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Numerical Simulation of Unsteady Aerodynamic Coefficients for Wing Moving Near Ground

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Abstract: An aerodynamic model based on the modified unsteady vortex-lattice method and method of images was developed. A numerical simulation is conducted to predict unsteady ground effect on the aerodynamic characteristics of thin wings. The wake is computed as a part of the solution by allowing it to deform and roll up into its natural force- free position. The present results show the influences of various parameters such as angle of attack, sweepback angle, taper ratio, ect. on the aerodynamic coefficients far of and with proximity to the ground in unsteady motion.

Key words: Aerodynamic coefficients, Ground effect, Unsteady motion, Vortex-lattice method.

INTRODUCTION

The ground proximity has a great influence on the aerodynamic characteristics of the aircraft during it's takeoff and landing. Near the ground and behind the wing, the downwash is interrupting with the wingtip vortices [1]-[4]. Because takeoff and landing are pose the most hazards to phases of flight, many researchers have studied this phenomenon [5]-[6]. Even though the aircraft is moving with constant velocity the flow is considered to be unsteady. It is very difficult to investigate unsteady ground effect experimentally or modeling a full aircraft analytically. Therefore, the possible way is by considering the lifting surface.

The ground plays an important role in modifying the trajectory of the vortex wake during takeoff and landing. The ground surface acts as a reflection plane, and the motion of vortex pair is determined not only by the mutual induction of the vortices, but also by the image vortex pair below the ground surface.

Based on [1], Wieselsberger was the first to model the effect by placing the image of the real lifting surface below the ground plane, thus automatically satisfying the no penetration boundary condition on the ground surface. Recent improvements in computational facilities and numerical techniques have made it possible to study the unsteady ground effect for airfoils, wings and more realistic geometries. Later, ground effect for three-dimensional configurations was investigated. Refer to [4] a vortex-lattice method used to allow the wake to deform freely to investigate the performance of a lifting surface of zero thickness close to ground.

Reference [1] used the vortex lattice method to study the unsteady flow past non-dimensional and three-dimensional lifting surfaces moving near a ground plane. Based on [5] the vortex lattice method of[1] was modified to obtain results for the unsteady flow past a flat and circular arc approaching the ground. In [6] the influence of the angle of attack on the normalized lift coefficient of airfoils in steady state ground effectwas investigated. Thin wings in steady and unsteady motion far and near ground ware studied [10].

Generally, the trends in aerodynamic coefficients variations for small ground heights are significantly different to those for large ground heights. As the height above the ground decreases the aerodynamic coefficients (lift and moment) increase, where the induced drag decreases due to the decreases of induced downwash.

The purpose of this paper is, investigating the influence of angle of attack, sweep back angle, taper ratio, ect. at the unsteady ground effect on the aerodynamic coefficients. The present method is an extension of the unsteady vortex-lattice method published by [4]. Based on this method, numerical solutions are presented for rectangular and tapered thin wings.

PROBLEM FORMULATION

The evaluation of the aerodynamic lift, drag and moment coefficients is all based on the proper integration of the pressure coefficient on the lifting surface. In this paper the pressure is obtained through an integral representation based on the potential model. The extension of this method into unsteady aerodynamic regime was done in [7]. The studies in this paper are restricted to low angle of attack. Fig 1 shows schematically a wing platform, which is divided into panels. Vortex rings are used as singularity elements for the wing, its image and its wake. The leading segment of the vortex ring is placed on the plane's quarter-chord line and the control point is at the center of the three-quarter chord line. The normal vector n is defined at this point, too, which falls at the center of the vortex ring. A positive circulation Γ is defined here according to the right-hand rotation rule.

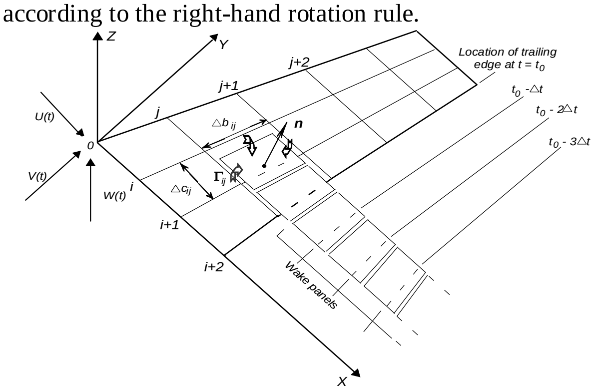

Fig 1: Nomenclature for the unsteady motion ofa thin wing along a predetermined path

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For an irrotational and inviscid flow, a velocity potential can be defined such that

$$q = \nabla\Phi \quad (1)$$

If the free stream Mach number is significantly small, the flow may also be considered incompressible. The principle of mass conservation for an incompressible flow has a form

$$\nabla . q = 0 \quad (2)$$

Equations (1) and (2) can be combined to yield Laplace's equation for the total velocity potential Φ

$$\nabla.\nabla\Phi \equiv \nabla^2\Phi = 0 \quad (3)$$

In order to complete the problem we need to give proper boundary conditions (BCs) on the body surface and its image, at the trailing edge TE (Kutta-Joukowski condition), and at infinity.

