ently because of the presence of a vortex burst point over the surface.

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Comparative Study of Delta Wings with Blunt Leading Edges and Vortex Flaps

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Introduction

STUDIES of slender delta wings have typically used models that are usually thin and consequently sharp edged. This leading-edge configuration is usually viewed as representing the best compromise in terms of supersonic performance, since linearized theory suggests that a sharp edge minimizes the zero lift wave drag penalty. However, as long as the wing's leading edge is subsonic (i.e., the Mach number normal to the leading edge is less than unity) and sufficiently rounded, leading-edge suction is developed, even if not at the level suggested by theory.[1] As shown in Ref. 2, nonlinear flow codes (and experiment) show that leading-edge bluntness has a small effect on zero lift wave drag, and additionally reduces the drag from lift compared to a sharp wing as long as the wing's leading edge is subsonic. In subsonic flow (and to a lesser extent supersonic flow) a sharp leading edge may be beneficial in that the enforced flow separation occurring at the wing's leading edge, results in a substantial increase in lift because of the suction of the leading-edge vortices that form. However, as shown by Polhamus,[3] lift enhancement effects are necessarily at the expense of a drag penalty because of the loss of leading-edge suction. Thus, not only is leading-edge thrust diminished, but after effective rotation[3] through 90 deg to supplement the normal force coefficient, it contributes to drag.

Recent studies[4–6] have shown the leading-edge vortex flap LEVF (and numerous variations thereof[7–9]) to be an effective solution to the major drawback of slender sharp-edged deltas as detailed previously. An effective vortex flap works by concentrating the suction of the leading-edge vortex on the flap so that when suitably deflected, a component of the vortex-induced suction acts as thrust. Performance improvements because of LEVFs are consequently attributed to this wing configuration generating an axial force component, i.e., thrust. In general, studies of vortex flaps usually compare the performance of the wing equipped with flaps to a planar sharp-edged equivalent, or the test configuration without the flaps, but still sharp edged. This is obviously a meaningful comparison if effects of deflecting a LEVF on an existing sharp-edged wing are to be studied. However, a more complete representation of LEVF effectiveness may be gauged by comparing the wing with a LEVF to a geometrically similar blunt-edged wing, which is thus also capable of generating leading edge thrust. In this Note, comparisons are made between vortex flap data, and that for a similar blunt-edged wing.

Discussion

The following discussion compares results from the three experimental investigations described next. All of these studies were conducted at low speed.

Reference 10 contains a study by Bartlett and Vidal that details the effect of leading-edge shape on the aerodynamic characteristics of various symmetrical low-aspect ratio wings. As may be expected, the results showed that a blunt leading edge delayed crossflow separation on the delta wings that were studied. It was also shown that for the Reynolds number Re of the tests (3 and 6×10^6) an elliptic leading edge showed less sensitivity to this parameter than a round leading edge. Generally, performance was seen to improve at the higher Reynolds number.

Levin and Seginer,[4] in an investigation of vortex flaps on delta wings, showed that there is in general no optimal flap deflection angle δ_F for best performance, but an optimum for a specific incidence. This required flap angle increased as angle of attack α increased. They also showed that the specific shape of the leading edge had little influence (all were sharp edged). Rinoie and Stollery[5] in a study of vortex flaps and vortex plates showed that maximum lift-to-drag occurred when there was smooth onflow onto the flap, with no separation. It was also found that a vortex plate has analogous performance to a leading-edge vortex flap.

All of the following data comparisons are made for a vortex flap deflection angle of 30 deg, as this deflection angle has been shown to be effective,[5] and represents optimal LEVF performance over a reasonable lift coefficient C_L range. Details of the three models compared are given in Table 1.

Figure 1 presents C_L as a function of angle of attack. Also included on the plot are results for a sharp-edged planar delta of AR = 2 determined using the method of Polhamus[3] (i.e., no thrust + vortex lift). Results are also included for 100% leading-edge suction (i.e., elliptic loading) and thus full thrust. The substantial theoretical lift enhancement effects caused by vortex lift are clearly shown. Good correlation is shown between the full thrust curve and the results of Bartlett and Vidal.[10] This figure also shows the cambering effect of LEVF deflection. Although on a sharp-edged delta wing flap deflection decreases vortex lift (mainly because of a suppression of vortex formation) for a given incidence, it may be seen that lift increases more rapidly for the LEVF configurations than the blunt-edged wing because of vortex suction. Figure 1 does demonstrate that at high lift coefficient, even with $\delta_F = 30$ deg, lifting performance for the LEVF models is superior to the blunt-edged wing.

