Nonplanar Wings in Nonplanar Ground Effect

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A discrete singularity numerical method is developed for solving the problem of a wing in arbitrary nonplanar ground effect. Numerical calculations were performed for various thin, uncambered planar and nonplanar wings (including two wings connected in tandem) in planar and nonplanar ground effect. Some of the numerical calculations were corroborated by experiment.

I. Introduction

THE search for new high-speed ground transportation water and rough terrain vehicles has spread in many directions. One of these directions involves the use of aerodynamic lift to support and stabilize a high-speed vehicle above a planar or nonplanar (regular or irregular) ground surface. The ram wing and the terrafoil are the most popular names associated with this mode of transportation. A ram wing can be described as a vehicle which is geometrically similar to a large low-aspect-ratio airfoil flying close to the ground and is subject to aerodynamic ground effects. A detailed description of a terrafoil vehicle is presented in Ref. 1. In general, it can be described as a tandem winged vehicle subject to close ground effect and which aerodynamically interacts with a surface or guideway to achieve static and dynamic stability.

The ram wing and terrafoil concepts for multiterrain travel have several advantages over other proposed guided and multiterrain vehicles, such as the air-cushion vehicle. Among these advantages are: 1) the utilization of ground augmented dynamic lift at high speeds, 2) the reduction in induced aerodynamic drag due to the presence of ground effect, 3) the reduction of wave and spray drag over water since these vehicles will in general (and particularly at high speeds) fly appreciably higher than the corresponding air-cushion vehicle, 4) the elimination of momentum or sink drag, which is the equivalent of induced drag for a wing, 5) the capability of being integrated with a captured air-bubble lift augmentation system, and 6) the capability for negotiating obstacles or drastic changes in height above the ground to facilitate travel over very rough terrain.

There have been, however, some major difficulties impeding the development of these vehicles for use in high-speed surface transportation. One of these difficulties has been the absence of analytical or numerical methods for determining the flowfield about completely arbitrary nonplanar wings in the presence of any arbitrary nonplanar ground situation. Another difficulty stems from the fact that there has been a lack of investigations into the static and dynamic stability characteristics of three-dimensional wings in arbitrary ground effect.

It is, therefore, the purpose of this investigation to develop a suitable numerical method for solving the problem of completely arbitrary lifting wings flying in the close proximity to arbitrary planar or nonplanar ground. A future paper will present the linearized equations of unsteady motion for nonplanar wings in nonplanar ground effect.

Previous to the present investigation, the only method used to represent a ground plane for use in calculations of wings in ground effect, was the imaging method. It consists of placing an identical wing in mirror image fashion on the opposite side of the plane designated as the ground plane. In this way, the boundary condition on the ground surface is automatically satisfied because the equal and opposite flow velocities exactly cancel at the plane designated as the ground plane. Kohlman[2] used the imaging method in conjunction with a discrete vortex digital computer program to determine the ground effect on wings of arbitrary planform. Saunders[3] also used the imaging method and the kernal function wing representation of Watkins[4] to determine the ground effect on some thin flat wings as well as thin nonplanar wings with sweep and taper ratio. Most recently, Kalman[5] used this method with the vortex-lattice method to compute the ground effect on thin flat rectangular wings of various aspect ratio. The results obtained by all three methods seem to be in general agreement with each other as well as with experimental data.

However, there have been no investigations conducted that have considered the problem of the arbitrary nonplanar ground. Gray[11] has used a multiple image method to solve certain nonplanar ground problems. However, all other numerical investigations have only considered the case of wings in planar ground effect. The reason for this is obvious; the imaging method cannot be extended to the arbitrary nonplanar ground problem. Therefore, if any solutions are to be obtained for the problem of an arbitrary wing in arbitrary nonplanar ground effect, they can only be obtained by developing a new method for representing ground interference.

