EVALUATION OF LOW-SPEED HANDLING AND DIRECT LIFT CONTROL CHARACTERISTICS OF A WING WITH COLLECTIVELY VARIABLE INCIDENCE TIP ELEMENTS

R H Barnard
University of Hertfordshire
Hatfield
Hertfordshire, U.K.

Abstract

A description is given of the wind-tunnel and flight testing of a wing which has tip sections that can be collectively varied in incidence relative to the main wing. Because of the low aspect ratio of these tip sections, they do not stall at high angles of attack, but generate stable separated conical vortices in the manner of a slender delta. At such high angles, $dC_L/d\alpha$ becomes small, and the tips are relatively insensitive to gust effects. It is shown that actuation of the tip incidence variation mechanism in flight produces a convenient means of producing direct lift control, and that an increment in overall $C_{L(max)}$ is obtainable because of the very high operating incidence of the tips. A description is given of a flight test programme which used a radio-controlled model to evaluate the practical viability of the concept, and demonstrated a safe and docile handling characteristic.

Introduction

Wing-tip ailerons show a number of potential advantages in comparison with conventional trailing-edge camber-change control surfaces. Pitching moment changes are smaller, and the surfaces can be aerodynamically balanced thereby requiring lower actuation forces.

Additional advantages may be obtained if the surfaces can move both collectively and differentially. Wing-tip ailerons that float collectively at near zero mean angle of attack but are actuated differentially have been studied extensively: refs. (1 to 5). In this mode they remain effective even when the wing has stalled, and they give no differential drag.

In our studies, we have looked at some other potential advantages related to their use collectively at very high angles of attack that have not apparently been considered previously. These are:-

1 they can operate with a low $dC_L/d\alpha$ and hence make the wing tips less sensitive to gust influence.

2 The vortical lift system generated at large angles of attack produces a high local C_L, and this can be used to increase the overall $C_{L(max)}$

3 In addition, collective use of the tips can provide a convenient form of direct lift control: a change in lift obtainable with no change of attitude of the aircraft.

The flow structure

Figure 1 shows the flow structure of a wing with collectively raised low aspect-ratio tip surfaces. Strong streamwise vortices are

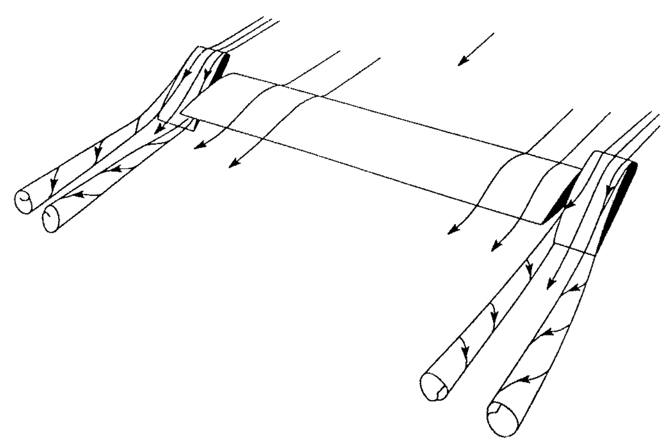

Fig.1 Flow structure for a wing with collectively raised tip sections

generated along the both the inboard and theoutboard edges of the tips, the inner vortex being weaker than the outer. These vortices draw in the boundary layer of the tip upper surface, and maintain attached flow for absolute tip incidences of up to 40° . This behaviour of very low aspect-ratio surfaces was reported by Winter (7) in 1936.

Wind-tunnel modelling

The effect on the lift properties of raising the tips was studied using the wind-tunnel model shown in figure 2. The aerofoil section was an Eppler 193, which was chosen as it is designed to give a reasonably high $C_{L(max)}$ at low Reynolds numbers. The wing was n-c machined, and the tips were simply off-cuts joined to the wing via a pivot at about 40% chord. The tips could be articulated in pitch relative to the wing. At zero relative tip incidence, they simply become extensions of the rectangular monoplane wing.