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Table 1 Model data and test conditions

Data source	AR	$(t/c)_{max}$, %	Re	δ_F, deg	Leading-edge profile
Bartlett and Vidal[10]	2	7.5	3×10^6	——	Elliptic
Rinoie[5]	2.08[a]	4.8	2×10^6	30	Sharp
Levin[4]	2.1[a]	3.2	0.5×10^6	30	Sharp

[a]Based on projected area with δ_F = 30 deg.

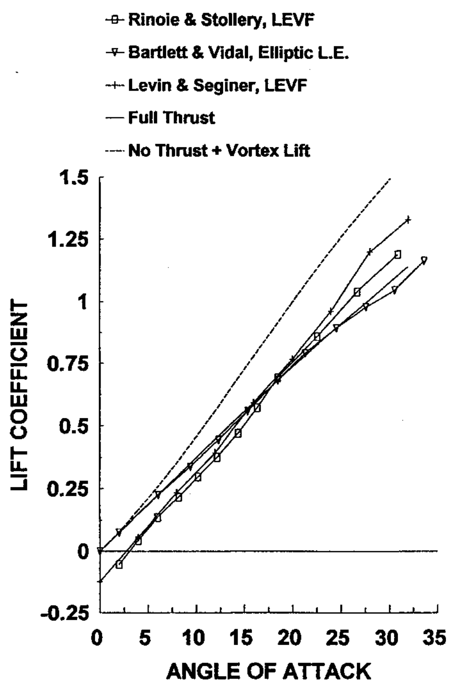

Fig. 1 Effect of leading-edge devices and shape on lift coefficient.

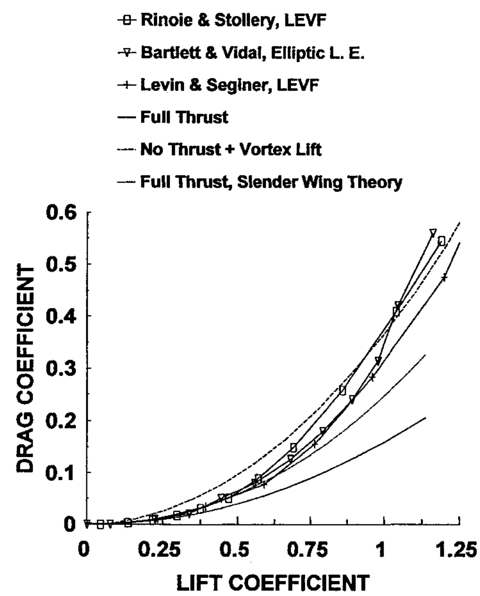

Fig. 2 Effect of leading-edge devices and shape on drag coefficient.

Drag coefficient C_D for the data sets is presented as a function of C_L in Fig. 2. The results presented have minimum drag for each configuration removed as the results of Ref. 10 were presented in this format, and the minimum drag values were not elucidated. Additional data for full thrust, and no thrust + vortex lift is also included. For slender deltas with elliptic loading the resultant force lies midway between the normal to the freestream and the normal to the wing surface,[10,11] such that the induced drag is given by $C_L \tan(\alpha/2)$. A plot representing this function is also included in the figure (denoted as full thrust, slender wing theory). This relation is easy to verify; for small incidence Jones[11] showed that for slender delta wings with elliptic loading, lift is given by $C_L = (\pi/2)\text{AR}\alpha$. Combining this expression with that for the induced drag of a wing with elliptic loading, i.e., $C_D = C_L^2/(\pi\text{AR})$ yields $C_D = C_L\alpha/2$. For this condition, it can also be shown that the axial force and drag coefficient of the wing are equal. It is seen in Fig. 2 that up to a lift coefficient of approximately 0.58 the three configurations have similar performance, which shows good agreement with that predicted using full thrust and slender wing theory. It is evident that the performance of the blunt-edged wing matches that of the LEVF of Levin and Seginer[4] up to C_L = 0.87.

The increase in drag beyond a C_L of 0.58 compared to the theoretical value for all of the wing configurations is because of a loss of leading-edge thrust (or vortex suction on the LEVF), culminating in a reduction in the axial force coefficient (Fig. 3). However, before this point all of the configurations show that full thrust is being developed with the characteristic parabolic increase in thrust with lift coefficient being evident. On blunt-edged slender delta wings loss of leading-edge thrust is associated with the onset of flow separation, such that a portion of the leading-edge suction is converted to vortex lift.[12,13] On LEVF configurations the reduction in the thrust recovered by the flaps is because of the vortex expanding and migrating inboard with increasing incidence such that its full suction is not concentrated on the flap. For $C_L < 0.4$ both the LEVF models apparently generate more thrust than would be achieved with full leading-edge suction. This is unlikely, and is probably attributable to the full thrust data being calculated for a wing of somewhat lower AR. There is also a small minimum drag penalty[4] associated with flap deflection, which would tend to mitigate any thrust increase over the planar blunt edged wing at low C_L. It is notable that at high-lift coefficients the elliptic-edged wing generates higher axial force levels than the LEVF configurations. As has been shown by Carlson and Mack,[1,13] the leading-edge separation for blunt-edged wings is not necessarily total, so that a certain amount of thrust is retained, and this is certainly evident in Fig. 3.

