MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

STRAKE-WING-BODY CONFIGURATION UNDER THE EFFECT OF TRAILING VORTICES

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ABSTRACT

An experimental study was conducted to investigate the effect of trailing vortices on a strake-wing-body configuration. This configuration was placed trailing a large rectangular leading wing of NACA 0015 airfoil section. The angle of attack of the leading wing was varied to obtain variable induced trailing vortices. The lift, drag and side forces in addition to the yawing, pitching and rolling moments were measured for the trailing configuration at different values of incidence and bank angles. Analysis of the experimental results shows a drop in lift, a slight influence on drag, and practically no effect on the longitudinal stability. In order to maintain the same lift, the results demonstrated that it is imperative to increase the angle of attack which consequently increases the drag and adds a smaller nose-down pitching moment. A negative rolling moment is produced for this symmetric tailless configuration for zero bank angle. During banking flight a small positive yawing moment and a negative side force are produced.

INTRODUCTION

Trailing vortices had been responsible for one accident per month, on the average, according to the National Transportation and Safety Board (NTSB). Piggot and Pask [1] reported full information on all accidents believed to have encountered wake vortex in the UK during 1972-1976. These incidents were mainly initiated by introducing huge airliners, and the B-747 Jumbo Jet in particular, to the skies. The threat probability of trailing vortices becomes more manifest when a small aircraft trails a larger one. However, the threat is not confined to small trailing aircraft. On April 17, 1983, a Lockheed 1011 experienced three partial rolls as it was approaching London Heathrow Airport. This was found to be a result of the trailing vortices, too, from a taxiing Jumbo Jet.

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In order to overcome the hazard of trailing vortices, most of the effort was devoted to understand the nature of trailing wing-tip vortices. El-Ramly [2] presented a survey of the trailing vortices problems related to vortices shed from high aspect ratio straight or swept back wings. Later, El-Ramly, Rainbird and Earl [3] reported measurements obtained in a low speed wind tunnel for the trailing vortices system behind a swept back wing. Chigier [4] described the nature, strength and persistence of trailing vortices for various types of aircraft. He presented practical means of reducing the hazard on existing aircraft by artificially inducing the vortices to break down. Hall [5] reviewed the phenomenon of vortex breakdown which is considered significant for the eventual decay of aircraft vortices. Smith and Beesmer [6] observed the vortex breakdown on trailing vortices of aircraft when they tried to suppress condensation trails from B-747 aircraft. In an attempt to understand the vortex breakdown and the mechanisms responsible for it, Grabowski and Berger [7] numerically solved the full steady Navier-Stokes equations for the breakdown of an unconfined viscous vortex. Hallock and Eberle [8] reviewed the efforts and approaches made to understand the nature of trailing vortices.

The conclusion of such efforts in the early seventies was to impose a minimum safe separation distance of 3 n.mi. between the two consecutive flights during takeoff and landing. Depending on the types and sequence of the two aeroplanes, the separation distance might has to be as high as 6 n.mi., thereby causing long queues and inconvenient delays. Rossow and Tinling [9] worked on reducing this wake vortex interaction hazard to a tolerable level such that the minimum separation distance is reduced to 2 n.mi. There had been other efforts to come up with shorter distances for some favourable conditions. Upon an extensive vortex measurements at several airports, Wood and McWilliams [10] suggested a reduction in the minimum imposed distance under certain wind conditions.

Olwi and Ghazi [11] conducted wind tunnel experiments to study the effect of wing tip vortices from a large leading wing on a trailing aircraft. The main observation of the study was the remarkable reduction in the lift coefficient of the trailing aircraft as the leading wing angle of attack increases. El-Ramly [12] studied the induced rolling moment on ten combinations of leading/trailing wings covering span ratios of 0.24 to 1.22. The wings included both straight and swept configurations covering aspect ratios of 4 to 8.5. Andrews [13] conducted a flight program to study the behaviour of wing wake vortices generated by large transport aircraft such as DC-9 and C-5A. The trailing vortices were measured at distances ranging from 1 to 15 n.mi.

In the case of battle fields, the issue is far more than a matter of inconvenience; it is a matter of winning or losing the war. The hazard of trailing vortices is not limited to civilian aircraft. The situation might be worse in the military for two reasons. First; in military operations, the frequency of flights might be so high leading to a conflict with the separation distance requirement to avoid the trailing vortices hazard. Secondly, there is tremendous disparity among the sizes of military aircraft. Consider an eagle F-16 fighter trailing a gigantic C-5 military transport aircraft or even a huge B-1 bomber. It is not perceivable that the order of takeoff and landing should be arranged such that small fighters are never in the trailing position, as the operation sequence might dictate otherwise.

Most of the experimental studies conducted thus far cover civil commercial aircraft. One of the main dissimilarity between the trailing (small) civil and military aircraft is the strake introduced in many fighters. From the aerodynamics point of view, the strake-wing combination was identified as an interesting fighter aircraft configuration. This configuration has been investigated quite extensively in the last decade, see for example Refs. [14-17]. It has been established that strakes positively affect the high angle of attack leeside flow separation and vortex breakdown of moderate sweep wings at subsonic and transonic speeds. This strake effect results from the strong leading-edge vortices generated by the strake as explained by Wedmeyer [18] and Fiddes and Smith [19]. These vortices induce an outboard flow on the main wing and thereby increase the effective sweep of the leading edge. The higher effective sweep stabilizes the leading edge separation on the main wing and, consequently, increases the onset angle of attack for vortex breakdown. As noticed by Stallings [20] the major advantage of the strake-wing combination is that favourable interference is created at high lift conditions without degrading the wing performance at lower angles of attack.