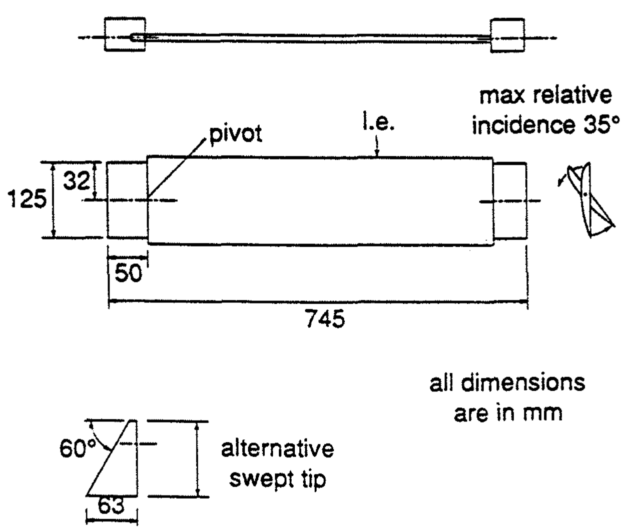

Fig.2 General Arrangement of the wind-tunnel wing model.

Direct lift control

Figure 3 shows the effect of changing the relative tip incidence angle α_{tr} on the lift characteristics. It can be seen from this figure that at wing incidences below 10°, raising the tip relative incidence to 30° generates an increase in C_L of about 0.2. As a means of direct lift control, the tips are therefore quite effective, The centre of lift does not change

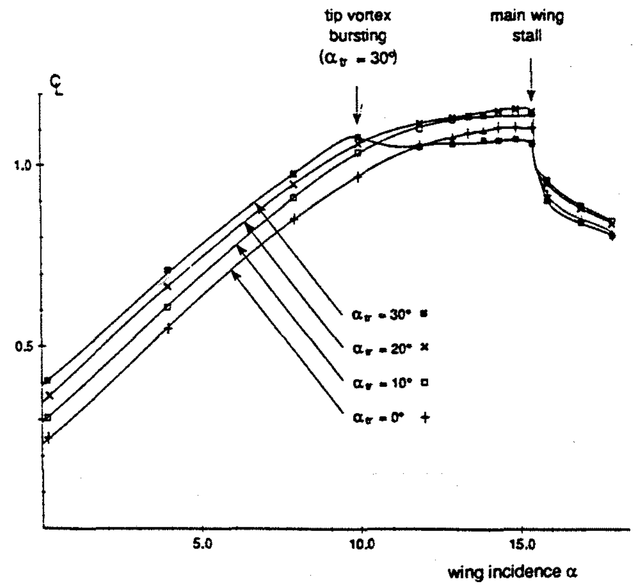

Fig.3 Variation of lift coefficient with incidence for various relative tip incidences.

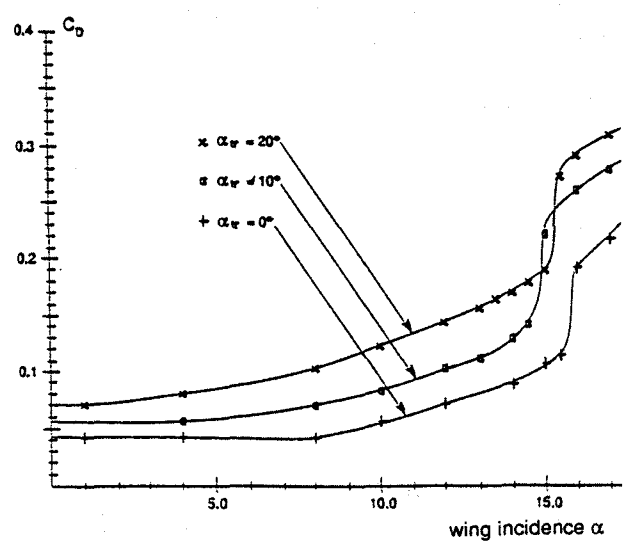

Fig.4 Variation of drag coefficient with incidence for various relative tip incidences.

appreciably, so little trim adjustment would be required. Also, torsional loads in the structure would be low. The main problem lies in the relatively large drag increase which may be seen in figure 4.

