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Formation Flight and Much More

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Conventional Formation Flight

ATHOUGH the aerodynamics of wing lift are in general well understood, the use of the upwash flow generated at wing tips to augment lift and lift/drag ratio has not, it seems, been used in a very focused and controlled way in a single flight vehicle. The use of wing-tip generated upwash is a relatively well-known phenomenon in formation flying [1] and particularly for long formation flights of large (and gregarious) birds such as geese. In each of these cases a following vehicle (or bird) positions itself to benefit from an upwash flow generated from a wing tip of an upwind vehicle (or bird). A recent formation-flying experiment involved a pair of NASA operated F/A 18 aircraft resulting in a fuel saving for the aft aircraft of approximately 20% for some of the tests [2].

More Than Formation Flight

An inherent possibility is to obtain, for aircraft, the advantages of formation flying, with only a single aircraft, as a consequence of employing aerodynamics surfaces mounted outboard, and downwind, of the tips of the wing or main plane. Such surfaces are therefore immersed in the upwash and inwash flow created by each wing tip. Conveniently such surfaces will contain horizontal and vertical components. Each set of such surfaces comprising at least a horizontal and a vertical component are secured to the end of a boom projecting downwind from each wing tip. Each essentially horizontal surface must, for such a configuration to be used advantageously, be arranged to contribute to the aerodynamic lift of the vehicle. In essence the proposed configuration is a tandem-wing arrangement but with a major departure from a traditional tandem wing in that the downstream wing, or tail, is in two sections with each section lying in an upwash flow and thereby avoiding the downwash generated by the upstream wing. Each downwind horizontal surface is preferably terminated, at the inboard end, by a vertical surface as indicated diagrammatically in Fig. 1.

To ensure that the aft horizontal surfaces do contribute to lift implies that the vehicle center-of-gravity location is moved rearward from that occupied when a wing, or main plane, is the sole, or primary, lift generating surface. Customarily the horizontal tail surface contributes only a zero, or a small negative, lift component. Because, for the proposed configuration, the horizontal tail surfaces are immersed in an upwash flow the upward inclination of the flow implies that the tail-lift vector is inclined forward in the flight direction and, therefore, tends to cancel the combined, induced, and frictional drags of the horizontal, lifting, tail surfaces.

Similarly the vertical tail surfaces are immersed in the inwash component of the flow generated by the wing tips. This situation has been shown experimentally to produce an inflow angle about 60% greater than that corresponding to the tail upwash angle. This is due, essentially, to the intensity of inwash exceeding that of upwash because of the additional contribution to such a flow from the downwash in the wake downwind of the wing [3]. This situation results in the generation, in the horizontal plane, of a liftlike aerodynamic force acting on the vertical surfaces. When the vertical surfaces are mounted above the tail support booms. This force acts toward the aircraft centerline but with a forward directed component. The forward directed component tends to serve, for the vertical surfaces, to cancel the induced and frictional drags.

Control Surfaces

The configuration of Fig. 1 shows diagrammatically an arrangement with straight wings intended for low speed flight, featuring outboard tail surfaces in accord with the foregoing description. Roll control is provided by traditional wing mounted ailerons. Pitch motion is controlled using simultaneously operated elevator surfaces, moving in unison, attached to the outboard horizontal tail surfaces. A rudder-type action is achieved by simultaneous operation, in unison of hinged rudders attached to the vertical tail surfaces. Alternatively the hinged surfaces on the horizontal and vertical stabilizers can be replaced by the use of "all flying" movable tail surfaces.

The use of traditional ailerons is to avoid a potential for extreme wing torsional loads that could be generated by differential use of the horizontal tail surfaces to provide roll control. To prevent stalling of the horizontal tail surfaces it is necessary, when maintaining level flight, to limit the lift coefficient of the tails to about 50% of the wing-lift coefficient to provide a margin for pitch control.

Performance Prediction

With a system of this type, a problem is to evaluate, analytically, the aerodynamic lift and drag. It has been found experimentally that the optimum span of each horizontal tail surface should be approximately twice the chord of the main plane tip [3,4]. This situation implies a tail-boom moment arm of about $2\frac{1}{2}$ wing chords ($\frac{1}{4}$