EXPERIMENTAL SETUP

The experiments were performed in a low speed open circuit wind tunnel, of 700mm x 500mm test section. The model, Fig. 1, consisted of a sharp-edged flat plate strake-wing combination with an aspect ratio of 1.84, root chord of 264 mm, span of 230 mm, uniform thickness of 3 mm and symmetrical, and wedge-shaped (apex angle of 30^o) leading and trailing edges. The fuselage of the actual configuration was approximated by a cylindrical body featured by a pointed nose. The cylindrical part had 258 mm in length and 32 mm in diameter

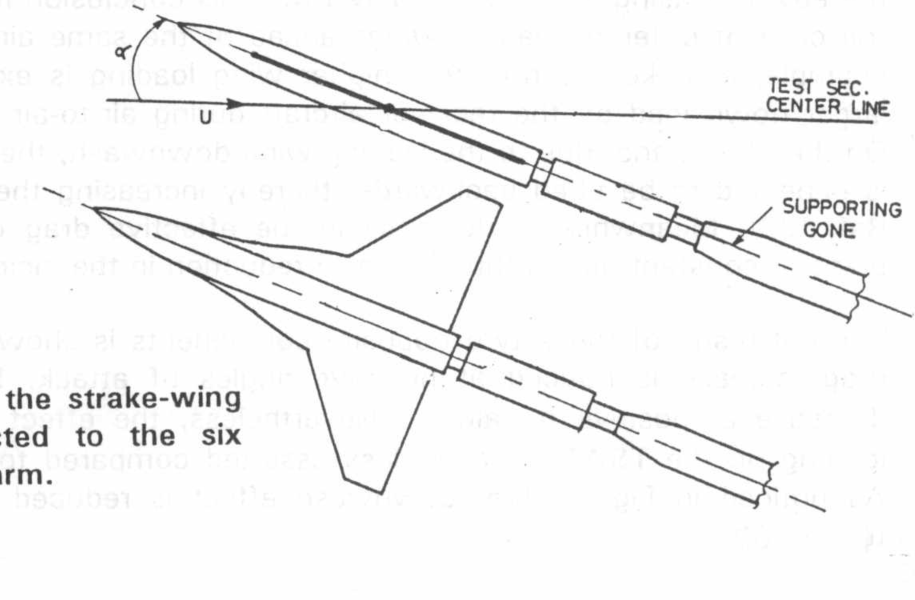

Fig. 1 Schematic of the strake-wing body model connected to the six component balance arm.

while the conical part smoothly matched the cylinder and was 99 mm long. The strake, which was almost identical to that of the F-16 fighter aircraft, was placed trailing of a rectangular wing of chord 275 mm and span 500 mm. The distance between the trailing edge of the leading wing and the strake nose point is approximately equal to one leading wing chord.

The strake-wing-body model was mounted on a six-component sting balance system manufactured by Aerolab. An HP data-acquisition system was integrated with the electronic part of the balance. Sensitive pressure differential electronic micromanometers were used for measuring the free stream velocity. The bank angle "ϕ" was varied between 0^o and 60^o at a step of 10^o . The lift, drag and side forces together with yawing, pitching and rolling moments were measured for angles of attack "α" ranging from -8^o to $+8^o$. Measurements were taken for the free stream velocity of 20 m/s, corresponding to Reynolds number of 3.6×10^5 based on the wing root chord. The angle of attack of the leading wing "$\alpha_{L.W.}$"was varied from 0^o to 6^o at a step of 2^o .

RESULTS AND DISCUSSION

Fig. 2 elucidates the effect of the leading wing on the lift coefficient of the Trailing Strake-Wing-Body Configuration **"TSWBC"**. As expected, downwash from the leading wing causes drop in the lift of the **TSWBC**. This is true for all bank angles "ϕ" of the trailing vehicle (at least up to $\phi = 60$). Consequently, it increases the zero-lift angle of attack and decreases the maximum lift coefficient. However, this effect is less pronounced for high bank angles ($\phi >= 60$). The figure further shows that the angle of attack of the leading wing has practically no effect on the slope of the C_L- α curve.

In order to visualize the amount of the drop in lift, Fig. 3 was plotted representing the change of the lift coefficient caused by the downwash "δC_L" versus the angle of attack "α". The figure shows that as the leading wing loading increases (i.e. its angle of attack increases), more downwash is formed, thereby increasing its effect on **TSWBC**. This conclusion may be generalized to the case of different leading wings ahead of the same aircraft, Ref. [21]. For example, a tanker aircraft with higher wing loading is expected to produce a larger down load on the receiver aircraft during air-to-air refuelling operations. On the other hand, due to the leading wing downwash, the lift vector of **TSWBC** is expected to be tilted backwards, thereby increasing the lift dependant drag, Ref. [22]. Meanwhile, a decrease in the effective drag of the **TSBWC** takes place at constant pitch attitude due to reduction in the incidence angle.

The net result of these two opposite components is shown in Fig. 4. A slight drag increase is noticed at negative angles of attack, but it turns back to decrease at positive α values. Nevertheless, the effect of the leading wing loading on the **TSWBC** drag is less asserted compared to its influence on lift. As noticed in Fig. 2, the, downwash effect is reduced at high bank angles ($\phi >= 60$).