Increments in $C_{L(max)}$

From figure 3 it can also be seen that there is

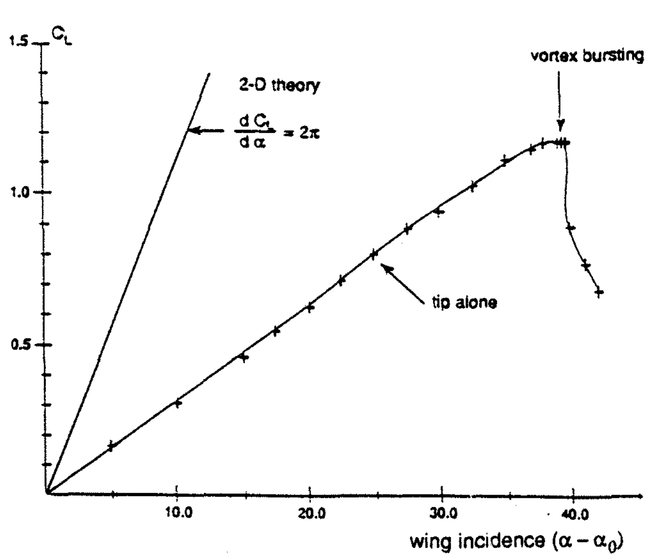

Fig.5 Variation of lift coefficient with incidence for an isolated tip of aspect-ratio 0.4:1

an increase in $C_{L(max)}$ for tip relative incidences of less than 30°, the maximum increment being about 0.06. This increment is due to the vortical lift system on the raised tips. The ability of the tips to generate an increment in $C_{L(max)}$ depends on the geometry of the wing and the tip, and can only occur if the $C_{L(max)}$ for the raised tip exceeds that which it can generate when it is simply part of a monoplane wing. Defining the optimum geometry is the subject of our current research.

Dynamic response

When the tips are raised to very high angles of attack, they behave like very low aspect-ratio isolated surfaces. Figure 5 shows our wind-tunnel measurements of the lift-incidence characteristics of an isolated tip. The low $dC_L/d\alpha$ slope may be seen in comparison with the theoretical value of 2π. This means that when raised, the tips become relatively insensitive to changes in the vertical component of wind velocity in a gust. This will reduce the vertical response to a symmetrical gust, and the rolling response to an asymmetrical gust.

From figure 3, it can be seen that at 10° main wing incidence, and 20° relative tip incidence, the lift slope of the overall wing is reduced to about 50% of its value in the linear part of the curve.

Stall characteristics

Stalling of the main wing starts with flow separation at the trailing edge near the centreline: a characteristic of rectangular planform wings. Separation starts at a wing incidence of around 11°, and this spreads over the wing, causing a sudden breakdown at around 15°. The tips do not stall until an absolute angle of attack of around 40°. This means that for tip relative incidences below 25°, the main wing will stall before the tips, leaving the tips effective as control devices. Tip stalling occurs when the vortices start to lift off, and thereby no longer control the upper tip surface boundary layer.

Limitations of wind-tunnel studies

Our wind tunnel tests included measurements of the damping-in-roll derivative C_{lp} which gives an indication of the response to asymmetric gusts. These experiments showed that its value was reduced by up to 11% at high relative tip incidences. In addition we have developed a theoretical model which enables us to investigate the influence of various geometric parameters such as wing taper and aspect ratio. However, it would be a major task to evaluate the handling characteristics of an aircraft, particularly in the non-linear stall region, and with a pilot in the control loop. To construct or modify a full-size aircraft would be expensive, and potentially dangerous with unpredictable stall and handling characteristics. As a safer and cheaper alternative, we constructed the RPV shown in figure 6.

The RPV

The RPV has conventional control surfaces, but an extra pair of actuators is fitted to operate the wing-tip elements. At present these actuators are mechanically coupled so that the tips can only operate collectively.

The model has a deliberately low inherent static stability. The optimum tip pivot position for minimum actuation force was determined experimentally. Placing the pivot further forward would have produced a fail-safe condition, but the actuators used were only marginally powerful enough.