The data comparisons described previously show that a planar blunt-edged wing can match the performance of a corresponding wing with a vortex flap, except at high C_L. Furthermore, as shown by Wood and Miller,[2] a blunt edge does not necessarily incur a performance penalty at supersonic speed compared to a sharp wing. At high C_L, the drag of the blunt-edged wing, despite its higher thrust levels, is greater than the LEVFs (Fig. 2). This is because of the superior lifting performance of the vortex flap configurations as seen in Fig. 1. Thus, the lower drag of the vortex flap at higher α compared to the blunt wing is not because of the LEVF configuration managing to develop and retain higher thrust levels than the elliptic-edged wing (as would be the case for a LEVF compared to a sharp-edged planar wing throughout the α range), but because of vortex lift enhancement. However, it is not being implied that LEVF performance is not dependent on their effectiveness in retaining the leading-edge vortex and so developing thrust. Comparison of Figs. 1–3 suggests that this is what principally differentiates the performance of the LEVF configurations as tested by Rinoie and Stollery[5] and Levin and Seginer.[4]

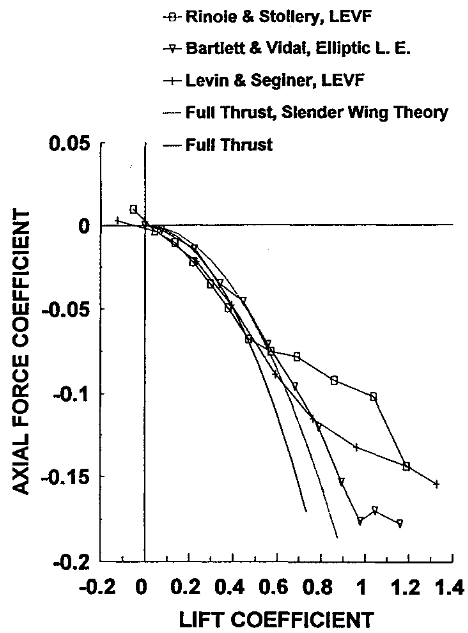

Fig. 3 Effect of leading-edge devices and shape on axial force coefficient.

Summary

A comparative study was undertaken to evaluate the effectiveness of vortex flaps when compared to a geometrically similar blunt-edged delta wing. The study shows that for the data presented in this Note, a planar blunt-edged wing is capable of matching the performance of a similar wing equipped with a vortex flap at low to moderate C_L. Furthermore the blunt-edged wing is seen to retain higher levels of axial force or thrust at high lift coefficients. Nonetheless, at high C_L, drag of the LEVF is lower than the blunt wing because of enhanced lift through vortex suction.

The LEVF concept would offer superior flexibility if the flap were movable, such that its deflection could be optimized for the particular operating conditions. If the blunt-edged wing were modified with a conventional leading-edge flap or slat, it is likely that the performance of the wing so modified, and a movable LEVF would be similar, as it has been shown that for optimum LEVF performance, separation is suppressed.[5]

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Ring Wing for an Underwater Missile

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Introduction

BY providing stealth capabilities to advanced torpedoes and scout-like unmanned underwater vehicles (UUVs), their mission success can be enhanced. Under a Defense Advanced Research Projects Agency (DARPA) contracted effort, a study was performed to evaluate the potential benefits in underwater flight performance that an extendable, novel ring wing and wraparound tail control surfaces may provide to a conventional heavyweight torpedo. With wrapped ring wing and tail surfaces, this bullet-like configuration is conducive to naval vessels having tubular launching systems. Once launched, the free-flight vehicle is reconfigured with extendable ring wing and wraparound tails.[1] These deployable lifting surfaces are activated by self-energizing materials including aluminum, steel, and composite structural members having internal spring-like qualities.

Ring Wing Benefits for an Advanced Torpedo

Hughes Aircraft has performed exploratory wind-tunnel studies of compressed carriage missile designs having extendable ring wing and wraparound tail control surfaces. These force and moment data show that significant improvements in a missile's lift and aerodynamic efficiency can be realized.

Low-speed test results of these data provided incompressible flow characteristics that were used to estimate potential improved hydrodynamic benefits that a ring wing and wraparound tail surfaces can bring to a novel torpedo design. Estimates of improved underwater flight performance for a heavyweight ring wing torpedo (4000 lb) were made.

By providing standoff capability to U.S. Navy submarines and surface ships, their survivability and mission success can

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