Experimental Investigation on the Aerodynamic Characteristics of a Tandem Wing Configuration in Close Ground Proximity

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Experimental Investigation on the Aerodynamic Characteristics of a Tandem Wing Configuration in Close Ground Proximity*

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Influence of ground clearance and angle of attack on the aerodynamic characteristics of a tandem wing configuration with a variable distance between them and held together by two flat end plates, is studied experimentally. A moving belt system was used to simulate the true ground effect. Both the wing sections were having SYM-1B profile, which is known to have excellent aerodynamic characteristics in ground effect. It was found that the ground clearance of the wings and the angles of attack to the wings have a very strong influence on the aerodynamic performance of the tandem wings. A strong interference effect between the wake of the front wing and the rear wing affects the aerodynamic performance of the tandem wing configuration, especially when the distance between the wings is shorter. The system showed high pitching instability for increased spacing between the tandem wings.

Key Words: Experimental Investigation, Aerodynamics, Tandem Wings, Ground Effect, Lift, Drag

1. Introduction

Efforts to utilize the favorable aerodynamic characteristics, which are obtained when a wing is in close proximity to ground, for realization of Wing-in-Ground-effect (WIG) vehicles for large transport purpose are going on for many decades. For small angles of attack, the lift force is found to increase with decreasing flight altitude. The flow around an airfoil or a wing is considerably modified under the influence of ground effect. The streamlines around the wing get modified, i.e. the dividing streamline and the stagnation point move down, hence more air flows above the wing; thus there is a decrease in velocity below the wing and then an increase in pressure. An air cushion is created by the high pressure that builds up under the wing when it is approaching the ground. For very small clearance, the air tends to stagnate under the wing, which will give the highest possible pressure, so called ram pressure. Simultaneously, the induced drag is lowered as the induced downwash velocity diminishes close to the ground. The increased lift and reduced drag obtained at the ground clearance (h/c, where h is the gap between the trailing edge of the wing and the ground and c is the chord length of the wing) being less than 0.1 give much higher efficiency, which is proportional to L/D. Due to the increased efficiency, increased flight range can be effectively achieved at a reduced specific fuel-consumption compared to the conventional aircraft. Besides, the WIG vehicle has other advantages over a conventional mode of air transport such as less energy consumption during take-off, no need of pressurized cabin, smaller infrastructure and safer runway because it is near the ground.

There have been some successful attempts to develop WIG vehicles that fly over water. The initial success in the development of WIG vehicles was accomplished in Finland, Sweden and the United States. A review of the various types of vehicles experimented at various times is made by Ollila(1).

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Ando[2] made a critical review of the design philosophies of overwater transport WIG vehicles. Work on development of overwater WIG vehicles is currently going on in many countries due to the potential fuel savings and speed advantages over other modes of water transport providing the impetus.

The development of the WIG vehicles for possible application in both overwater and overland transport necessitates a thorough investigation of the flow characteristics over the wings and other lifting surfaces. There have been some experimental as well as theoretical studies on influence of different wing configurations on the aerodynamic characteristics[3]-[8].

It is felt that the ground effect can be utilized much more effectively for overland transport as the surface conditions are negligible. The streamlines will be tangential to the surface when the wing is over ground; however, when the surface is free, the streamlines are forced to bunch together because of the presence of waves, hence there is an increase in velocity and a decrease in pressure behind the wing, resulting in an increase in drag, which gives the well-known hump in the drag curve at speeds below the cruising speed. There is a proposal to develop a guideway type train which can "fly" in close proximity to ground. Such a vehicle will be free from surface conditions.