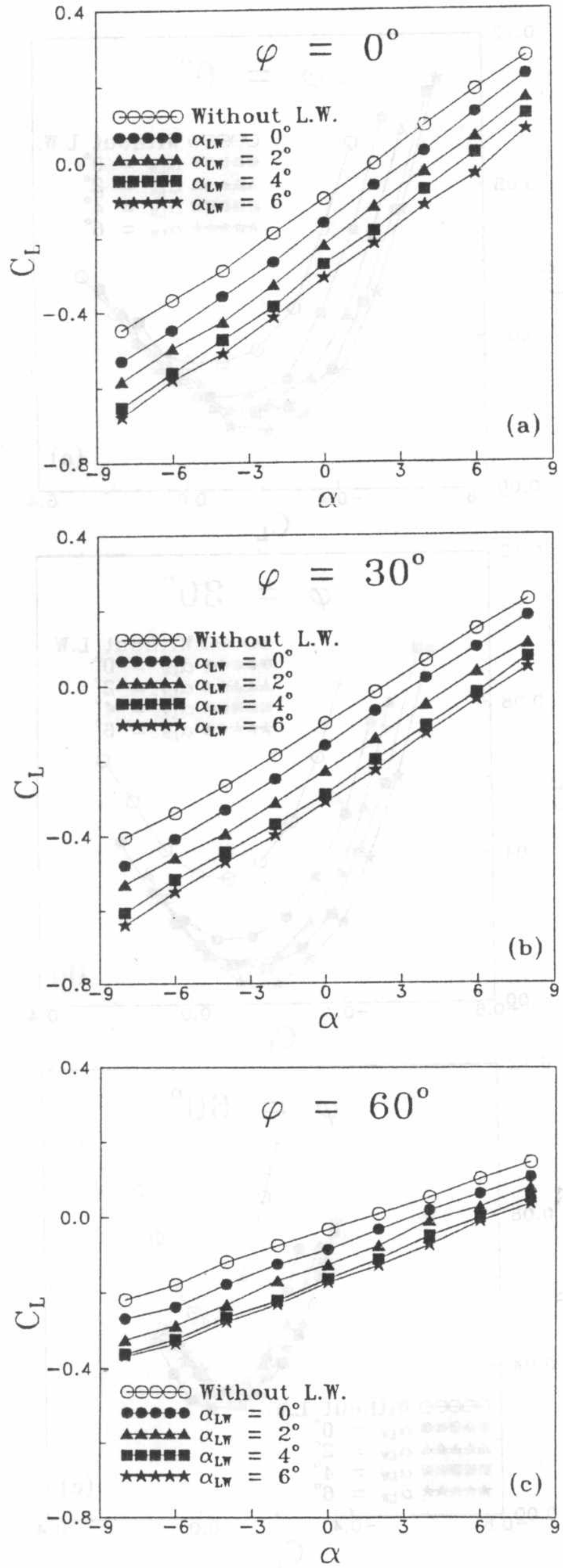

Fig. 2 Lift coefficient of the trailing configuration for various bank angles and different leading wing settings.

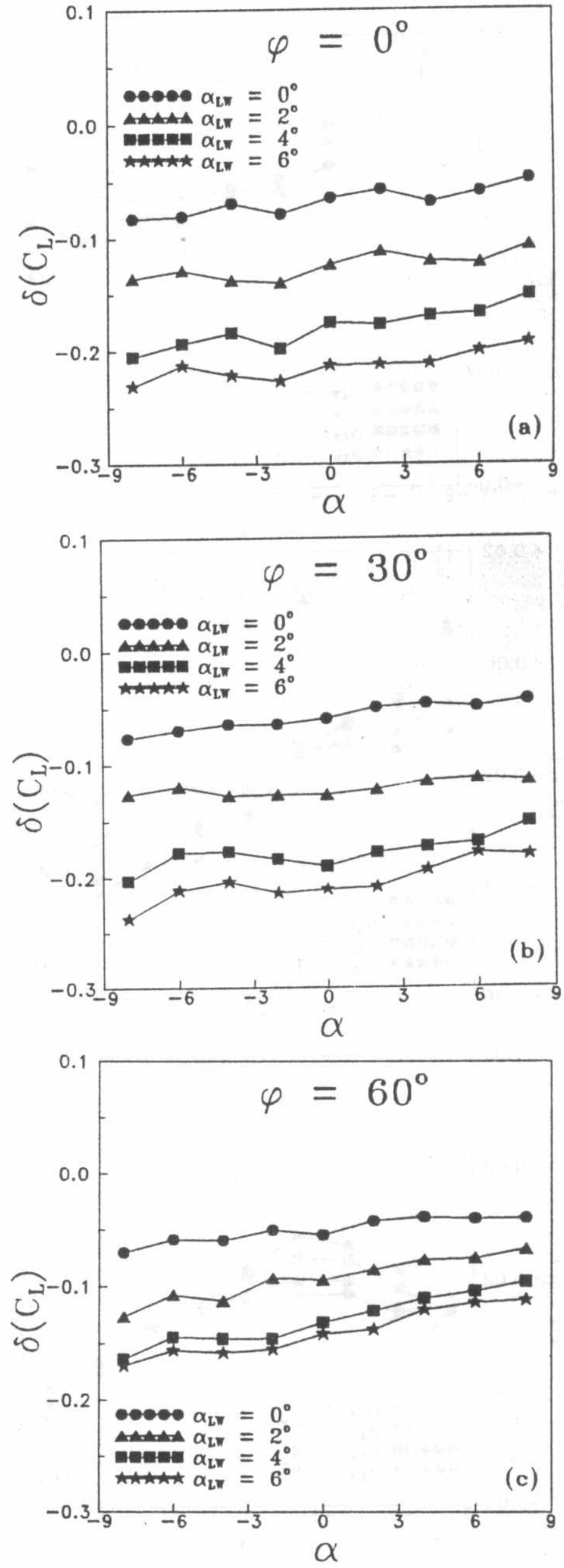

Fig. 3 Change in the lift coefficient caused by trailing vortices for various bank angles.