The first BC requiring zero normal velocity on the wing surface and the ground plane.

$$\nabla\Phi . n = 0 \quad (4)$$

where n is a unit vector normal to the body and ground plane surfaces, respectively.

Along the wing's *T.E* the velocity has to be limited in order to fix the rear stagnation line and therefore

$$\nabla\Phi < \infty \quad (5)$$

The third *BC* requires that the influence of the wing on the flow field must vanish at large distances from the wing is:

$$\lim \nabla\Phi = 0 \quad (6)$$

It is also important to note that what so-called Kelvin's condition

$$\frac{d\Gamma}{dt} = 0 \; for \; all \; t \quad (7)$$

is a form of momentum conservation so that the Helmholtz theorem is thus automatically satisfied at each step.

There are many versions of Vortex Lattice Method VLM available for solving equation (3). The modified Vortex Lattice Method is the proposed method, which is an extension of the classical VLM [8] for the calculation of the aerodynamic forces on lifting surfaces undergoing complex 3-D unsteady motions. Vortex rings are used to represent the bound vortices on the wing and the trailing vortices in the wake. The proposed is based on the equivalence between constant doublet panel and ring [9].

NUMERICAL APPROACH

The flow is considered to be potential; by flowing the Wieselsberger, we add the image of the wing and its wake below the ground and thereby make the ground a plane of symmetry. If the ground is rough and not to be modeled as a lane, then can omit the images and instead place panels on the ground. Fig 2 shows a schematic representation of the wing and its image near the ground.

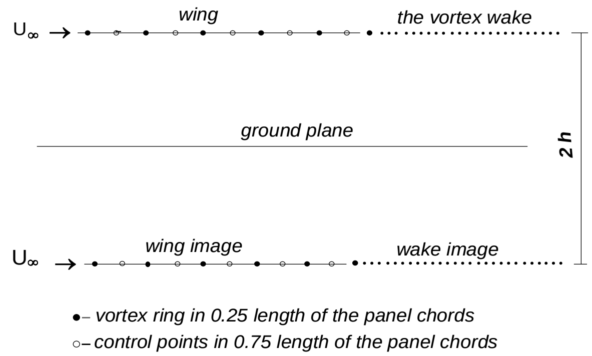

Fig 2: Wing and its image near the ground

Reference [9] proposed a technique indicated that steady state flow can be extended to treat the time dependent problem (unsteady motion) with only a few modifications. These modifications include the treatment of the condition (4) and the use of the unsteady Bernoulli equation. Therefore, the solution can be reduced to solving an equivalent steady state flow problem; at each time step, this method is called the time-stepping technique [9].

The lifting surface is divided into panels or elements. Vortex rings as singular distributions for the wing, its image and the wake are used. When we treat time-dependent motions of an airplane, a selection of frame systems becomes very essential. Two frames are used, one is an inertial (X,Y,Z) fixed to an undisturbed air and the other is fixed to the body (x,y,z) frame of reference. It is usually useful to describe the unsteady motion of the body on which the zero normal flow BC (4) is applied in the body frame of reference. The motion of this frame is then prescribed in the inertial frame and is assumed to be known. However, the BC (4) in this frame becomes;

$$\nabla\Phi . n - V_f . n = 0 \quad (8)$$

Where V_f is the kinematic velocity as viewed from the inertial frame. Equation (4) and the *Kutta* condition (6) are also satisfied by closed vortex representation.

The velocity of the control point is computed according to the relationship for a rigid body

$$V_f = V_o + \Omega \, x \, r + v_{ref} \quad (9)$$

Where $V_0 = \left(\dot{X}_0, \dot{Y}_0, \dot{Z}_0\right)$ is the velocity of the origin of a moving reference frame (point 0) that is attached to the wing, Ω is the rate of rotation of the body's frame of reference, and $v_{ref} = \left(\dot{x}, \dot{y}, \dot{z}\right)$ is the angular velocity of the moving reference frame, and r = (x,y,z) is the position of the control point relative to the moving reference frame. In general the spatial orientation of the wing is given by a set of Euler angles. Derivatives of the Euler angles can be specified and used to compute Ω. In the present paper Ω =0.