II. Numerical Solution

The main considerations involved in choosing the numerical technique used in this investigation were simplicity, flexibility, and cost minimization. Therefore, the method chosen for the simulation of the presence of a wing in the flowfield was the vortex-lattice method. This method can be used for any arbitrary wing shape, since the Kutta condition is automatically satisfied. The method also generates the proper singularity at the leading edge automatically. In addition, the simple calculations involved in satisfying the boundary condition on the wing, which avoided any problem with singularities, were very attractive. The vortex-lattice method consists of subdividing a wing surface into a number of discrete quadrilateral surfaces. The bound portion of a horseshoe vortex is placed along the one-quarter chord of the quadrilateral, and the vortex strengths are determined by satisfying the

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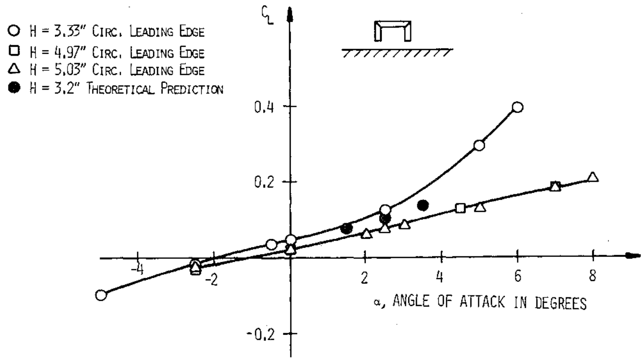

Fig. 1 Lift coefficient vs α planar ground.

tangent flow boundary condition at the midpoint of the three-quarter chord of each quadrilateral.

However, a new method had to be developed for representing the presence of the ground in the flowfield. This method had to be equivalent to the method of images for two-dimensional and three-dimensional planar ground problems, but had to have the capability of being extended to three-dimensional nonplanar ground problems. Therefore, it was decided to represent the presence of the ground in the flowfield by a distribution of mass sources and sinks. The distribution of sources and sinks were placed on the ground surface. The boundary condition prescribing that there be no normal flow through the ground was satisfied at a discrete number of points. The strengths of the sources or sinks at these discrete points as well as the strengths of the horseshoe vortices representing the wing were then determined by solving a set of simultaneous equations developed by satisfying the boundary conditions on the wing and ground. There were many problems associated with this technique. Among them was the need to truncate the ground plane rather than extending it to $\pm \infty$. Another problem evolved in the choice of locations on the ground plane for which the boundary condition on the ground was to be satisfied. This problem was especially critical in the region beneath the wing and in regions near any corners in the ground plane. Additional problems also arose due to the singular nature of the source strength directly at the corners on the ground plane. The details as well as the resolution of these and other problems involved with this method are discussed in Ref. 6.

Another entirely different technique for representing a nonplanar ground plane was also developed. This technique was actually an extension of the principles of images and is thus referred to as multiple imaging. It involves the placement of more than one image of a given wing in the flowfield to represent the effect of a nonplanar ground. This method, however, was only useful for solving problems where the nonplanar ground consisted of two straight infinite ground planes intersecting each other at a certain angle. However, the development of this technique was essential in order to check some of the results of the source/sink distribution technique. The mathematical treatment of all these methods was applied to three-dimensional planar ground problems, and the treatment of the source/sink method and the multiple imaging method was also applied to three-dimensional nonplanar ground problems.

The numerical solution techniques outlined in the foregoing paragraphs were formulated in several computer programs. In fact, separate programs were written for two-dimensional wings using the method of images, three-dimensional wings using the method of simple and multiple images, and three-dimensional wings using the source sheet distribution method. These programs were written in Fortran IV language for use on an IBM 370/155 computer at Cal Tech and for use on an IBM 390/91 at UCLA. Typical nonplanar cases involved about 50 vortices, 100 sources, and required about 2 min of run time on the 360/91.

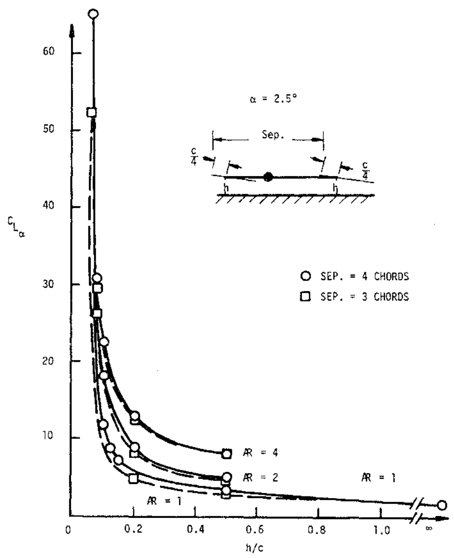

Fig. 2 Lift curve slope vs h/c, tandem flat rectangular wings in ground effect.