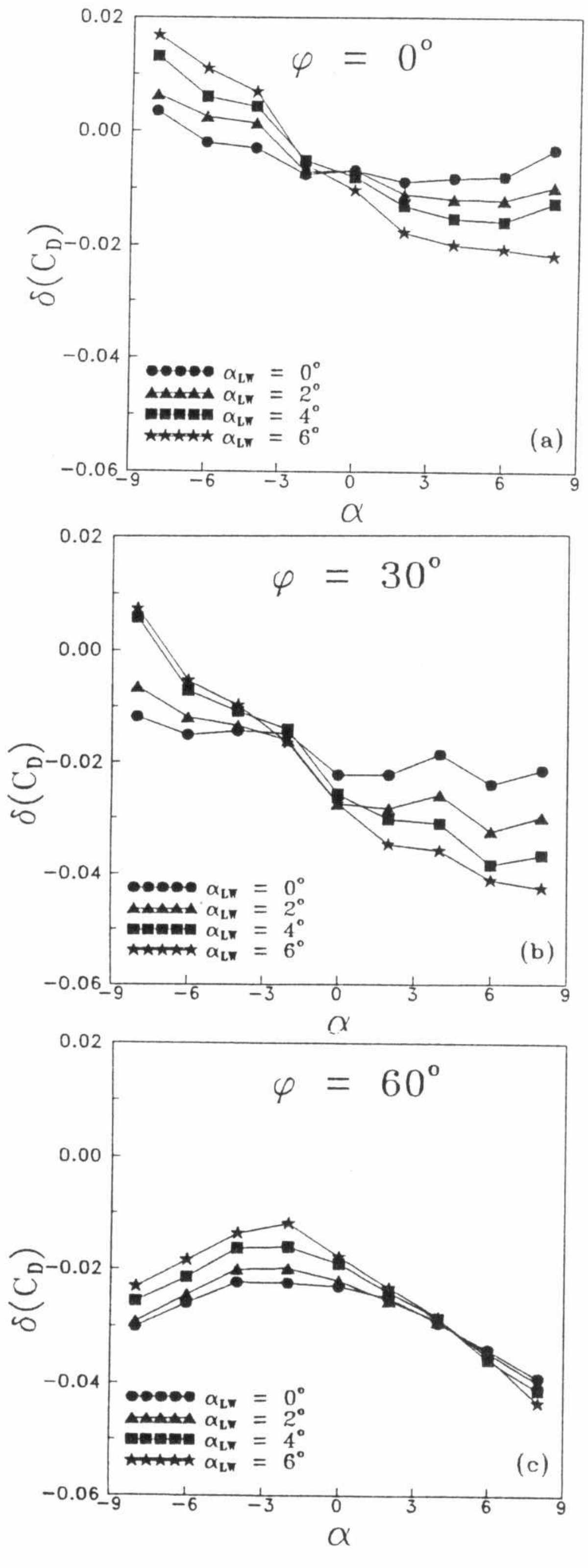

Fig. 4 Change in the drag coefficient caused by trailing vortices for various bank angles.

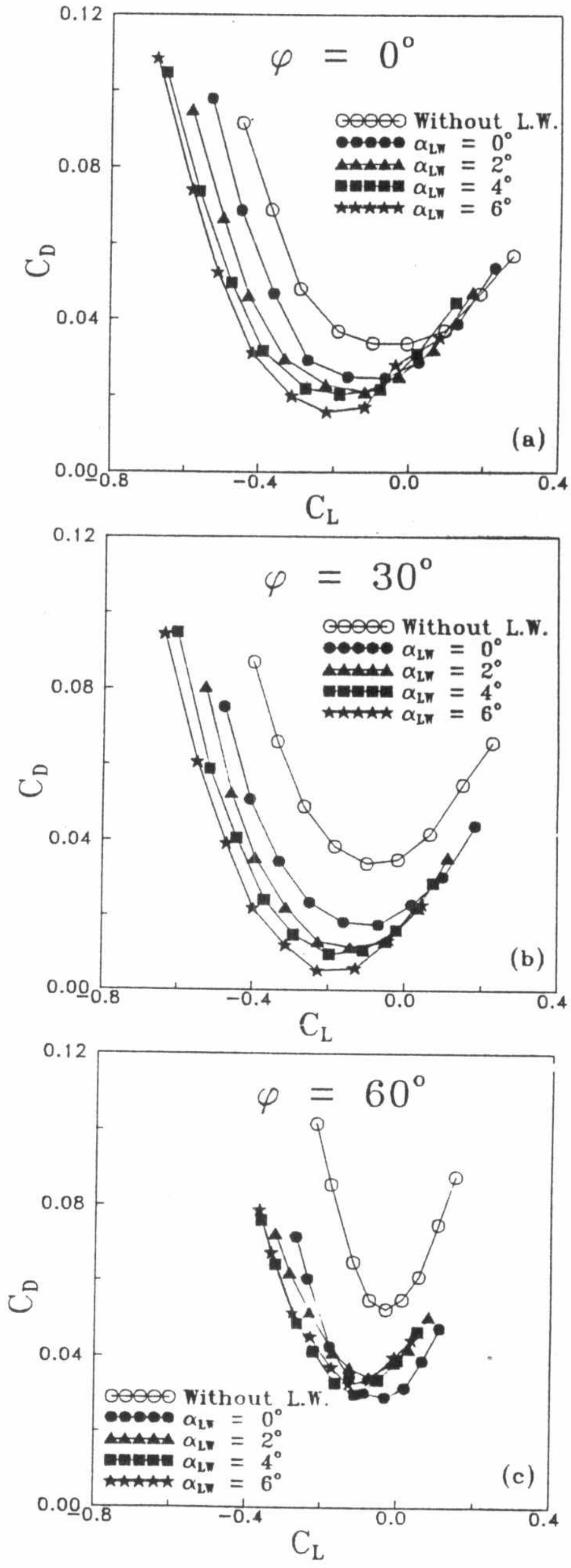

Fig. 5 Drag polar of the trailing configuration for various bank angles and different leading wing settings.

