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MECHANICAL ENGINEERING

Interference Effects of a Large Wing on the Performance of a Trailing Wing

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Abstract. Interference of trailing vortices from a flapped large leading wing on a flapped small trailing wing is experimentally investigated. The effect of such wake turbulence is investigated through wind tunnel measurements of lift and drag forces and the pitching moment on the trailing wing. The threat of wake vortices was manifested in substantial reduction in the lift performance. Such reduction of lift was magnified as the leading wing flap angle increased, but without affecting the slope of the lift coefficient curves. The resulting shift of those curves resulted in delayed separation on the trailing wing to higher angles of attack. Within the domain of parameters used in the study, the trailing wing stall angle has roughly doubled when a large wing equipped with a 30° flap was placed in the leading position. The drag force had been reduced as the leading wing flap angle was increased. However, the trailing wing stability had not been harassed by such hazard.

Introduction

A pair of counter-rotating vortices is produced at the tips of any lift generating finite surface. Hence, trailing vortices are generated in the wake of all aircraft as a direct consequence of lift generation. Trailing vortices from a large finite lift generating wing cause disturbance, that could be dangerous to other aircraft flying nearby behind the leading one. This phenomenon is referred to as "wake turbulence". Although this phenomenon had been known since the beginning of powered flight, its threat to aviation safety had not been recognized till the introduction of the wide-bodied jets, such as B-747 Jumbo jet, with their increased weight and hence stronger vortices. Since then, scientific research and investigation of wake turbulence has been eminent as it affects aviation safety. The wakes of such aircraft not only causes aerodynamic loss in lift of trailing aircraft, but can also damage its components and equipment. Examples of such accidents are reported in Refs. [1-4].

The main course of earlier research in wake turbulence was towards understanding the physics of trailing vortices. To this end, Ciffone [5] measured the vortex trajectories and velocity profiles in lift-generated wakes. The wakes were generated by towing 2-ft span models of B-747 and DC-10-30 aircraft under water in a ship model basin. Measurements were obtained using laser velocimetry. Other papers on wake turbulence avoidance may be found in the Proceedings of FAA/NASA Workshop on wake vortex aviation and avoidance held in 1979 and compiled by Wood [6].

Many sensor systems were assessed for detecting and tracking vortices near the ground, as compiled by Burnham [7]. These include acoustic, electromagnetic, passive ground wind, pressure distribution and laser Doppler measurement. Burnham *et al.* [8] and Sullivan *et al.* [9] tested and calibrated the most promising ones. Then large scale data of vortices trailing from landing aircraft, Refs. [10;11], and from departing aircraft, Ref. [12], were compiled into a huge data base. Analysis of such enormous amount of data collected led to the concept of the Vortex Advisory System (VAS), upon which minimum landing separation distances between consecutive flights were regulated. Depending on the type and order of the two planes, this separation distance varies from 3-6 n.min.

The Federal Aviation Administration (FAA) adopted these separation distances, and was followed later by the International Civil Aviation Association (ICAO). As the world of aviation is ever increasing, the necessity to keep the conservative separation distance of 3-6 n.min. has been seriously questioned. Rossow conducted several studies on this issue, see for example Refs. [13;14], and came up with proposals that would allow shorter separation distances while maintaining the trailing aircraft safety.

The key factor for evaluating the threat of wake turbulence is the vortex strength. Corsiglia *et al.* [15] measured the rolling moment induced on a wing trailing a subsonic transport model in the NASA-Ames 40-by-80 Foot Wind Tunnel. Tossow [16] performed a theoretical study to explore whether the roll-up of lift-generated vortex sheets can be suppressed. It was found that substantial reductions in the rolling moment could be obtained.

Numerical simulation and calculation of turbulent vortex wakes were carried out by Hah *et al.* [17] and Patel *et al.* [18]. Mathematical modeling of the vortes decay in the atmosphere was done by Greene [19]. Melander *et al.* [20] studied the merger phenomenon of two sufficiently close together symmetric vortices. They presented the causes and conditions for the restricted process of symmetric vortex merger. Bilanin *et al.* [21] used inviscid and viscous mathematical models to investigate the dynamic response of aircraft to wake vortices. They concluded that the minimum hazard wake could be obtained if the leading aircraft generates flap and wing tip vortices of the same strength and sign. This could be achieved if the flap vortex is located outboard approximately 40% of the distance to the tip vortex.