The class of wings investigated was thin planar and nonplanar wings without camber or twist. The ground planes investigated were flat ground planes, in two and three dimensions, and three types of three-dimensional nonplanar ground situations representing three possible high-speed ground transportation vehicle guideways. Numerical solutions were determined for a large number of cases of two and three-dimensional wings in planar and nonplanar ground effect. However, only the results of a few of the more interesting cases will be presented here. For a more complete presentation of results as well as ample comparisons with experiments and other numerical calculations, the reader is referred to Ref. 6.

Results for a Planar Ground

Flat wing with end plates at angle of attack

Calculations were made of the lift coefficient as a function of the height above the ground for the nonplanar wing shown in Fig. 6. The horizontal wing segment had an average aspect ratio of 0.2564 and was placed with an angle-of-attack of 2.5°. The two end plates were 0.154 chord in average width and were also placed at an angle-of-attack of 2.5° to the X-Z plane. The bottom edges of the end

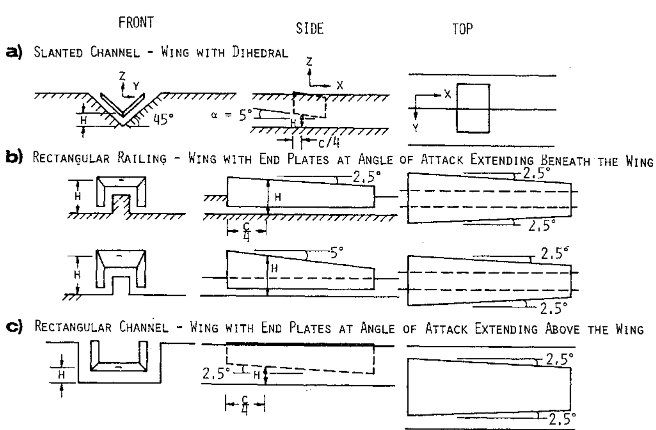

Fig. 3 Nonplanar ground effect configurations.

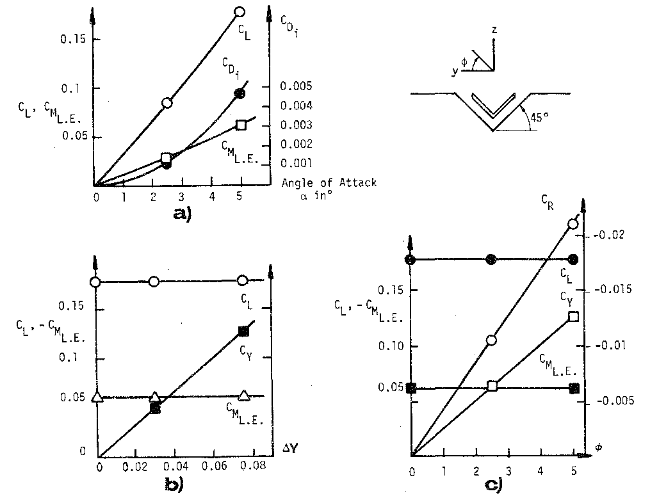

Fig. 4 a) Slanted channel wing with dihedral C_L, $C_{ML.E.}$, C_{Di}, C_Y, C_R vs angle-of-attack. b) Lateral shift from L.E. equilibrium ΔY in chords. c) Slanted channel C_L, $C_{ML.E.}$, C_{Di}, C_Y, C_R vs roll angle from equilibrium.

plates were parallel to the ground plane. The results were compared to an experiment which was performed as part of the investigation. The details of the experiment can be found in Sec. III. The agreement between the numerical calculations and the experiment were reasonable at all heights except where the bottom edges of the wing touched the ground. At this height, the turbulent boundary layer beneath the wing caused the ground plane to become effectively closer to the wing thereby creating higher lifts.