Fig. 5 presents the effect of the leading wing on the polar curves (C_D - C_L) of **TSWBC**. Fig. 5 demonstrates that the minimum drag decreases with increasing leading wing angle of attack. The effect of increasing ϕ is to decrease this ratio furthermore. If the same lift is maintained, the downwash effect on **TSWBC** tends to decrease its drag. This reduction is more manifested as the leading wing angle increases. In other words, it is imperative to increase the **TSWBC** angle of attack to offset the wake effect on the lift, and consequently the drag would increase. On the other hand, the lift value for which the drag is minimum decreases with the increase of the leading wing angle of attack, although this is not clear at $\phi >= 60$. The value of this minimum drag is reduced with the increase of the leading wing loading.

Fig. 6 displays typical linear relationships between the pitching moment coefficient and the lift coefficient of **TSBWC**, where the pitching moment is considered about the 1/4 mean aerodynamic chord of the trailing wing. The curves indicate a non-stable longitudinal behaviour if the centre of gravity of **TSWBC** coincides with the quarter-chord point. The figure affirms that the leading wing angle of attack has practically no effect on the longitudinal stability of the trailing configuration. Nevertheless, a slightly smaller nose down (negative) pitching moment persists as ϕ increases if the same lift is maintained. On the other hand, Fig. 7 shows that at constant à a nose-down pitching moment is added as the leading wing angle of attack increases. The amount of this added pitching moment is more ascertained at smaller bank angles and seems to be practically independent of the trailing configuration angle of attack.

Fig. 8 demonstrates the effect of the leading wing on the rolling moment of **TSWBC**. At zero bank angle, the leading wing produces a negative rolling moment on the trailing configuration. This value remains almost constant over the range of angles of attack investigated. At high bank angle (ϕ = 60), the leading wing contributes a positive rolling moment at positive α, while negative values are obtained at small or negative α. This is better demonstrated in Fig. 9 which represents the incremental changes in the rolling moment caused by the leading wing at different angles of attack. It is clear that at a fixed α, the negative induced rolling moment caused by downwash decreases with the increase of ϕ until it turns even positive at high ϕ and α.

Since the **TSWBC** is a tailless configuration, the yawing moment and side force curves are not expected to portray conclusive results. The incremental change in the yawing moment coefficient of **TSWBC** is shown in Fig. 10. A slight positive contribution is noticed as the bank angle increases. Results for the incremental drop in side force coefficient are illustrated in Fig. 11. As anticipated, the side force for the symmetric **TSWBC** remains unaffected (δC_S =0) during straight flight (ϕ= 0). However during banking flight, negative side force values are produced in a proportional manner with the leading wing incidence angle. This phenomenon is more strongly highlighted at higher bank angles.

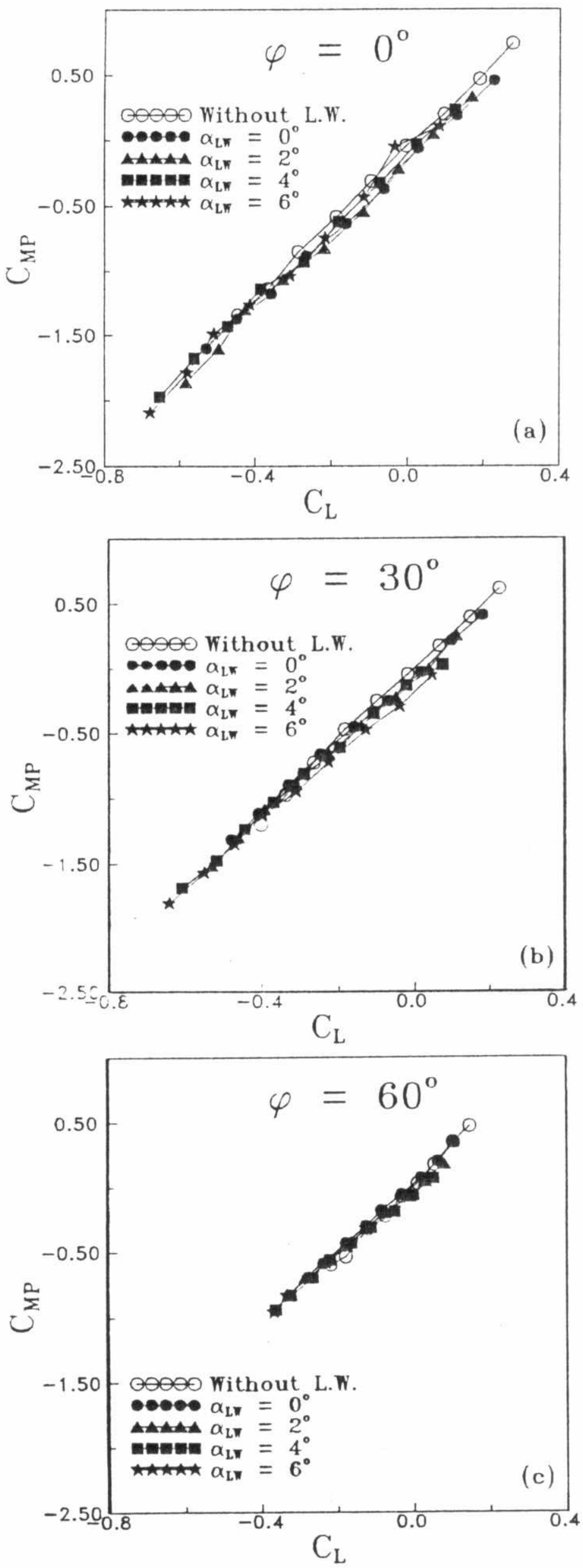

Fig. 6 Pitching moment coefficient for various bank angles and different leading wing settings.