Wind tunnel tests were performed by Olwi *et al.* [22] to investigate the wake turbulence effect of a leading wing on a trailing aircraft. They found that the trailing aircraft suffered remarkable loss of lift as it encountered trailing vortices. This became more significant as the vortices intensified by increasing the leading wing angle of attack. The investigation included effect of the leading wing model position on the lift, drag and pitching moment of the trailing aircraft. The results show that the maximum amount of lift-to-drag ratio is obtained when the leading wing is positioned lower than the trailing aircraft, and the former is at zero angle of attack. Ghazi *et al.* [23] presented results of an experimental study on the effect of trailing vortices caused by a large leading wing, at 5° angle of attack, on a smaller trailing wing. In spite of the considerable reduction in lift experienced by the trailing wing, the stall angle of attack increased with increasing the flap angle of the leading model.

In this paper, wind tunnel tests are reported for the aerodynamic response of a wing subjected to the interference of wake turbulence. The trailing vortices are generated from a larger leading wing. Flaps are installed on both wings so as to simulate actual wing configurations during takeoff and landing. The forces of lift and drag along with the pitching moment are measured with and without the presence of wake turbulence.

Experimental Setup

The experimental setup consisted of a three-component balance, a leading wing and a small trailing wing. The experiments were conducted in a low speed wind tunnel of the open type with a $0.5 \times 0.7 \times 2.6\ m^3$ test section. The air-speed in the tunnel could be varied continuously up to a maximum of 45 m/s. The wind tunnel was integrated with a three-component external electronic balance to measure lift, drag and pitching moment. The trailing wing was attached to the balance, and was supported by a main and tail struts. A schematic diagram of the test model and the balance is given in Fig. 1.

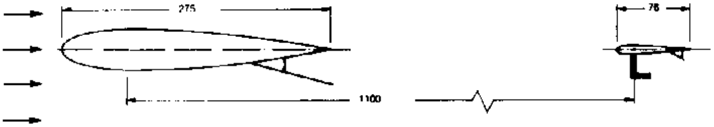

Fig. 1. Schematic diagram of the experimental set up; all dimensions are in mm.

The trailing wing was leveled horizontally, and the leading wing was mounted such that its chord plane became horizontal. The horizontal distance between the quarter chord of the leading wing and the trailing wing was 14.14 C_t, where C_t is the trailing wing chord. The trailing wing model was a rectangular wing type RAE 01, of 10% thickness ratio, with a chord length of 0.0762 m and a span of 0.343 m. A split flap was fitted to the trailing wing with a flap chord ratio of 0.236 and flap angles of 15°, 30° and 45°. The wing itself was made of aluminum.

The leading wing was rectangular of NACA 0015 profile, 0.27 m chord length and 0.5 m span. It, too, was fitted with a split flap of 0.327 flap chord ratio, 0.5 m span and 15°, 30° and 45° flap angles. The leading wing was machined from a solid block of wood while its flap was made of galvanized steel.

All measurements were conducted at a Reynolds number of 1.5×10^5 based on the tunnel free stream velocity of 30 m/s and the trailing wing model chord of 0.762 m. The reference length for the lift and drag coefficients was taken to be the trailing wing chord of 0.0762 m, and the reference area for the moment coefficient was taken to be the trailing wing area of 0.02614 m^2. The experimental uncertainty in lift and drag forces reading was ± 0.25%, while it was ± 0.5% for the pitching moment readings.

Results and Discussion

Results of the investigation are presented in terms of the wake turbulence interference on the trailing wing lift coefficient, C_L, drag coefficient, C_D and pitching moment coefficient, C_M. The latter was measured about the mounting point of the trailing wing, which was located 0.289 C_t from the leading edge. While the leading wing angle of attack was kept at 0°, the trailing wing angle of attack was varied from 0° to 18°, and the results were recorded at every 2°. The configuration of the trailing wing is changed from the case of no flap to flap angles of 15°, 30° and 45°. The effect of wake turbulence interference is studied in comparison with the wing performance if no leading object exists. The leading wing was also equipped with split flaps such that the results include cases of 0°, 15°, 30° and 45° falp angles. All experiments were carried out at a Reynolds number of 1.5×10^5, based on the trailing wing chord.