Additional calculations were made to determine the lift coefficient as a function of angle-of-attack at a height of 0.2123 chord. These results were compared to experimental measurements of the same situation and are presented in Fig. 1. The numerical results were slightly below the experimental results, but were within the expected accuracy of the experiment.

Flat rectangular wings in tandem

Numerical calculations were made for a pair of thin flat rectangular wings in tandem. The downwash on the rear wing due to the presence of the front wing was accounted for automatically by the trailing vortex portions of the horseshoe vortices used to represent the wing. The only assumption necessary with regard to these trailing vortices was that they shed from the front wing surface parallel to the ground. The validity of the trailing vortex distribution for representing the wake was assumed to extend to wings in ground effect.

The lift-curve slope as a function of height above the ground for flat rectangular wings in tandem is presented in Fig. 2. Calculations were made for identical wings of aspect ratio 1, 2, and 4, with each wing at an angle-of-attack of 2.5°. The wings were rigidly attached by a thin fuselage and were placed 3 and 4 chords apart. The centers of gravity and rotation were placed at the vehicle center of pressure.

The numerically calculated values for the lift-curve slope became astoundingly large as the ground was approached. This was due to the fact that the rotation arm was large and the center of pressure was closer to the front wing than to the rear wing. Small rotations about the vehicle c.p. caused large variations in the height of the rear wing, and also caused large variations in the downwash induced on the rear wing. The result of these variations was a large lift-curve slope.

The results further indicated that the downwash did not vary significantly with the separation distance between the two wings. This is indicated by the fact that $(\partial C_L/\partial \alpha)$ and the induced drag did not change significantly with separation distance. Calculations of the stability derivatives for these thin flat rectangular wings in tandem are presented in Ref. 6.

Results for a Nonplanar Ground

Numerical results were obtained for three types of nonplanar ground effect geometries. Schematics of these three geometries are shown in Fig. 3. Two cases were solved with the same ground geometry but with slightly different wings. In addition, a simplified check case was run to compare the numerical results obtained by the source distribution method with the results obtained by the multiple image method for the same problem. The check case is presented first, and then the results of the important cases are presented separately.

Slanted channel-wing with dihedral

Calculations were performed on a wing of aspect ratio 2 with 45° dihedral at a height of 0.5 chord above the vertex of a slanted channel ground plane. Plots of the lift coefficient, the leading-edge moment coefficient, the induced drag coefficient, the lateral force coefficient, and the leading-edge roll moment coefficient as a function of angle of attack, roll angle, and lateral deflection from equilibrium are shown in Fig. 4. There are three important features of these results. The first is that the lateral force and roll moment are nearly linear with roll angle and lateral shift from equilibrium even for relatively large perturbations from equilibrium. This indicates that a linearized approximation for the equations of dynamic stability would be very suitable at least for the roll and lateral deflections from equilibrium. The second important feature of these results is the fact that the longitudinal forces and moments seem to be decoupled from the lateral perturbations. This is very important since it means that the equations of dynamic stability can be decoupled into the longitudinal equations of motion and the lateral equations of motion which will simplify the analysis greatly. It was expected that this configuration could not be decoupled because of the peculiar oblique type of ground effect. Since, however, it is apparent that the equations of motion can even be decoupled for this case, it can be concluded that the equations of motion can be decoupled for most nonplanar ground effect situations within reason. This conclusion was substantiated by all subsequent cal-

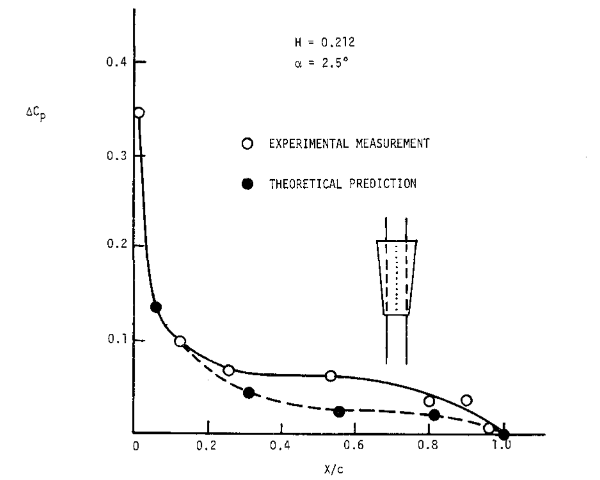

Fig. 5 Load distribution along top centerline of wing, nonplanar ground.

culations on other configurations. The third important result is that the lateral force with a perturbation in roll angle is unexpectedly destabilizing. This shows that the change in the direction of the normal force coefficient is a larger effect than is the change in the lift due to the change in proximity to the ground for roll perturbations.