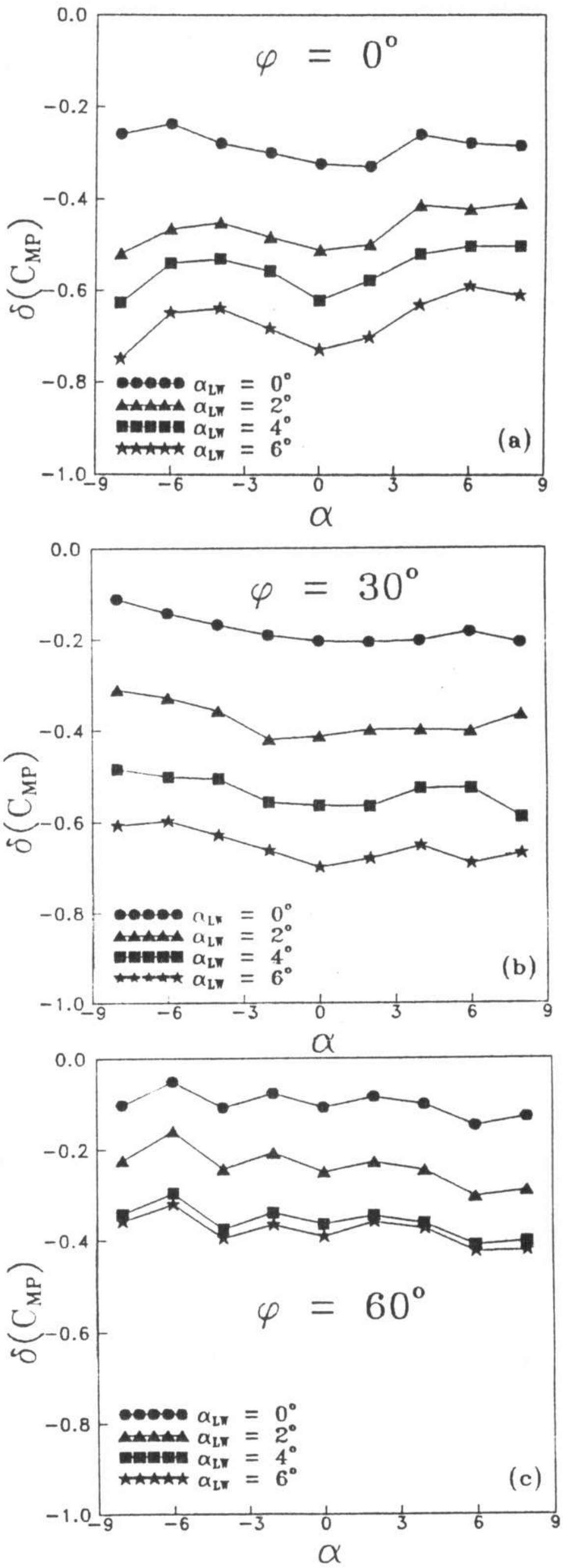

Fig. 7 Change in the pitching moment coefficient caused by trailing vortices.