It is known that wings having a low aspect ratio are more suitable for sports or pleasure vehicles, while those having a large aspect ratio are better suited for transport purposes[2]. However, for the specific application of train, it is not possible to have large wing span. Tandem wings (one wing in the wake of the other) may be regarded as a solution for this problem. It is found that use of tandem wings for WIG vehicle helps in getting better lift/drag characteristics and also in providing the necessary longitudinal stability when the angle of attack (α) is not large[9]. However, in such a configuration, flow trailing from the front wing will modify the flow pattern over the rear wing and change its aerodynamic characteristics. Little is known about this influence on the performance of the tandem wings.

The present paper deals with a study of the aerodynamic characteristics of a tandem wing configuration for different angles of attack for the wings in close ground proximity; the distance between the wings (l) and the gaps between the trailing edge of the wings and the side plate base (h_f, h_r) were varied to study their influence on the performance of the tandem wings. The pitching moment acting on the test model about quarter the length of the side plate was also computed for different cases.

Nomenclature

b : wing span
c : chord length of the rear wing
c_1 : chord length of the front wing
C_D : coefficient of drag$\left(\frac{D}{0.5\rho.U_\infty^2.(c+c_1).b}\right)$
C_L : coefficient of lift$\left(\frac{L}{0.5\rho.U_\infty^2(c+c_1).b}\right)$
C_M : coefficient of moment about quarter the length of the side plate$\left(\frac{M}{0.5\rho.U_\infty^2(c+c_1)^2 b}\right)$
D : drag force
h_f : gap between the front wing trailing edge and the side plate base
h_m : gap between the test model trailing edge and the ground
h_r : gap between the rear wing trailing edge and the side plate base
l : distance between the tandem wings
L : lift force
M : pitching moment
U_∞ : freestream velocity
x : axial coordinate
y : transverse coordinate
α_f : angle of attack for the front wing
α_r : angle of attack for the rear wing
ρ : air density

2. Experimental Method

2.1 Wind tunnel

The experiments were carried out at a velocity of 15 m/s in a return circuit low turbulence wind tunnel at the Institute of Fluid Science. The air flow in the tunnel was generated by a single stage axial flow fan having a rated discharge of 3 180 m^3/min at the total pressure of 1.18 kPa and driven by a thyristor controlled 95 kW DC motor having a maximum speed of 1 100 rpm. With the help of thyristor system, it is possible to vary the speed of the motor smoothly. A velocity range of 5 m/s to 80 m/s can be realized in the open test section. The airflow was discharged through the square outlet of the duct, having a side width of 810 mm, to the test section through a contraction nozzle having an area ratio of 12. The mean velocity at the test section, which is having a length of 1 420 mm, can be controlled with an accuracy of 1 %. The freestream turbulence level at the velocity of 15 m/s was found to be about 0.07 %. The variation in the mean velocity in the core region of the test section was found to be within 1 % although the test section was open. Similarly, the flow velocity close to the moving belt surface was found to vary very little in the axial direction. The boundary layer thickness at the exit of the contraction nozzle was found to be about 30 mm. The boundary layer was minimized by applying suction at the exit of the contraction nozzle. With the application of suction, the boundary layer remained only 1 mm thick at that station.

Further details of the wind tunnel and the flow characteristics in the tunnel can be found in Ref.(11)

2.2 Moving belt system

A moving belt system was used in the present studies to simulate the ground effect. As the ground clearances of the side plate/wings are small in the studies on wing in ground effect, such a system is highly desirable to simulate the true ground effect. The belt used in the present studies has an effective length of about 1 000 mm and a width of about 800 mm. The speed of the belt can be varied smoothly from 1 m/s to 45 m/s with an increment of 0.1 m/s. The boundary layer thickness on the moving belt was found to be about 1 mm at the beginning and slightly more than 2 mm at stations 700 mm downstream. Further details of the velocity profiles over the moving belt are described in Ref.(10)