Rectangular rail—end plates at angle-of-attack beneath the wing

Figure 3b illustrates this nonplanar ground effect situation. The top segment has an average aspect ratio of 0.2564 (average span divided by chord). Cases were solved with the top segment at an angle-of-attack of 2.5° at various heights above the ground. Cases were also solved for this wing in the presence of planar ground effect and were discussed earlier in this section. Another nonplanar ground case was solved with the top wing segment at 5° at a quarter chord height of 0.2452 chords above the ground. The end plates have average aspect ratio of 0.2014 and 0.2233 for each case and were placed at 2.5° lateral angle-of-attack in both cases. The end plates are 0.0783 chord from the side walls measured at the quarter chord. The bottom edge of the end plates are parallel to the plane. The rectangular rail is 0.1323 chord high and 0.1215 chord wide.

A plot of the load distribution along the centerline of the top wing segment is shown in Fig. 5 and compared with experimental measurements for the 2.5° angle-of-attack case at a height of 0.2133 chord. In addition, plots of the lift coefficient as a function of height above the ground are compared with experimental measurements for the 2.5° angle-of-attack case in Fig. 6.

Due to computer storage limitations, the ground plane was only extended to a distance of 0.2 chord in the $\pm Y$-direction and from -0.45 to 1.2 chord in the X-direction. From results of calculations on finite ground planes discussed in Ref. 6, this should have caused the results for the lifts and moments to be 10–15% lower than if the ground plane were extended to infinity, and the same percentage higher for the drags. This conclusion is consistent with the comparisons to the experimental measurements.

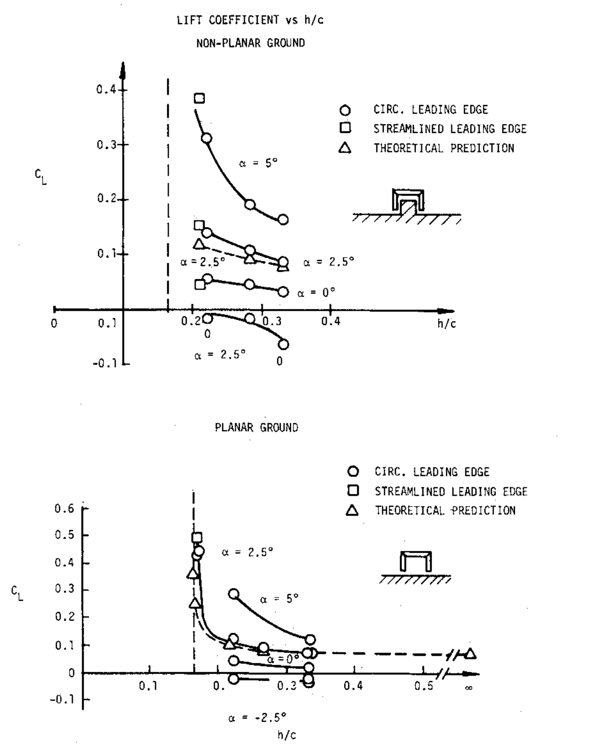

Fig. 6 Lift coefficient vs h/c, nonplanar ground and planar ground.

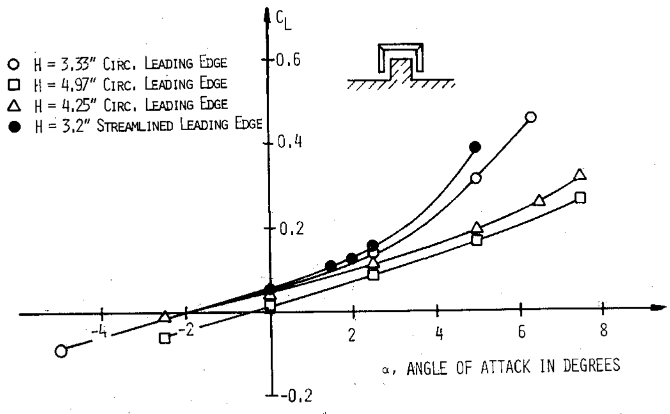

Fig. 7 Lift coefficient vs angle-of-attack, nonplanar ground.