The pressure P can be determined from unsteady Bernoulli equation, written either in the body frame of reference or in the inertial frame. In the inertial frame this equation is

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$$(P_\infty - P)/\rho = -V^2 + \Phi_t \qquad (10)$$

where $V^2 = \Phi_x^2 + \Phi_y^2 + \Phi_z^2$, $\Phi_t = \partial\Phi/\partial t$ and ρ is the air density.

Concluding, the steady state solution technique can be updated to treat unsteady flows. The first step is to compute the influence matrix A_{ij}, where A_{ij} is the normal component of the velocity at the control point of element ***i*** generated by the unit circulation around the vertex segments enclosing element ***j*** and its image. Since only a half wing is considered, the influence of the other half wing, its image and wake has to be accounted for. At the start of the motion *BC (4)* becomes

$$\sum_{j=1}^{N} A_{ij}\Gamma_j = RHS_j \quad (11)$$

where $A_{ij} = \left[(u,w)_{ij} + (u,w)_{ij}^{image}\right] n_i$,*i =1,2, .. ,N*, where *N* is the number of panels and Γ_j is the circulation around the vertex segments enclosing element *j*. The right hand side *RHS* vector is

$$RHS_J = -\left((U+u_w)\sin\alpha + w_w\cos\alpha\right)_j \; (12)$$

When the circulation distribution Γ_j after solving (11) is obtained, the difference in pressure a cross the lifting surface is computed at each control point. The pressure difference is defined as

$$P = P_l - P_u$$

$$= \rho\left[(V^2/2)_u - (V^2/2)_l + (\partial\Phi/\partial t)_u - (\partial\Phi/\partial t)_l\right]$$

For this vortex ring, the velocity potential time derivative of upper and lower wing can be obtained by using the relation

$$\pm\partial\Phi_{ij}/\partial t = \pm\partial\Gamma_{ij}/\partial t$$

To obtain the loads, the difference of pressure is multiplied by the area of the panel to produce the force on the panel. The panel forces and their moments are added and the resultants are resolved into lift (*L*), drag (*D*), pitching moment (*M*) etc.

NUMERICAL RESULTS AND DISCUSSION

One of the examples of unsteady aerodynamic is the motion after a sudden acceleration of the wing [9]. The ground effect is simulated by placing a system of image vortices equidistant below the ground plane with opposite sign on the circulation. By using the method of image, the ground is again a plane of symmetry and stream surface with a zero normal velocity component The present code is used to predictthe aerodynamic characteristics of a thin wing in unsteady motion.

This method described has been programmed and run on computer. To get a feel for the program performance, it was run for a thin rectangular wing with aspect ratio(*AR* = 4) far of and near the ground, if the wing forward velocity (*U*), mean aerodynamic chord (*c*)and non-dimensional time step (*U*Δ/c*) was taken initially as 0.1 with an angle of attack α = 5 degrees. Fig 3 shows the transient lift coefficients obtained near and far of the ground. As can be seen the ratio of the transient lift coefficient seems to be increasing with the ground effect. Finally, both curves increase monotically with time towards an asymptotic (unity) value.

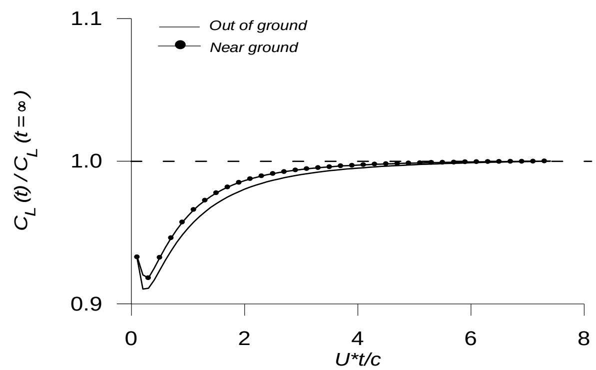

Fig 3: Effect of ground effect on non-dimensional transient lift

SWEPT AND UNSWEPT RECTANGULAR WING

A thin rectangular wing of aspect ratio equal to 4, the angle of attack α = 5 degrees was considered if otherwise mentioned. Figs 4, 5 and 6 show the coefficients of lift, drag and pitching moment (relative to the main wing's quarter chord) out of and in ground effect at unsteady motion, respectively, are plotted as functions of the angle of attack. The non-dimensional wing height (*H=h/c)* was taken equal to 0.5 where *h* is height of mean quarter chord point above ground. From these figures, two things can be concluded, first, the aerodynamic coefficients (lift and pitching moment) are higher near ground due to the increase of the effective angle of attack; second, as the angle of attack increases, the effect of the ground effect increases and the increasing of aerodynamic coefficients (lift and pitching moment) becomes more noticeable. Therefore, in ground effect, the wing will require a lower angle of attack to produce the same amount of lift. The include of unsteady motion near ground is very important. In order to get better and more accurate aerodynamic results near ground the unsteady solution is suggested and recommended to be used. Because of wingtip vortices are unable to form effectively due to the obstruction of the ground, the result is lower induced drag which increases the speed and lift coefficient.