2.3 Test model and experimental set-up

The wing section chosen for the present investigation was a modified form of SYM-1B having a maximum thickness of 16 %. This airfoil was found to have excellent aerodynamic performance in ground proximity(12). Geometric details of the SYM-1B airfoil can be found in that paper. The trailing edge of the rear wing was extended to prevent the flow leaving the airfoil from 'hitting' the ground at a high angle, when the angle of attack is high. This will result in a higher drag due to the formation of a thicker and larger wake region. The chord lengths of the wings are 130 mm for the front wing and 150 mm for the rear wing and the span is 400 mm. Figure 1 shows the schematic of the tandem wing arrangement for the present investigation. The wings were held by two end plates, each having a length of 810 mm, height of 100 mm and thickness of 5 mm. The spacing between the plates was 400 mm (wing span). The assembly of the wings and the end plates (henceforth, it will be called the test model) was positioned on the moving belt system and was held with the help of steel wires having a diameter of 0.75 mm. The experiments involved measurements of the normal and axial forces. A six-component Göttingen type wind tunnel balance was used to measure the lift forces. For measurement of drag forces, a dynamic strain amplifier was used. Both the balance and the amplifier were calibrated for force measurements.

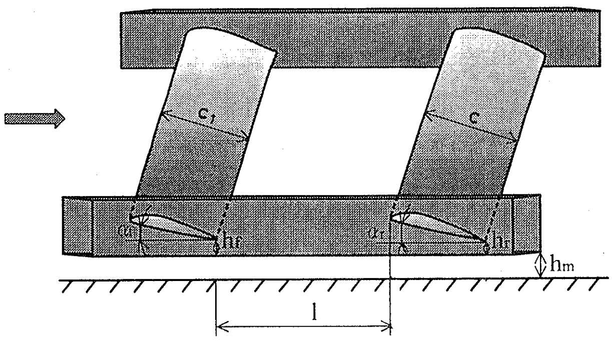

Fig. 1 Schematic diagram of the tandem wing arrangement

2.4 Experimental procedure

The mean velocity in the test section was set to 15 m/s with the help of thyristor system. The velocity was also measured with the help of a calibrated hot-wire anemometer to ascertain that the variation in velocity is within 1 % of the above value. The angles of attack for the wings (α_f, α_r) were varied from 0° to 8° in steps of 2°. Measurements were performed at different values of ground clearance of the wings, h_f/c, $h_r/c=0.02$ to 0.3 for different distances between the tandem wings, $l/c=1.0$ to 3.0. The ground clearance of the test model (h_m/c) was varied from 0.02 to 0.3. The test variables were incremented gradually to study each effect separately. However, only a few results are presented in this paper. The Reynolds number, based on the freestream velocity of 15 m/s and the total chord length was found to be about 2.8×10^5.

3. Results and Discussion

Figure 2 (a) shows the variation of the lift coefficient with ground clearance of the rear wing. A remarkable increase in lift coefficient is registered when both angles of attack are changed from 0° to 2°. However, due to interference between the wake of the front wing and the rear wing, the lift coefficient decreases at a value of h_r/c which is close to that of h_f/c. It can be noted that as the angles of attack are increased, only a slight increase in lift coefficient is observed at a lower value of h_r/c. This will be due to curving of the streamlines trailing from the front wing towards the ground for the higher angles of attack and hence passing of many streamlines above the rear wing; as these streamlines may get reflected from the ground and may pass above the rear wing, hence lower air-cushion effect. The drag force is only slightly lower for the case of $\alpha_f=\alpha_r=0°$ than that of $\alpha_f=\alpha_r=2°$ (Fig. 2 (b)). It can also be seen that there is a slight reduction in drag coefficient when the wings are in 'tandem effect' (rear wing exactly behind the front wing). We will see in the following results that the drag coefficient for smaller spacings between the

