fig. 11. In Fig. 11, the fluctuation amplitude of \( C_L \) in the downstroke is slightly larger than that in the upstroke when the amplitude is measured from the steady lift. As a result, the unsteady lift of the wing with end-plates is a little larger than that of the wing without end-plates in Fig. 14. On the other hand, the friction component is rather dominant when the drag is focused upon. \( U^w \) in Fig. 15 is a function of \( \omega \) because of the relation \( U^w = \sqrt{U^2 + (A_{r0} \omega \cos \omega t)^2} \). Therefore, \( U^w \) becomes larger as \( \omega \) increases. From this reason, all the amplitudes of the unsteady aerodynamic forces and moment in Fig. 14 increase gradually as \( Kc \) increases (note; the unsteady aerodynamic properties are also nondimensionalized by \( U \) as equation (24), not by \( U^w \)).

![Fig. 15 Velocity field and forces acting on the main wing with end-plates flying with heave motion.](image)

As already explained above, the thrusts are generated on both the wing and the end-plates by the unsteady heave motion, and they are promoted by the ground effect in the downstroke especially when the wing equips the end-plates. Therefore, it is expected that the unsteady drag of the wing with end-plates becomes smaller compared with the wing without end-plates. But, the end-plates increase the surface area and the friction drag is increased. This amount of the friction drag increase may be larger than that of thrust increase. This will be the reason why the unsteady drag of the wing with end-plates is larger than that without end-plates.
in Fig. 14. The present calculations including the friction drag in heave motion by means of the 2-D CFD seem to succeed to predict this phenomenon since their results agree well with measured results as seen in the figure.

The phases of the unsteady lift for the main wing with end-plates is also different about 90 degs. to the heave motion. This implies that the unsteady lift acts as a damping force and will prevent the growth of the airframe motion.

All of the calculation results on the unsteady aerodynamic properties agree well with the experimental results. The T-D BEM presented in this paper is a useful method for estimating the unsteady aerodynamic forces and moment not only on the rectangular wing but also on the main wing with end-plates.

4.3 Unsteady pressure distributions on the ground

In this section, the unsteady pressure distributions on the ground when the wings fly over the ground with heave motion are investigated. The ‘Multifold method’ is applied to the measurement of the unsteady pressure distributions on the ground as stated in section 3.3. The same method can be used for the calculations. It simply can be done by replacing the experimental time-histories with the computed time-histories obtained by the T-D BEM.

(1) Rectangular wing

Figure 16 shows the unsteady pressure distributions on the ground for the rectangular wing towed at $\alpha = 3.0$ degs., $h/c = 0.30$. $Re = 5.3 \times 10^5$ and $A/c = 0.042$. Left side of Fig. 16 is the result of $KC = 1.0$ and right one is that of $KC = 4.0$. Upper figures (a1) and (a2) show the computed pressure contours on the ground. The steady term $P_s(x,y)$, the cosine component $P_c(x,y)$ and the sine component $P_s(x,y)$ are illustrated with the rectangular wing. The trailing edge and the leading edge correspond to $x/c = 0.0$ and 1.0. As explained in section 4.2.1, the reference time of the phase is a moment when the heave motion reaches to the top position. Therefore, $P_s(x,y)$ shows the unsteady pressure distribution at a moment when the wing is at the maximum position in its heave motion. Similarly, $P_c(x,y)$ shows the unsteady pressure distribution at a moment when the wing is at the zero position in downstroke of heave motion. And the unsteady pressure distribution becomes $-P_s(x,y)$ at a moment when the wing reaches the bottom position in heave motion. These unsteady pressure distributions indicate that the unsteady pressure takes the maximum value at a moment when the wing is passing the zero position, not at the bottom position. This time-lag of the unsteady pressure to the heave motion is an interesting phenomenon. Regarding the magnitude of the unsteady pressure, it becomes larger as $KC$ increases. It can be also noticed from the figure that the negative pressure field can be observed at the downstream along the wing tip line.

The sectional distributions of the unsteady pressure are shown in Fig. 16 (b1), (b2), (c1) and (c2). Computed and measured results are compared in the figures. The measured steady pressure in figure (b1) and (b2) is a little larger than the computed one. This will be the influence of the thin strut which is attached to the wing model to support the model. The computed steady pressure shows negative value in the downstream in (c1) and (c2), which shows the pressure distribution along the wing-tip line. This negative pressure can be considered to be induced by the wing-tip vortex. In the experiment, the wing-tip vortex will disappear due to the viscosity, and measured steady pressure converged to zero as shown in these figures. Except these differences seen along the midspan line and the wing-tip line, the present T-D BEM seems to estimate the pressure distributions in good accuracy.