Figure 2-5 illustrate the variation of the lift coefficient with the angle of attack, $C_L - \alpha$. The Figures portray a remarkable loss of lift, especially when the leading wing model is employed with a large flap angle. As the wing flap was increased, more drop in lift was experienced. In fact, the lift force vanished totally in some cases as summarized in Table 1, which lists the minimum angles of attack that the trailing wing has to attain in order to get any lift. It should be noted that the flap deflection angle of the lifting surface is increased progressively from 0° in Fig. 2 to 45° in Fig. 5. Obviously, as the flap deflection was increased, more lift was obtained. This is also manifested in Table 1, where the leading wing flap angle was 15°, 30° and 45° at trailing wing angles of attack of 1°, 5° and 8°, respectively, when the flaps of the trailing wing were not deflected (Fig. 2). But at the same time, the lift coefficient never dropped to negative values when the trailing model flaps were deflected 45° (Fig. 5).

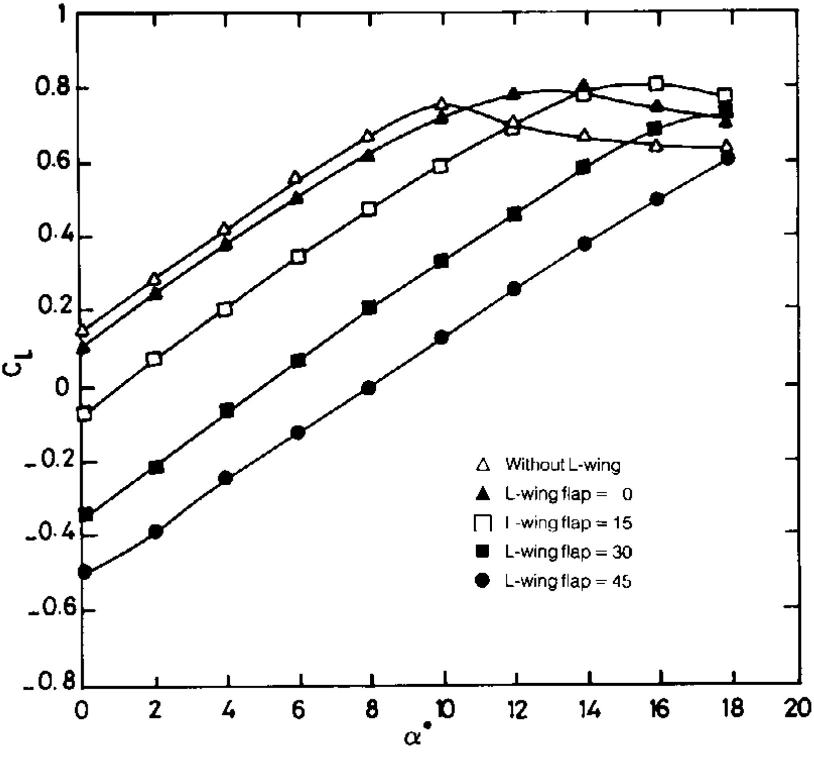

Fig. 2. Effect of the leading wing configuration on the lift of the trailing wing without flap.

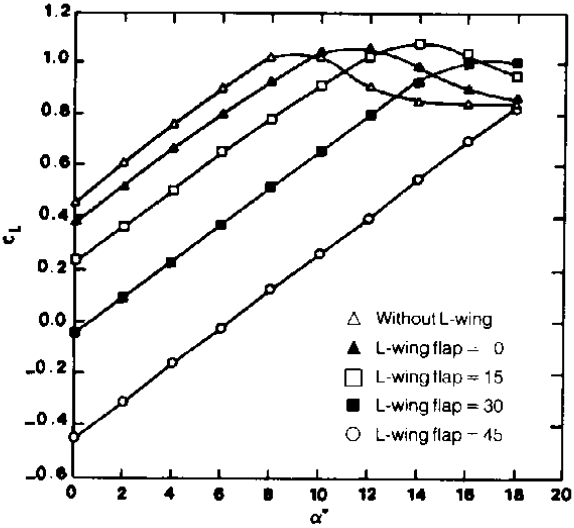

Fig. 3. Effect of the leading wing configuration on the lift of the trailing wing with flaps deflected 15°.