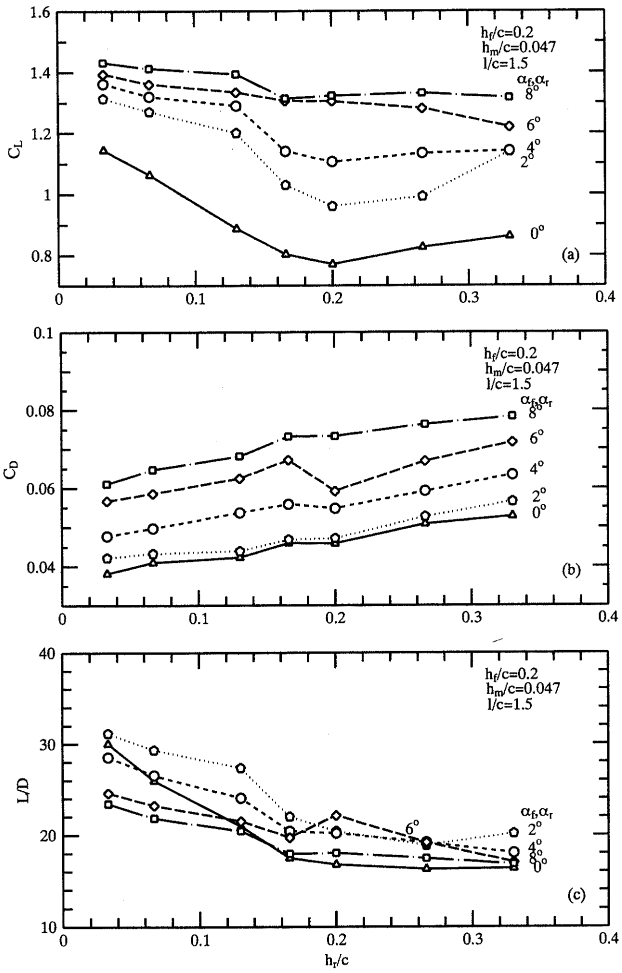

Fig. 2 Variation of C_L, C_D and L/D with ground clearance of the rear wing

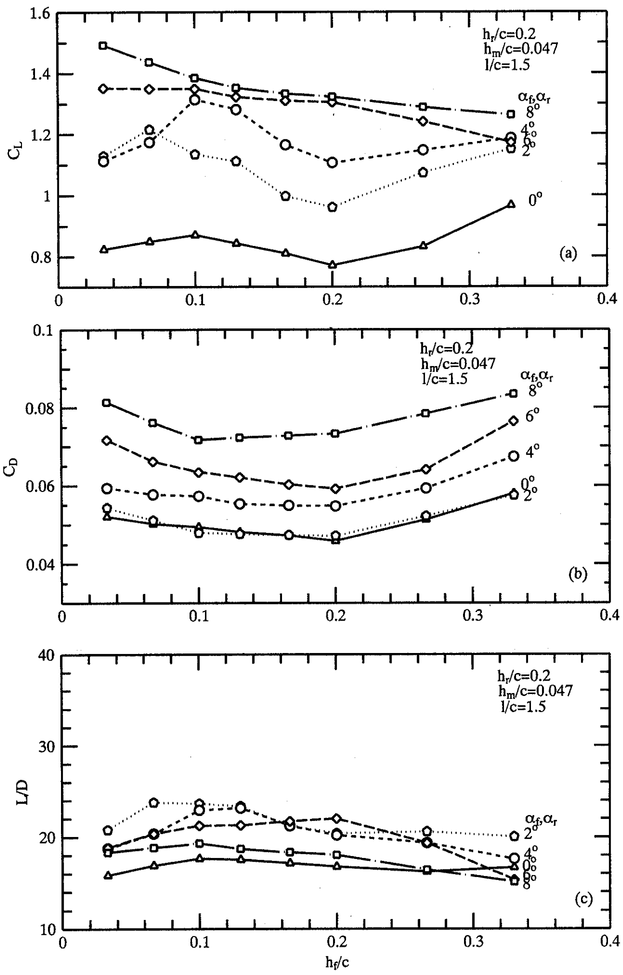

Fig. 3 Variation of C_L, C_D and L/D with ground clearance of the front wing

wings is higher than for the case when the spacing between the tandem wings is larger. There will be a considerable loss in total pressure behind the front wing especially at higher angles of attack, hence not only the effective lift but also the effective drag decrease due to the tandem wing configuration. We know from the starting vortex concept that there will be a region of intense vorticity because of the large velocity gradients at the sharp trailing edge when the flow is just started. This vorticity rolls up downstream of the trailing edge, forming the starting vortex. This starting vortex has associated with it a counterclockwise circulation. Therefore, as an equal and opposite reaction, a clockwise circulation around the airfoil is generated. As the starting process continues, vorticity from the trailing edge is constantly fed into the starting vortex, making it stronger with a consequent larger counterclockwise circulation. In turn, the clockwise circulation around the airfoil becomes stronger, making the flow at the trailing edge more closely approach the Kutta condition, thus