(2) Main wing with end-plates

Figure 17 shows the unsteady pressure on the ground for the main wing with end-plates towed at $h/c = 0.35$, $\alpha = 3.0$ degs., $Re = 7.5 \times 10^5$ and $A/c = 0.033$. Almost the same tendencies as observed in case of the rectangular wing can be also observed in case of the main wing with end-plates. One difference is the magnitude of the unsteady pressure. The magnitude of the unsteady pressure in case of the main wing with end-plates is smaller than that in case of the rectangular wing. One simple reason is the difference of their flight altitudes $h/c$. However, this reason can not explain the relative difference between the magnitude of the steady pressure and that of the unsteady pressure. In Fig. 16 (a2), for example, the magnitude of the sine component shown in the bottom figure is equivalent to that of the steady term shown in the top figure. Meanwhile, in Fig. 17 (a2), the magnitude of the sine component shown in the bottom figure is clearly smaller than that of the steady term shown in the top figure. The main wing with end-plates has the cathedral angle and the midspan wing section with maximum chord length is geometrically located at higher position than the wing tip. This may reduce the change amount of the unsteady pressure on the ground induced by the unsteady motion of the wing.

Overall, the present T-D BEM estimates the unsteady pressure distribution on the ground in good accuracy even if it is applied to the geometrically complicated wing such as the present main wing with end-plates.

5. Conclusion

In this paper, the authors investigated the characteristics of the unsteady aerodynamics and pressure field for WIGs flying with heave motion. Through this study, the following conclusions are obtained.

(1) The unsteady aerodynamic coefficients for the WIGs flying with heave motion were investigated focusing on their time histories. It is confirmed that they fluctuate around the steady positions and, especially, the drag coefficient $C_D$ fluctuates with strong nonlinearity. The amount of the fluctuations becomes larger as the increase of the amplitude of heave motion $A/c$, and as the decrease of the flight altitude $h/c$.

(2) In the time history, the center of pressure coefficient $C_p$ also shows the fluctuation with strong nonlinearity. The influence of the amplitude of heave motion $A/c$, is dominant on the fluctuation amount compared with that of the flight altitude $h/c$, and the former influence decreases drastically as $A/c$ decreases. The large shift of $C_p$ does not affect the pitch moment coefficient around steady center of pressure $C_{M_{p0}}$. The $C_{M_{p0}}$ nonlinearly oscillates with the $h/c$ decreases and $A/c$ increases.

(3) The unsteady aerodynamics were evaluated by the Fourier analysis. The time averaged-thrust generation due to the heave motion was confirmed also for the present WIGs. The
Fig. 16  Contours & sectional unsteady pressure distributions of the rectangular wing at $h/c = 0.30$, $\alpha = 3.0$ degs., $A/c = 0.042$ ($Re = 5.3 \times 10^5$ in towing tank experiment)
Fig. 17  Contours & sectional unsteady pressure distributions of the main wing with end-plates at $h/c = 0.35$, $\alpha = 3.0$ degs., $A/c = 0.033$ ($Re = 7.5 \times 10^5$ in towing tank experiment).
time-averaged thrust increases as the increase of the frequency of heave motion $\omega / c / g (= K_c)$, and as the decrease of the flight altitude $h/c$. 
(4) The magnitude of the unsteady aerodynamics becomes remarkable as the flight altitude $h/c$ decreases and the frequency of heave motion $K_c$ increases. The phase difference of the unsteady lift to the heave motion is about 90 degs. and acts as the damping force. This property will prevent the growth of the airframe motion. 
(5) The unsteady pressure distributions on the ground were measured by applying the multifold method used to measure the unsteady wave field around the ship. The unsteady pressure on the ground, while WIG is flying with heave motion, takes the maximum value at a moment when wing is passing the zero position, not at the bottom position. The magnitude of the unsteady pressure becomes larger as $K_c$ increases. 
(6) Through the comparisons between computed and measured results, it is confirmed that the present T-D BEM incorporated with 2-D CFD for the estimation of the friction drag can well predict not only the unsteady aerodynamics but also the unsteady pressure distributions on the ground, even if it is applied to the geometrically complicated wing such as the main wing with end-plates. 

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