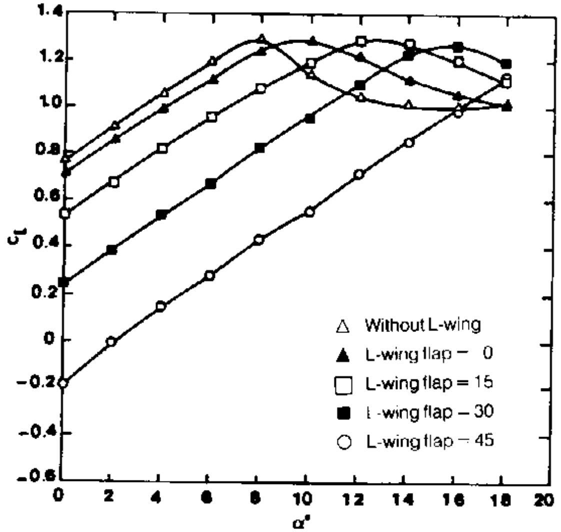

Fig. 4. Effect of the leading wing configuration on the lift of the trailing wing with flaps deflected 30°

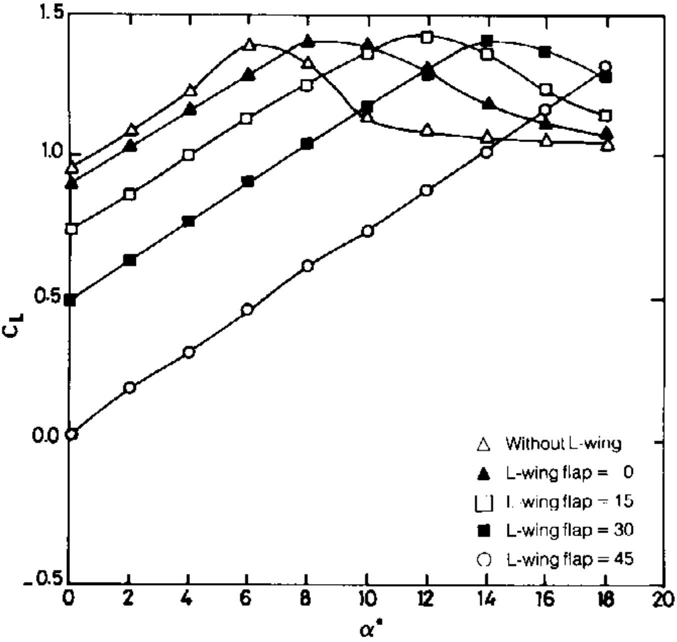

Fig. 5. Effect of the leading wing configuration on the lift of the trailing wing with flaps deflected 45°.

Table. 1. Minimum values of trailing wing angle of attack required to obtain lift, as a function of flap deflections on both leading and trailing wing models

Leading wing flap angle Trailing wing flap angle	0°	15°	30°	45°
0°	<0°	1°	5°	8°
15	<0°	<0°	0.5°	6.2°
30°	<0°	<0°	<0°	2°
45°	<0°	<0°	<0°	2°

In spite of the loss of lift, wake turbulence improves the trailing wing performance in terms of delaying stall. This observation suggests that the maximum attainable angle of attack for an aircraft, experiencing wake turbulence, could be attained before experiencing stall. On the other hand, it is observed that the slope of the lift coefficient curves are not influenced by introducing a leading wing. These two observations were valid for all flap angles covered in the investigation. This brings up another resource to be utilized by the pilot experiencing wake turbulence; he may activate the flaps to their full extended position and angle. Fortunately, flaps would most favorable be activated when encountering wake turbulence, *i.e.* during takeoff and landing.

Introduction of leading wing causes disturbance of the flow over the trailing wing, and hence drag is reduced. The amount of this reduction, ΔC_D, is presented in Figs. 6-8 for different flap configurations of both wings. It is observed that the drag does not vary appreciably with the trailing wing angle of attack until high angles are reached ($\alpha = 8°$ for 0° or 15° flap deflection, and $\alpha = 6°$ for 30° flap deflection). Then the drag drops sharply as α increases until it reaches minimum values, after which the drag increases due to flow separation on the trailing wing. Figures 6 to 8 demonstrate that the maximum amount of drag reduction is obtained when the trailing model employs its flaps and the leading model's flaps are deflected to 45°. However, drag may increase if the leading wing flaps are not activated and the trailing aircraft does not deflect its flaps to high values.