weakening the vorticity shed from the trailing edge. Finally, the starting vortex builds up to just the right strength such that the equal and opposite clockwise circulation around the airfoil leads to smooth flow from the trailing edge. This starting vortex from the front wing, which has a counterclockwise direction, counters the clockwise circulation around the rear wing to some extent, thus reducing the lift generated by the rear wing.

Thus, the effective lift of the tandem wings will be much less than the combined lift of the two wings, had there been no interaction between the wake of the front wing and the rear wing. Similar will be the case for the drag force. As a result, the lift-to-drag ratio drops considerably. As can be seen from Fig. 2 (c), a maximum value of about 32 is obtained when the angles of attack are 2° for the wings.

At high angles of attack, the curving of the streamlines above the front wing as they leave the trailing edge is expected to change the effective angle of attack for the rear wing when the spacing is smaller. As explained earlier, the streamlines after leaving the front wing get reflected from the ground and hence

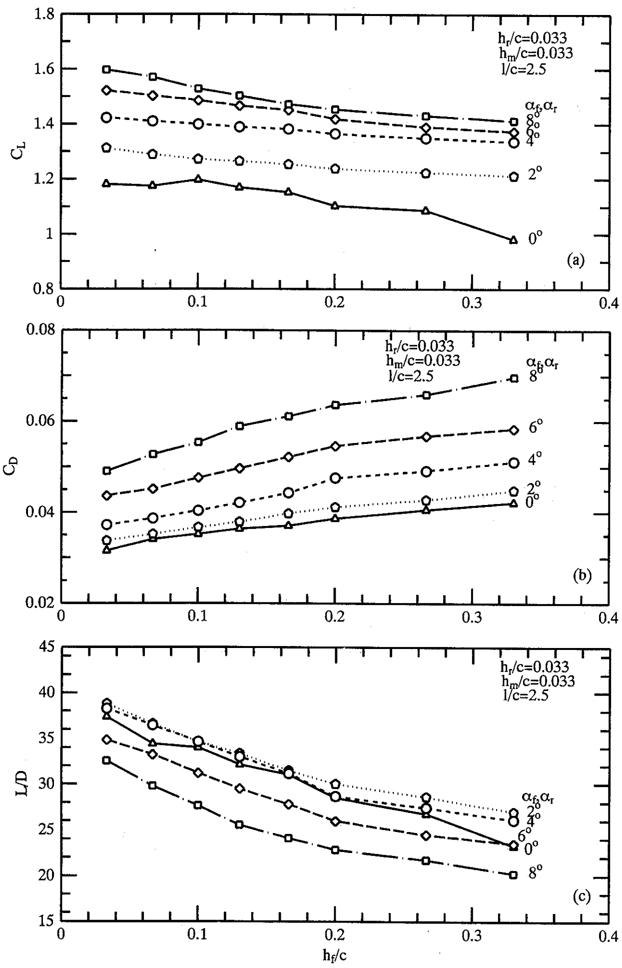

Fig. 4 Variation of C_L, C_D and L/D with ground clearance of the front wing for increased spacing between the wings