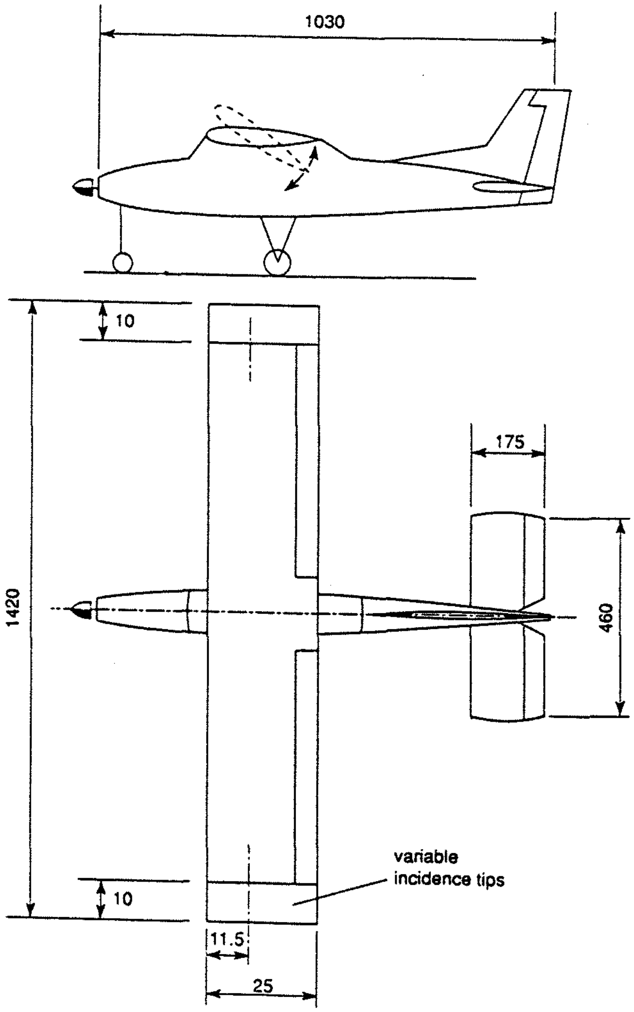

Fig.6 General arrangement of the RPV.

Flight testing

Handling characteristics

1 The baseline aircraft with the tips not actuated was flown to evaluate its handling characteristics. It was found to be easy to fly with no handling problems.
2 The tips were actuated in flight to relative angles up to 20°. This produced the expected result of a sharp increase in lift. Little or no corrective elevator trim was required.
3 With the tips actuated to angles up to 20°, the model was put through a series of rolling manoeuvres. The behaviour appeared no different from that of the baseline aircraft except for a slight reduction in aileron effectiveness.
4 With the tips at less than 20°, the aircraft simply dropped its nose at stall. At tip incidences above 25°, one wing dropped on stall. Recovery could be effected in less than two seconds by returning the tip incidence to zero. We have not yet attempted to evaluate the spin characteristics, as the model was quite expensive.
From our flight experience, we have found no adverse effects due to tip actuation for angles below about 20°.

Landing and take-off

Landing approaches were made with the tips deployed at various angles up to 20°.
With 20° tip incidence, the increased drag and increased lift made it possible to consistently obtain landing runs of around 3m in comparison with 12m required for the baseline aircraft. A slight yawing tendency was noted.
The take-off distance was also reduced, but this was thought to be mainly due to the fact that a much smaller rotation angle was required in order to reach any C_L value.

Gust sensitivity

During the second day of testing, the mean wind speed at head height was around 8 kt, and gusty. The aircraft seemed very stable with the tips deployed. This observation was of course subjective, and may have been influenced by some wishful thinking. The only reliable method of assessing the gust respose would be to fit the aircraft with accelerometers. In principle, this is not difficult, and we are currently working on the data acquisition and telemetry system required.

Conclusions

The wind-tunnel experiments and flight test conducted thus far are encouraging, but a great deal of further work needs to be carried out in order to determine the technical and commercial viability of the concept. Our current plans include quantitative flight test measurements.

Theoretical considerations show that the greatest advantage will occur on unswept rectangular planform wings of the general form used in our experiments. Unfortunately, the least suitable planform would be the swept and tapered wings of subsonic airliners. However, even for this category, White (6) has shown that wing tip ailerons are well suited for active load alleviation systems.

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