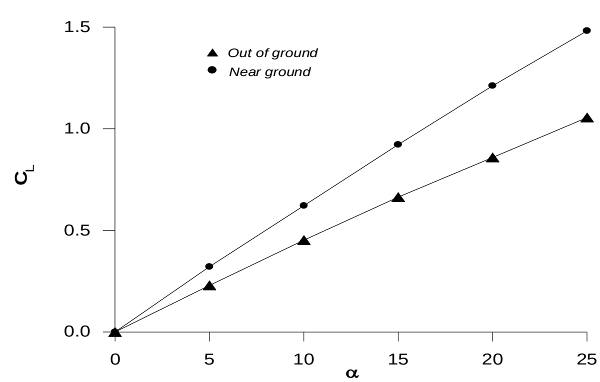

Fig 4: A comparison of computed lift coefficient nearand far of ground as functions of angle of attack

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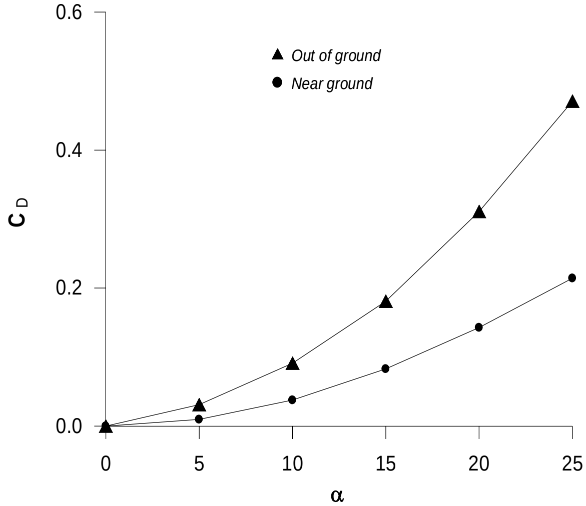

Fig 5: A comparison of computed lift coefficient near and far of ground as functions of angle of attack

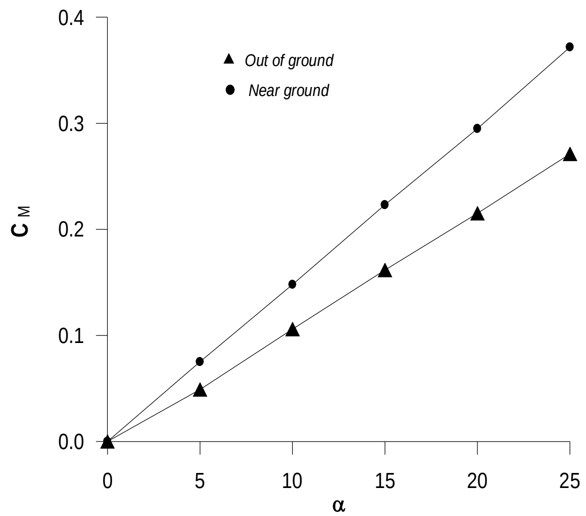

Fig 6: A comparison of computed pitching moment coefficient near and far of ground effect as functions of angle of attack

Figs 7, 8 and 9 show the non-dimensional aerodynamic coefficients (C_L,$C_{L\infty}$ are lift coefficients in and out of ground effect, respectively) which are plotted as a function of the height of 1/4 chord point above the ground in unsteady motion (height change with time) for different angles of attack. A thin rectangular wing with zero sweep back angle and aspect ratio equal to 4 was considered. Both lift and pitching moment are increased as the wing approaches the ground, that is, the ground effect increases with the increasing of the angle of attack. This is not the case for the induced drag which decreases near the ground as the angle ofattack increases due to the decreasing of the induced downwash near ground.