In addition, the experimental measurements were probably too high due to boundary layer effects on the simulated ground.

Calculations of all the stability derivatives for the case of $h = 0.2123$, angle-of-attack 2.5, and the case of $h = 0.2452$, angle-of-attack 5° are presented in Ref. 6.

Comparisons of the 2.5° angle-of-attack case in the presence of a nonplanar ground with the same wing in the presence of a planar ground show that the presence of the nonplanar ground piece adds at least 10% to the lift.

III. Experimental Verification

In order to investigate the validity of some of the assumptions and idealizations used in the numerical calculations presented in the previous chapter, and experiment was conducted.

This experiment consisted of a wind-tunnel study where measurements were taken of the lift and drag on a nonplanar wing in planar and nonplanar ground effect. The Reynolds number of the test was 1.35×10^6 and the chord length of the model was 15 in. This wing was also investigated numerically so that a valuable check could be made between theory and experiment.

Results

Experimental measurements of the lift coefficients as functions of angle-of-attack and height above the ground are shown in Figs. 1 and 5–7 for the planar and nonplanar cases. The theoretically predicted results for these cases are also shown in Figs. 1, 5, and 6. The aforementioned measurements were taken for two different wing model leading-edge shapes. This was necessary because the original leading-edge shape (a semicircle of radius 3/32 of an inch) produced a small separation bubble about 2 in. in length near the leading edge. This bubble occurred because the flow had a much larger local angle-of-attack beneath the leading edge than the 2.5° to the freestream. The flow between the wing and ground was slowed down as it attempted to pass through the converging channel produced by the wing and ground. Therefore, the flow near the leading edges went around rather than through the channel. This produced the higher local angle-of-attack near the leading edge. A second set of measurements were taken with a different leading-edge shape. This shape was streamlined to eliminate the separation bubble. As expected, the drag was reduced significantly with the second shape. The lift, however, was not changed significantly except at very high angles of attack.

The measurements taken at the lowest heights for both the planar and nonplanar ground were significantly affected by the boundary-layer displacement thickness on the ground plane. In the planar ground case, the boundary layer was completely removed 7 in. ahead of the wing leading edge; however, the extremely large adverse pressure gradient on the ground just ahead of the leading edge of the wing caused transition of the boundary layer to occur. In the nonplanar ground case, the boundary layer was not completely removed due to limitations in the suction slot of the nonplanar ground piece. Therefore, a turbulent boundary layer developed before the large adverse pressure gradient was encountered. Then the adverse pressure gradient undoubtedly thickened the boundary layer substantially. In both the planar and nonplanar cases these effects were very significant.

The effect of the highly adverse pressure gradient cannot be determined beyond the qualitative deduction that it causes the boundary layer to thicken more rapidly than it would under zero pressure gradient conditions. A plot of the load distribution along the centerline of the top wing segment is shown in Fig. 5. The numerically predicted load distribution is shown also. The difference in the two distributions is most prominent over the rear portion of the model where the experimentally predicted load distribution is much larger than expected. This indicates that the rear portion of the wing is effectively closer to the ground than indicated by the numerical results. Hence, the measurement at the height of 0.215 chord in the presence of the nonplanar ground is not a valid comparison to the equivalent numerical results.

The numerically predicted results were in good agreement with the experimental results in all cases considering that the numerical results were for a truncated ground plane which reduced the lift augmentation of the ground. The greatest deviations were at the wing positions nearest the ground. However, in the planar ground case these deviations were accounted for in a simple manner, and in the nonplanar ground case, possible reasons for the deviations are presented.

IV. Conclusions

The method presented in this paper appears adequate for solving problems of arbitrary wings in arbitrary ground effect. Further experiments will be required to fully determine the accuracy of the method.

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