Figure 9 is presented to show the drag characteristics of the trailing wing, when equipped with a 45° split flaps for several leading wing configurations. The drag polars display similar parabolic shapes up to stall conditions. The influence of wake turbulence on lift and drag characteristics is depicted in the Figure. It is asserted that increasing the leading wing angle of attack reduces both lift and drag. If the lifting force is to be maintained at some fixed value, the drag would increase by increasing the angle of attack.

The drag polar of the situation where there is no flap on the leading wing is identical, up to maximum lift, to that where there is no leading wing at all. It is confirmed from the Figure that the maximum lift/drag ratio decreases with increasing the leading wing flap deflection angle. As a matter of fact, the maximum lift force obtained in each setting was not influenced by the leading wing presence or configuration. Furthermore, this Figure demonstrates that the continuous increase in the angle of attack is associated with progressive increase in drag and appreciable sudden loss of lift, *i.e.* the stall phenomenon.

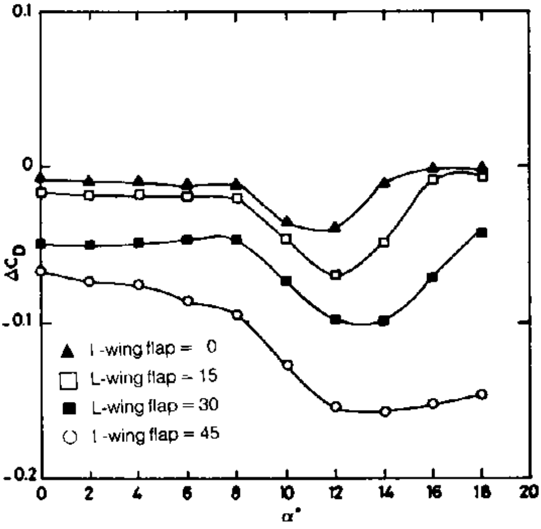

Fig. 6. Effect of the leading wing configuration on the increase in drag of the trailing wing without flap.

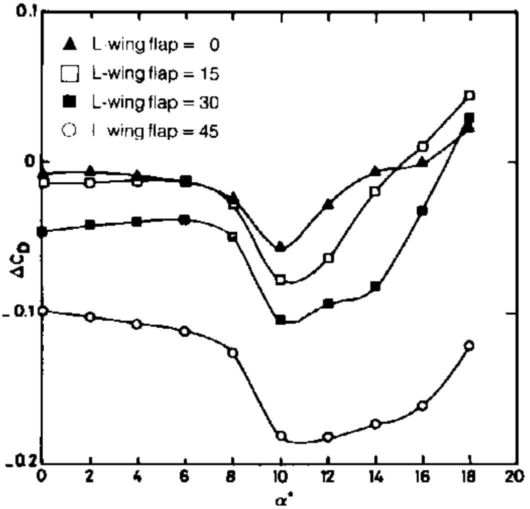

Fig. 7. Effect of the leading wing configuration on the increase in drag of the trailing wing with flaps deflected 15°.

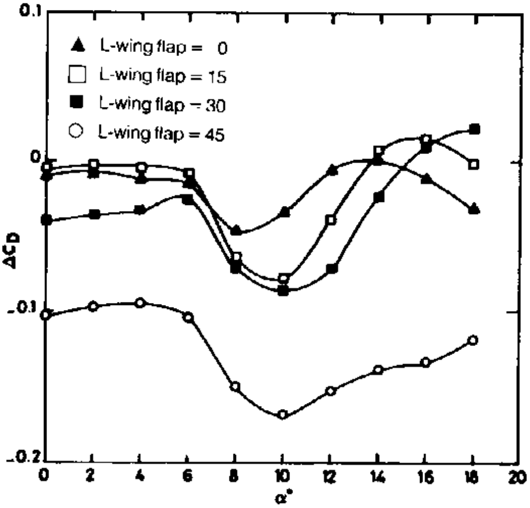

Fig. 8. Effect of the leading wing configuration on the increase in drag of the trailing wing with flaps deflected 30°.