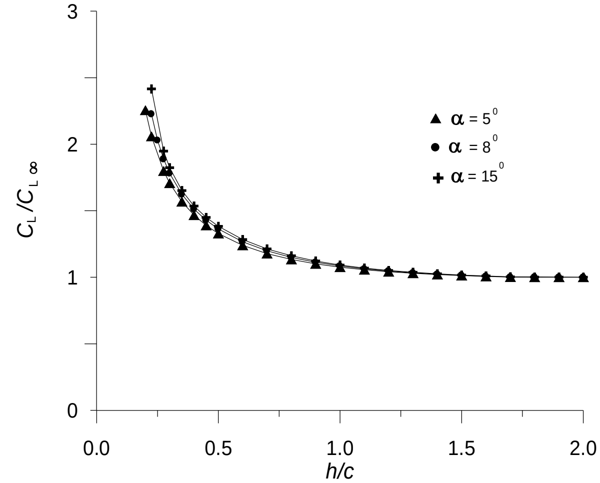

Fig 7: Non-dimensional lift coefficient in groundunsteady motion for different angles of attack

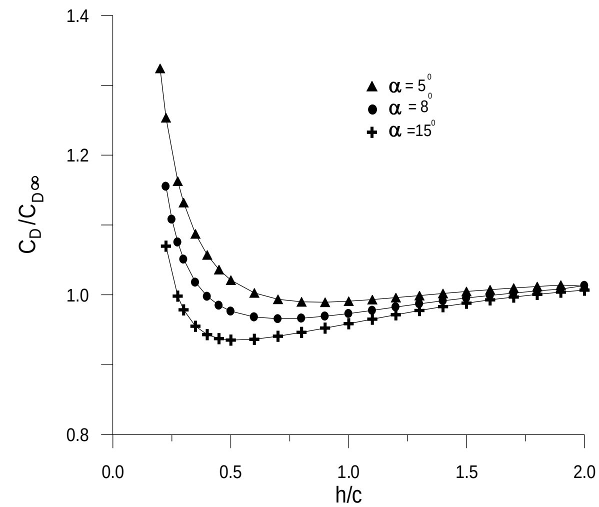

Fig 8: Non-dimensional drag in ground unsteadymotion for different angles of attack

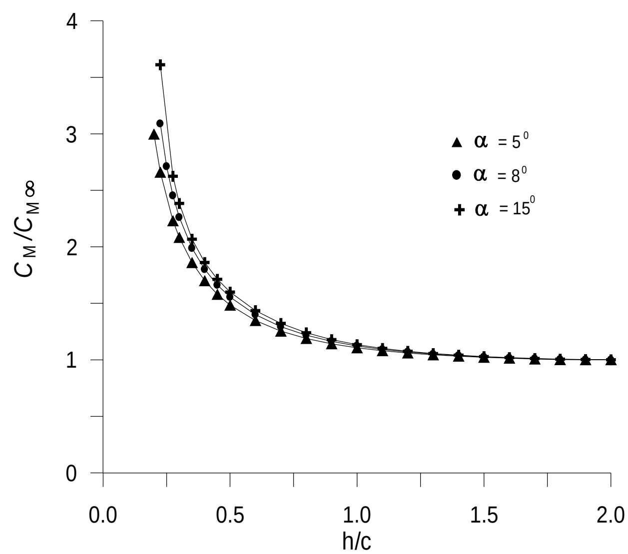

Fig 9: Non-dimensional pitching moment in groundunsteady motion for different angles of attack

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Fig 10 shows non-dimensional center of pressure plotted as a function of *H* for unsteady ground motion for the same rectangular wing mentioned above. The ground effect shifts the center of pressure backward; this situation appears to be increased with the increase of the angles of attack.

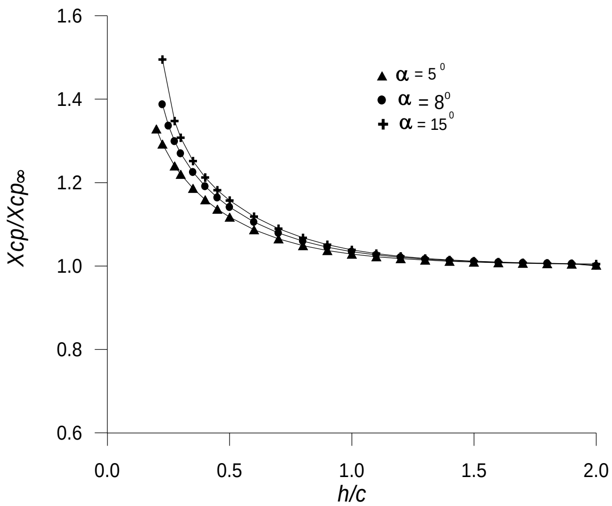

Fig 10: Non-dimensional center of pressure in groundunsteady motion for different angles of attack

Figs 11 and 12 show the changes in the aerodynamic coefficients plotted as functions of the height of the *1/4* chord point above the ground for different aspect ratios for unsteady flow motion. The ground effect increases the coefficients and the effect is stronger for larger aspect ratios. The obtained results are in agreement with the similar results in Ref. [6].