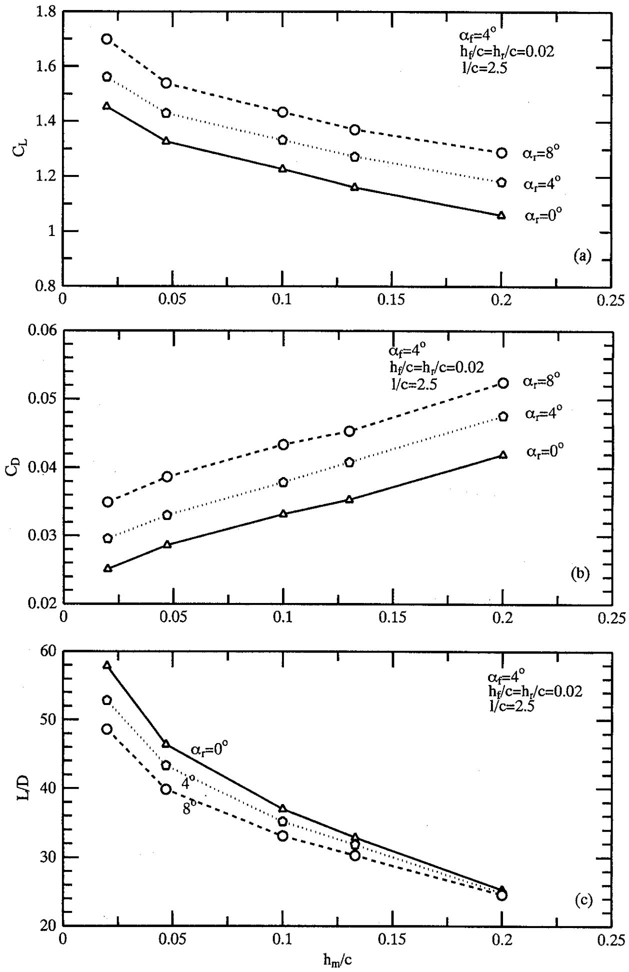

Fig. 5 Variation of C_L, C_D and L/D with ground clearance of the test model

modification of the flow of air over the rear wing, though the velocity measurements were not made in the present studies.

Variation of C_L with ground clearance of the front wing is shown in Fig. 3(a). The coefficient is found to decrease with increasing ground clearance of the front wing for the higher angles of attack. For the lower angles of attack, the coefficient first increases a little and then decreases due to the interference effect as the spacing between the wings is small ($l/c=1.5$). The trend for the drag coefficient is found similar to the previous case except that for this case, the drag coefficient for the 0° angle of attack is higher for some values of h_f/c (shown in Fig. 3(b)). The variation of L/D for this case is shown in Fig. 3(c). The highest lift-to-drag ratio is obtained for the case when the angle of attack is 2° for the wings. It can be seen that the values of L/D are quite low due to the interference effect.

The lift coefficient is found to increase when the spacing between the wings is increased to $l/c=2.5$. However, the ground clearance was also changed in this set of experiments. Figure 4(a) shows the variation of the coefficient of lift, C_L, as a function of ground clearance of the front wing for different angles of attack for the tandem wings when the spacing between the wings, l/c, is 2.5. The ground clearance of the rear wing, h_r/c, was kept constant at 0.033 in this set of experiments. The lift coefficient increased with decreasing ground clearance, as expected. However, the smaller increase in the coefficient can be attributed to the interference between the wake of the front wing and the rear wing. The variation of the drag coefficient, C_D, for the above case is shown in Fig. 4(b). A reduced drag coefficient at lower values of h_f/c shows the ground effect. Due to the combined effect of increased lift coefficient and reduced drag coefficient, considerably higher value of lift-to-drag ratio was obtained when the ground clearance is small (Fig. 4(c)). A maximum value of nearly 40 is obtained. The trends for both C_L and C_D are found to be supporting the earlier conclusions about the influence of ground effect[(1),(9),(13)].