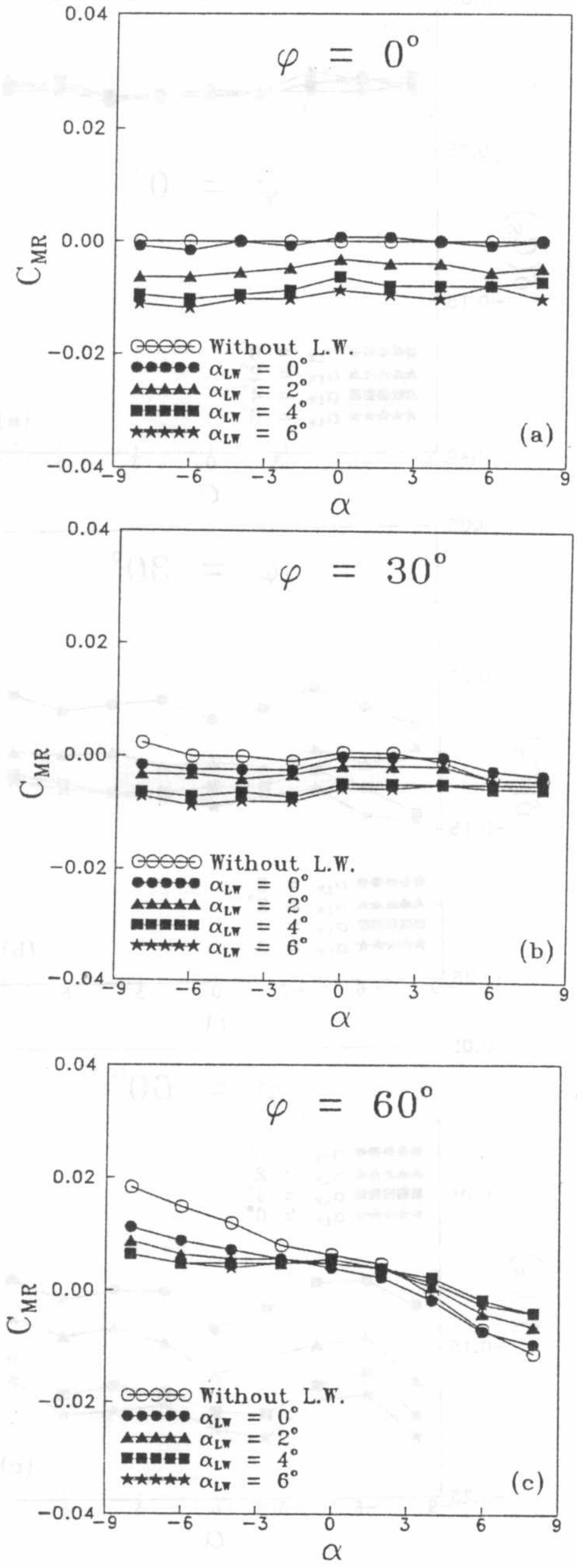

Fig. 8 Rolling moment coefficient for various bank angles and different leading wing settings.

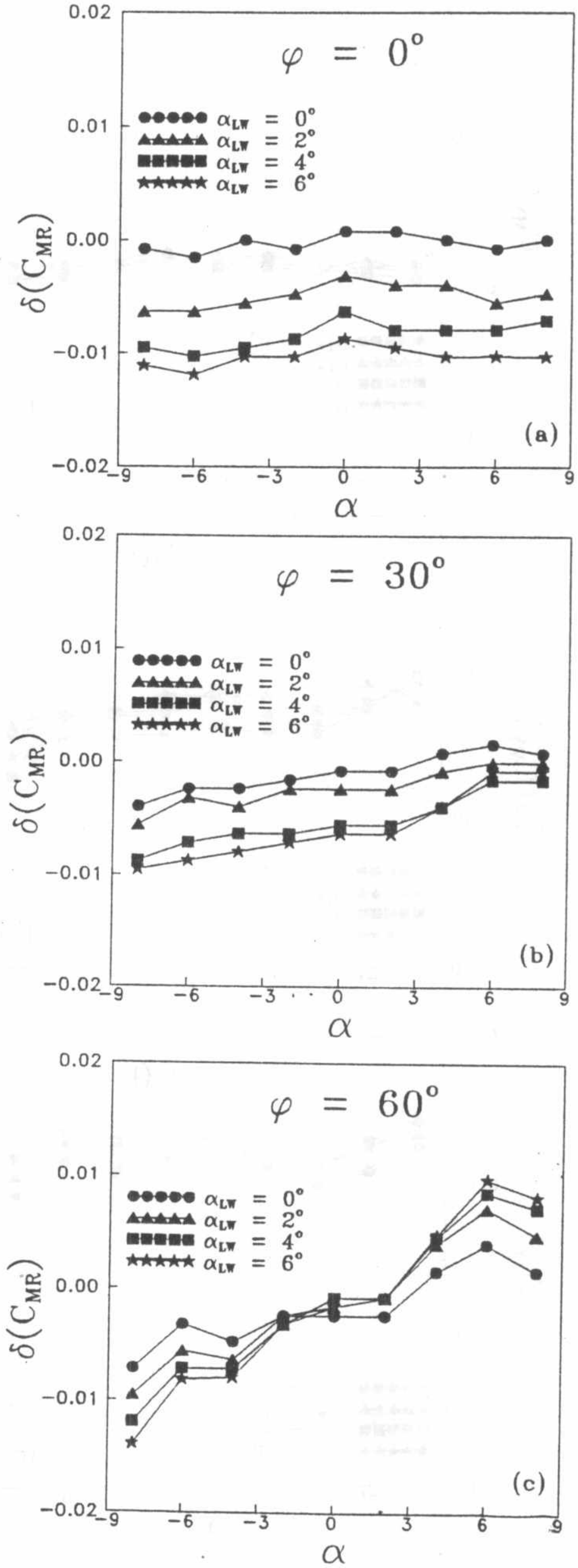

Fig. 9 Change in the rolling moment coefficient caused by trailing vortices.