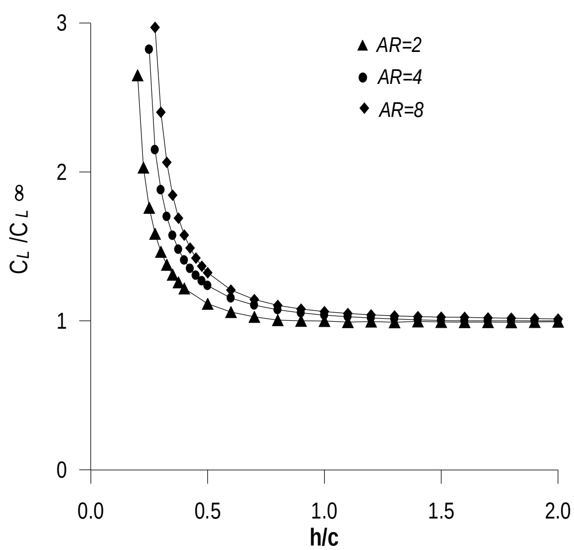

Fig 11: Computed non-dimensional lift coefficients inground unsteady motion for different aspect ratios

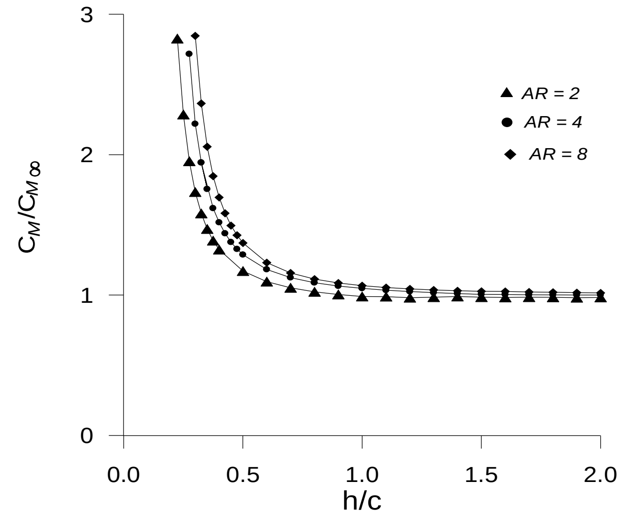

Fig 12: Computed non-dimensional pitching moment coefficients in ground unsteady motion for different aspect ratios

Fig13 shows the changes in the lift coefficient verse as functions of the height of the 1/4 chord point above the ground for different sweep back angles (Λ) for unsteady flow motion. As the ground effect increases; the lift coefficient and the effect becomes stronger for larger sweep back angles.

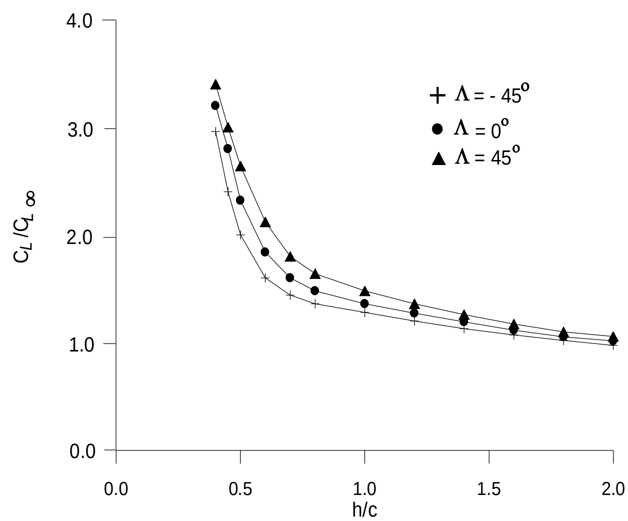

Fig 13: Computed non-dimensional lift coefficient in ground unsteady motion for different sweep back angles

Fig 14 shows the lift-drag ratio *(L/D)* plotted against the lift coefficient for different wing height above the ground. In this time the height of wing 1/4 chord point is a function of wing half span (in this case $H = h/b$, where b is the wing half span). The rectangular wing has aspect ratio equal to 4, and zero sweep back (Λ). As can be seen, generally the lift-drag ratio increases with increasing of ground effect due to increasing of lift and decreasing of drag near ground. Flying close to a surface increases air pressure on the lower wing surface, known as the ram or cushion effect and thereby improves the aircraft lift to drag ratio. The high values are obtained as the lift becomes minimum and it is decreasing with the increases of lift; that means, in order to get large lift-drag ratio we have to fly at a low angle of attack.