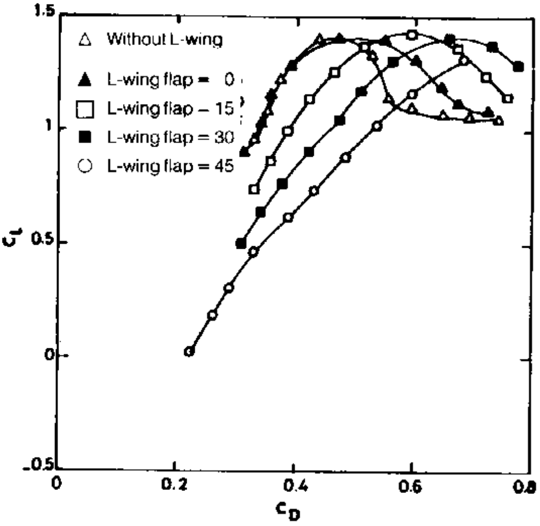

Fig. 9. Effect of the leading wing configuration on the increase in drag of the trailing wing with flaps deflected 45°.

The effect of the wake turbulence on the trailing wing pitching moment is depicted in Figs. 10-12. All three Figures demonstrate that, under all leading wing configurations and for all trailing wing settings, the pitching moment versus lift coefficient curves exhibit unstable longitudinal behavior, *i.e.* dC_M/dC_L is positive in the linear part of the $C_M - C_L$ curves. The leading wing configuration does not portray any effect on the trailing wing stability; they only affect the magnitude of the pitching moment at the same lift coefficient. This indicates that the leading wing configuration influences the position of the lift center, which moves towards leading edge when flaps are not installed on the leading wing. But when those flaps are activated, the position of the lift center reverts and moves backward. However, the trailing wing flap does improve the wing stability.

It is observed from Fig. 13 that increasing the leading wing flap deflection angle results in increasing the maximum angle of attack. The trailing wing stability is changed abruptly, in Fig. 13, with a strong nose-down pitching moment overriding it as the leading wing configuration changes. This is due to the fact stated earlier that increasing the leading wing flap deflection angle results in increasing the maximum attainable value of the trailing wing angle of attack before stall develops. Essentially, this limits the linear part of the static pitch stability.

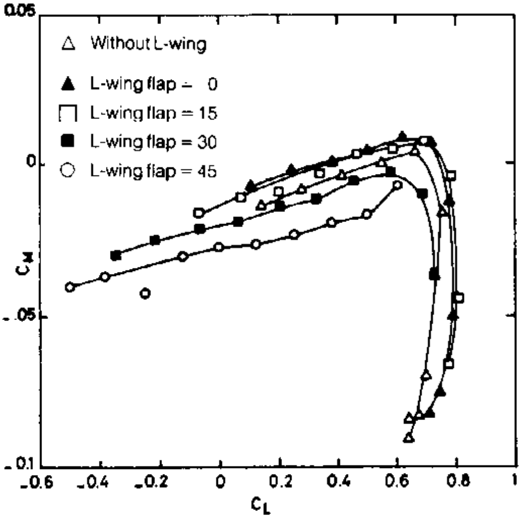

Fig. 10. Effect of the leading wing configuration on the pitching moment - lift coefficient of the trailing wing without flap.

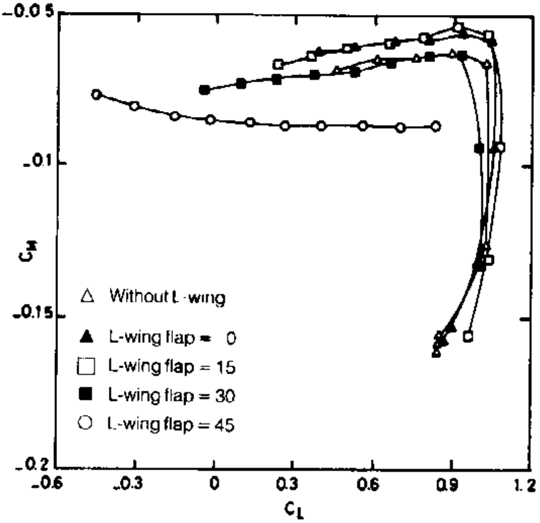

Fig. 11. Effect of the leading wing configuration on the pitching moment - lift coefficient of the trailing wing with flaps defected 15°