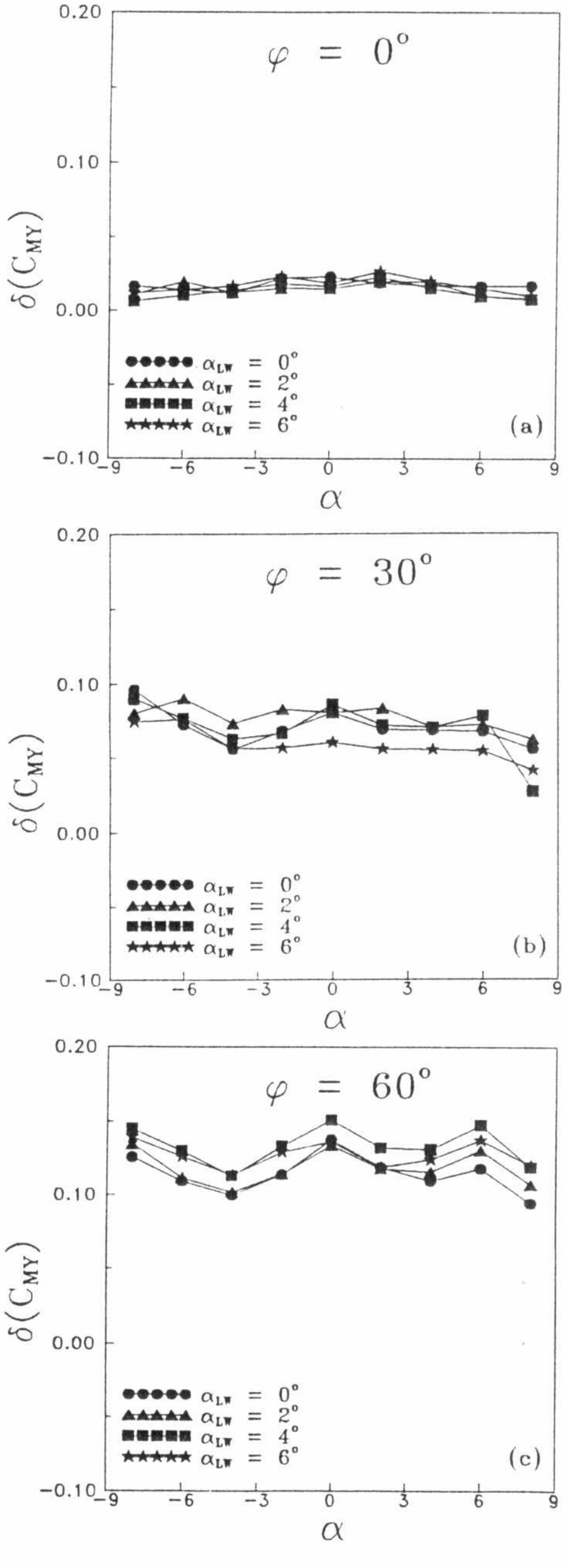

Fig. 10 Change in the yawing moment coefficient caused by trailing vortices.

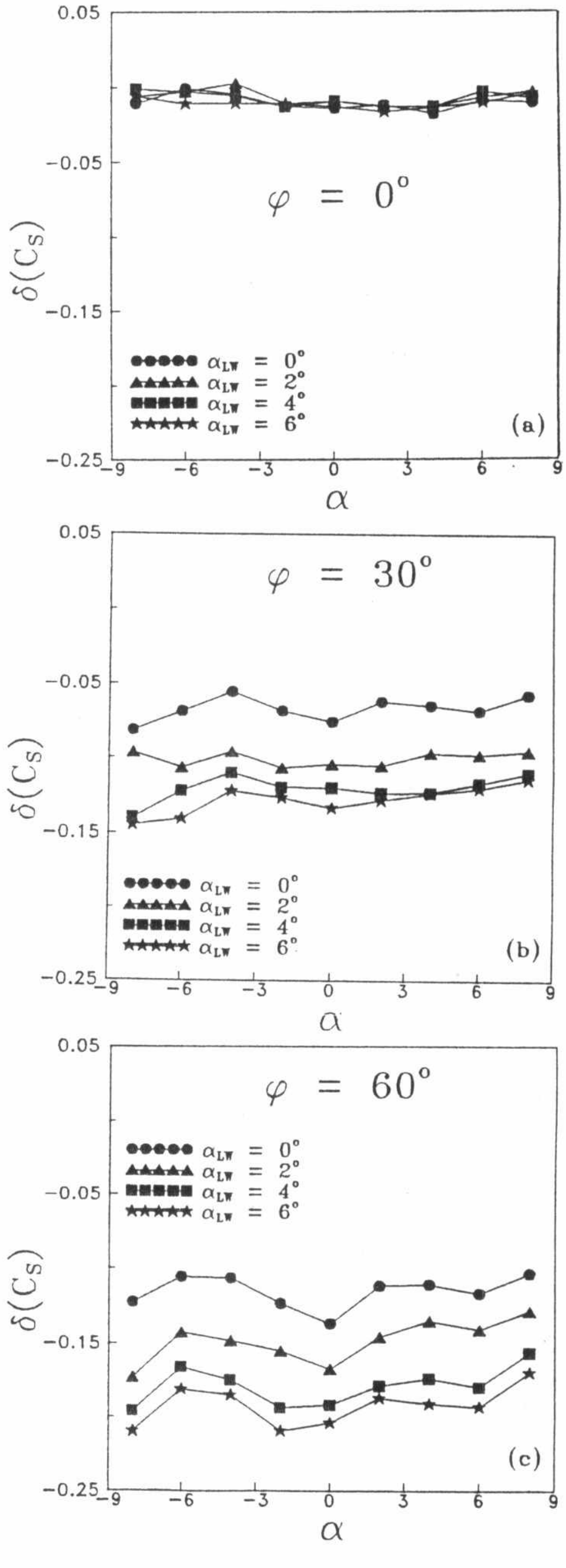

Fig. 11 Change in the side force coefficient caused by trailing vortices for various bank angles.

CONCLUSIONS

An experimental investigation has been conducted to determine the effect of trailing vortices from a large leading wing on a trailing tailless strake-wing-body configuration model. Lift, drag, and side forces as well as pitching, yawing, and rolling moments are measured for $R_e = 3.6x10^5$ and various bank angles. The angle of attack for the trailing model and those for the leading wing was varied respectively from -8^o to 8^o and from 0^o to 6^o. Results from these tests lead to the following conclusions:

- Increasing the leading wing angle of attack causes a reduction in lift. This drop does not incorporate changes in the lift curve slope. Consequently, the zero lift angle of attack is increased and the maximum lift value is decreased.
- The minimum drag value decreases as the leading wing angle of attack increases. This value also decreases as the bank angle increases.
- In order to maintain the same lift force, it is imperative to increase the angle of attack of the trailing model to offset the wake effect, thus increasing the drag force acting on the trailing model.
- The leading wing angle of attack has a slight effect on the stability margin of the trailing configuration.
- For a zero bank angle, the leading wing produces a negative rolling moment on the trailing model. This induced roll decreases with the increase of bank angle, and even turns positive at high bank and incidence angles.
- During banking flight, negative side force values are produced in a proportional manner with the leading wing incidence angle.
- The leading wing has practically no effect on the yawing moment for this symmetric tailless strake-wing-body configuration.

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