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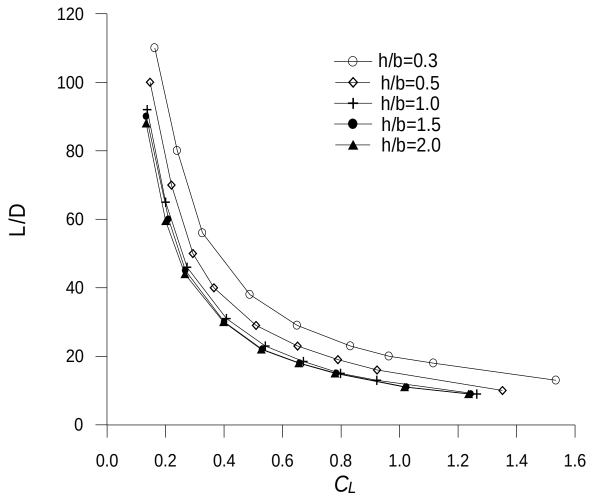

Fig 14: Lift-to drag ratio at different wing height abovethe ground

TAPERED WING

A thin wing of taper ratio equal to 0.4, aspect ratio equal to 4, the angle of attack α = 5 degrees, and sweep back Λ = 15 degrees were considered.

Figs 15 and 16 show the changes in the aerodynamic coefficients plotted as functions of the height of 1/4 chord point above the ground for different taper ratios for unsteady flow motion. It is clear that as the taper ratio increases, and if the ground effect increases, the effect is stronger for higher taper ratios.

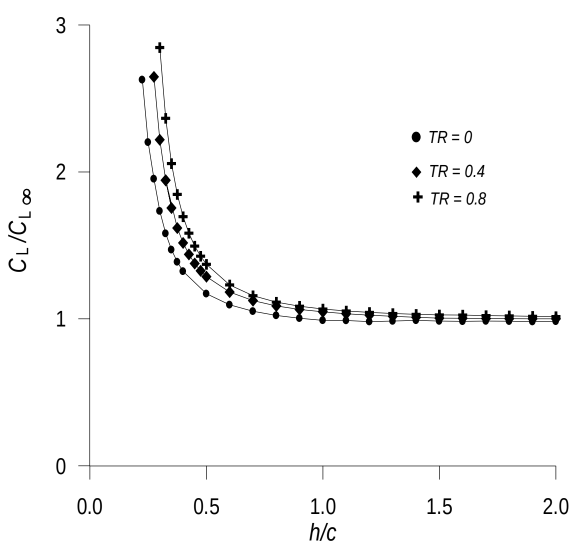

Fig 15: Computed non-dimensional lift coefficients in ground unsteady motion for different taper ratios.

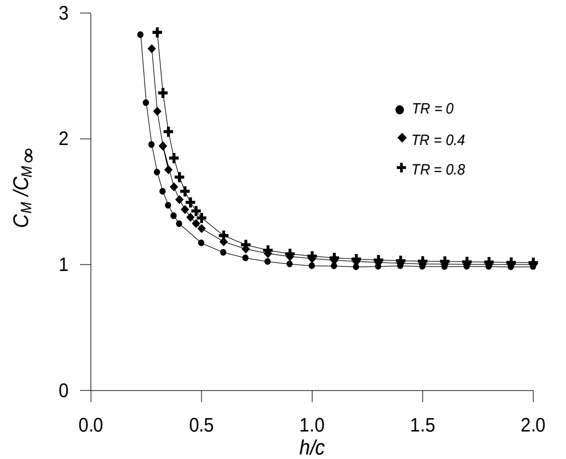

Fig 16: Computed non-dimensional pitching moment coefficients in ground unsteady motion for different taper ratios

Figs 17 and 18show the changes in the aerodynamic coefficients are plotted as functions of the height of 1/4 chord point above the ground for different aspect ratios for unsteady flow motion. The ground effect increases, the coefficients and the effect is stronger for larger aspect ratios.