Figures 5(a) to 5(c) show the plots of C_L, C_D and

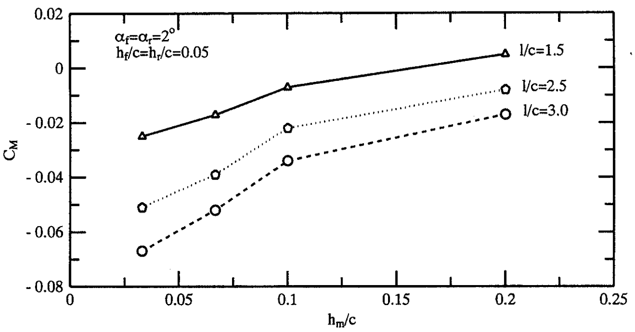

Fig. 6 Pitching moment as a function of ground clearance of the test model for different spacings between the wings

L/D against the ground clearance, h_m/c, for different angles of attack for the rear wing when α_f is kept at 4°. The ground clearance of the two wings is same at $h_f/c=h_r/c=0.02$. As can be seen, the coefficient of lift is higher when the angle of attack is higher. The effect of ground proximity can also be seen from this figure. A C_L value of about 1.7 is obtained when the angle of attack for the rear wing is 8°. The lift force decreases continuously with increasing ground clearance of the side plates. The trend is opposite for the drag coefficient. For the α_r af 8°, the drag coefficient is also higher. The maximum lift-to-drag ratio is obtained when α_r is zero. A value of about 60 is obtained.

However, it must be noted that the the boundary layer over the moving belt is 1 to 2 mm thick in the present case. Because of the defect in velocity, more air flows over the wing, the effective gap between the wing and ground decreases. Hence, the experimental results in the present studies are likely to give a higher value of lift and also a higher value of drag, than what will be observed in real case when the boundary layer is absent.

Experiments conducted for velocity measurements showed that the wake defect in velocity profile disappears after a length of $l/c=2.0$. Hence, it can be stated conclusively that a distance of slightly more than 2.0 between the wings gives nearly optimum lift-drag ratio.

The plots for pitching moment, C_M, against ground clearance, h_m/c, for different values of l/c are shown in Fig. 6. The strong influence of ground on the stability characteristics can be seen from this figure. The test model is apparently more stable for smaller distances between the wings. The flow trailing from the front wing, in this case, will be directed towards the ground, as discussed earlier. Due to this, the system is likely to loose its stability characteristics if the spacing between the tandem wings is relatively large ($l/c>3$). We had seen earlier that the flow characteristics over the rear wing became complex for smaller distances between the tandem wings due to a strong interaction between the wake and flow angularity of the front wing. This highly turbulent flow, when enters the small gap between the wing and the ground, may deteriorate its stability characteristics for larger spacings between the wings. However, these results are for static stability. For a more complete evaluation of the flight qualities, it is necessary to consider the dynamic stability. Measurements on a prototype are planned in the near future to study these characteristics.

The maximum error in the mean force measurements was found to be about 0.4%.

4. Conclusions

In the present work, a detailed study of a tandem wing configuration in close proximity to ground was carried out. It was found from the experiments that both, the angle of attack and the ground clearance of the wings have a strong influence on the aerodynamic characteristics of the configuration. Higher angle of attack results in higher lift coefficient, but at the same time, drag coefficient is also increased. For smaller spacings between the tandem wings, a larger interference effect between the wake of the front wing and the rear wing was observed. At angles of attack of 2° (for both wings), maximum lift to drag ratio was obtained. For small ground clearance of the wings, lower clearance of the side plates resulted in higher values of lift to drag ratio. The system showed high pitching instability for the present case of the static testing.

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