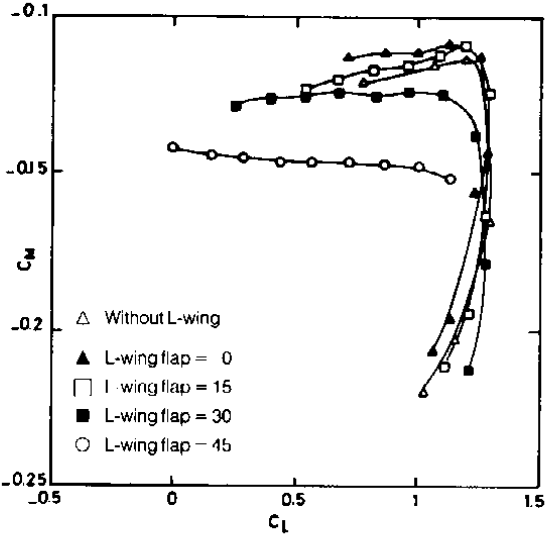

Fig. 12. Effect of the leading wing configuration on the pitching moment - lift coefficient of the trailing wing with flaps deflected 30°.

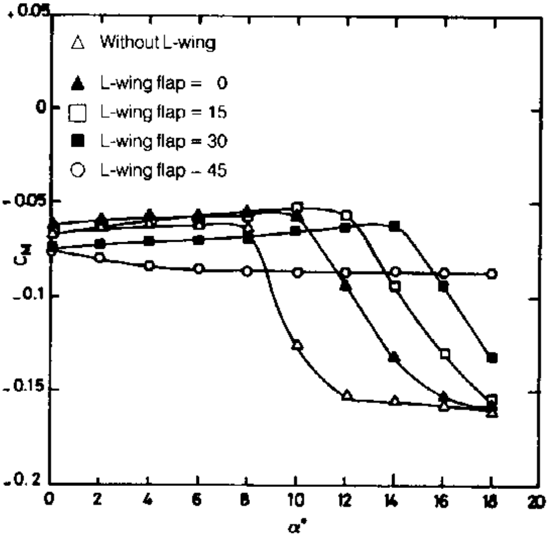

Fig. 13. Effect of the leading wing configuration on the pitching moment coefficient - angle of attack of the trailing wing with flaps deflected 15°.

Conclusion

A critical review of the experimental results concerning wake turbulence on a flapped trailing wing due to a larger flapped leading wing leads to the following conclusions:

1. The lift force of the trailing wing is reduced drastically in the presence of a leading wing, for all arrangements, to the extent that lift vanishes and turns into a downward force at low angles of attack and small flap deflection. However, using flaps helps in alleviating this effect. Therefore, the pilot facing wake turbulence may activate the flaps to their full extendible position and angle.
2. Wake turbulence does not affect the slope of the trailing wing lift coefficient curves.
3. Despite the unfavorable lift performance of the trailing wing, the results do expose some remedial effects. In particular, the stall angle of attack would increase, indicating delay of flow separation. This observation suggests that the maximum allowed angle of attack for an aircraft, experiencing wake turbulence, could be increased before experiencing stall.

4. In order to regain some of the lift lost, due to wake turbulence, the angle of attack may be increased, but at the expense of accumulated drag.
5. The leading wing configuration has no influence on the stability criterion of the trailing wing. Its effect is confined to limiting the linear part of the static pitch stability, and changing the magnitude of the pitching moment.

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تأثير التداخل من جناح كبير على أداء جناح خلفي

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(استلم في ٢٧/١١/١٩٩١م؛ قبل للنشر في ٥/٢/١٩٩٤م)

ملخص البحث. يعرض هذا العمل بحثًا تجريبيًا لدراسة تأثير الموران الخلفي من جناح متقدم كبير ذي قلّابة على جناح خلفي صغير ذي قلّابة أيضًا. فقد تمّ بحث تأثير الاضطراب الخلفي من خلال قياسات النفق الهوائي لقوى الرفع والجر وعزم الخطران على الجناح الخلفي. يتضح من هذا البحث أن خطر الموران الخلفي يكمن في إنقاص قوى الرفع. ويزداد هذا النقص في الرفع بزيادة زاوية القلّابة للجناح الأمامي، ولكن بدون أي تغيير في ميل منحنيات الرفع. وينتج من زحزحة هذه المنحنيات تأخير الانفصال إلى زوايا هجوم أعلى للجناح الخلفي. تتضاعف زاوية انهيار الجناح الخلفي عندما تكون زاوية قلّابة الجناح الأمامي ٣٠°؛ في حدود العوامل المستخدمة في هذه الدراسة. كما تنخفض قوى الجر بزيادة زاوية قلّابة الجناح المتقدم، بينما يبقى استقرار الجناح ثابتًا مع وجود مثل هذا الخطر.