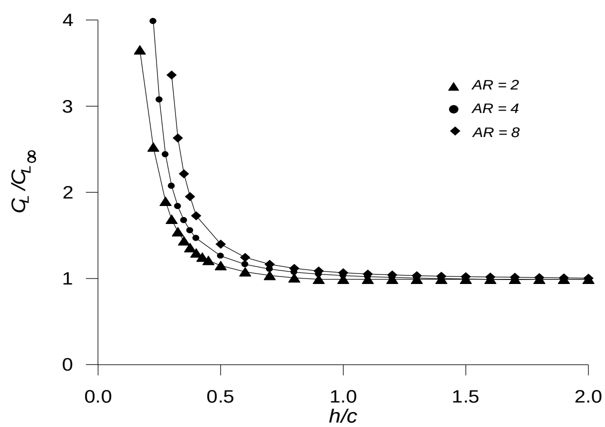

Fig 17: Computed non-dimensional lift coefficients in groundunsteady motion for different aspect ratios

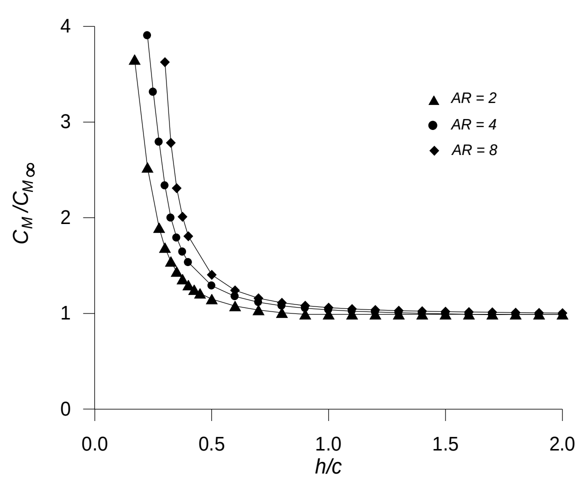

Fig 18: Computed non-dimensional pitching moment coefficients in ground unsteady motion for different aspect ratios

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The lift-drag ratio *(L/D)* plotted against the lift coefficient for different wing height above the ground is shown in Fig 19. As can be seen, generally the lift-drag ratio increases with increases of ground effect due to the above mentioned reasons. However, the lift-drag ratio is larger with tapered wing than rectangular wing.

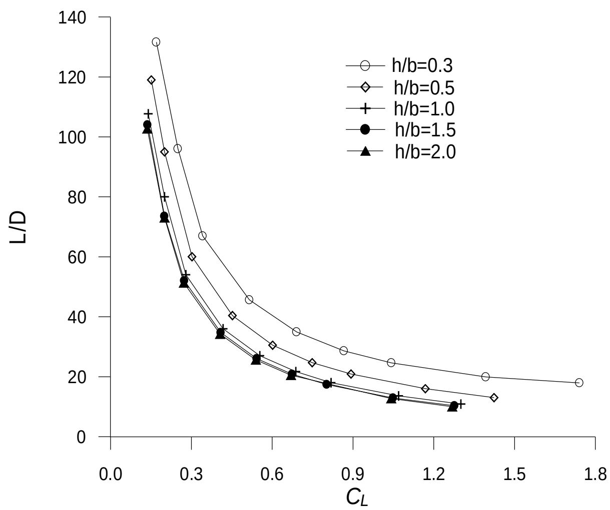

Fig 19: Lift-drag ratio at different wing height above ground

From the above results, it is clear that the ground effect has a significant effect on aerodynamic loads. The lift and its corresponding pitching moment increase near ground while the induced drag decreases. The unsteady motion is very important near ground especially in the case of aircraft takeoff and landing and at a higher angle of attack. Therefore, for better and more accurate results near ground, the ground effect and unsteady motion have to be considered in any aerodynamic model.

CONCLUSIONS

A numerical model of a thin wing in unsteady motion as it approaches the ground has been developed. The most important conclusions are:
The ground has a significant effect on the wake; the wake has a noticeable influence on the aerodynamic coefficients. Its inclusion in the study is important and essential, especially in the case of aircraft takeoff and landing when a light aircraft passing through a strong wake left behind by a larger aircraft at congested airports or where an aircraft is flying closely to another in the air.
Generally, the aerodynamic coefficients (lift and moment) increase with proximity to the ground. The present simulation, the ground effect shows higher aerodynamic coefficients for unsteady cases than steady cases. Case study showed that, increasing angle of attack, sweep back angle, aspect ratio and taper ratio increases the ground effects in both steady and unsteady flows for rectangular and tapered wings.
As the angle of attack increases and becomes high near ground, the unsteady solution becomes very important It is recommended to be used to get better and more accurate results. It is necessary to take the ground effect into account when the wing height above the ground is beyond twice the wing chord.

Finally, the full model of unsteady aerodynamics in ground effect of lifting surfaces has not been completed yet. More investigations should be done to study this effect on the aerodynamic coefficients for low and high wing aircraft, other aerodynamic coefficients, stability derivatives, the runway surface (concrete or other smooth hard surface and water or broken ground) etc. The investigation could be extended to study the effect of this phenomenon on aircraft dynamic behavior, structural dynamics etc.

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