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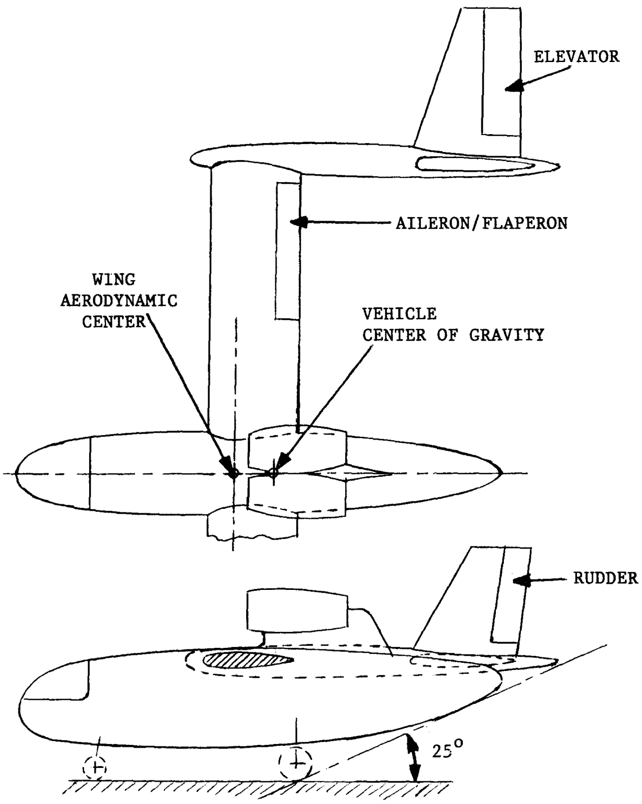

Fig. 1 A light OHS-type transport with twin turbofan engines (diagrammatic).

chord of wing aft of the leading edge to tail $\frac{1}{4}$ chord station). Because the maximum lift coefficient of each outboard horizontal surface corresponds to approximately half the main plane maximum lift coefficient and with the outboard horizontal surfaces providing, typically, about 20% of the total lift of the vehicle, severe constraints are placed upon the main plane design. It becomes apparent, therefore, that an optimum main plane is unlikely to be of the classical elliptically loaded type, found to be ideal for a conventional wing, because the nominally zero tip-chord width of such a wing is a major departure from the provision of a finite tip chord and is also impractical from a structural viewpoint. A way in which the main plane design problem can be resolved is to employ a simple uniform chord wing. Just this one consideration implies that an optimum aerodynamic design of a configuration of the type described here involves an unavoidable departure from the design of a traditional main plane.

The aerodynamic design, for lift prediction, of the outboard horizontal tail surfaces can be handled on the basis of a first approximation, by assuming that the applicable flow conditions involve the average net upwash angle of incidence when account is also taken of the area distribution of the tapered horizontal tail surfaces. Similar considerations apply to the vertical tail surfaces, subjected to the wing-induced inwash flow, when these surfaces are mounted above the booms. Here a purpose of the aerodynamic design is to evaluate the angle, in the horizontal plane, of the aerodynamic liftlike force to the line of flight and also the force magnitude.

The third, and ultimate, task of the fundamental aerodynamic design process is to evaluate and sum the net forward acting components of the aerodynamic forces acting on the tails that serve to assist in canceling the induced and frictional tail drags.

The aerodynamic design process involves, therefore, essentially three interactive steps. The first step is the design of the main plane, the second step results in the evaluation of the lift of the horizontal tail surfaces, and the final step involves the offset of the induced and frictional drags of the tail surfaces resulting from the local flows being inclined to these surfaces. For most situations, except at very low wing-lift coefficients, it can be shown that tail drags are fully canceled and the tail surfaces produce a small thrust assisting propulsion of the aircraft. In this sense the tail surfaces act somewhat in the manner of the sails of a yacht but here employing a flowfield generated upwind by the aircraft wing or main plane.

By proceeding as described, the aerodynamic performance can be predicted. However attention should also be paid to the results of a test to confirm the inherent stability in pitch of the configuration. This test is usually carried out by evaluating the static margin by means of, for example, the procedure described by McCormick [5].

Advantages

The process presented here, in outline form, will result in the prediction of the performance of an outboard horizontal stabilizer (or OHS) configuration, derived from a conventional aircraft design, with a reduced main plane area and, due to a resultant drag reduction, an increase in range and/or speed. Figure 2 shows, for the aerodynamic wing and tail surfaces only, the comparative lift/drag ratio of a conventional and a derived OHS configuration both with a wing aspect ratio of 6. A significant weight reduction should not be expected for the OHS unit because the reduced wing area and reduction of fuselage afterbody structure will likely be traded against an increase of wing torsional stiffness, the weight of the booms, and the relatively large horizontal stabilizers of the OHS configuration.

More can be done if a range or speed increase is not required because the drag reduction will result in a fuel (and emissions) savings and hence a reduction in takeoff weight resulting, in turn, in a reduction of engine power, or thrust, required for a prescribed passenger and/or cargo load without compromising takeoff conditions.

In addition to the considerations presented here for incorporating the advantages of formation flying in a single aircraft, it is possible to extend the analysis to configurations with wing sweep suitable for

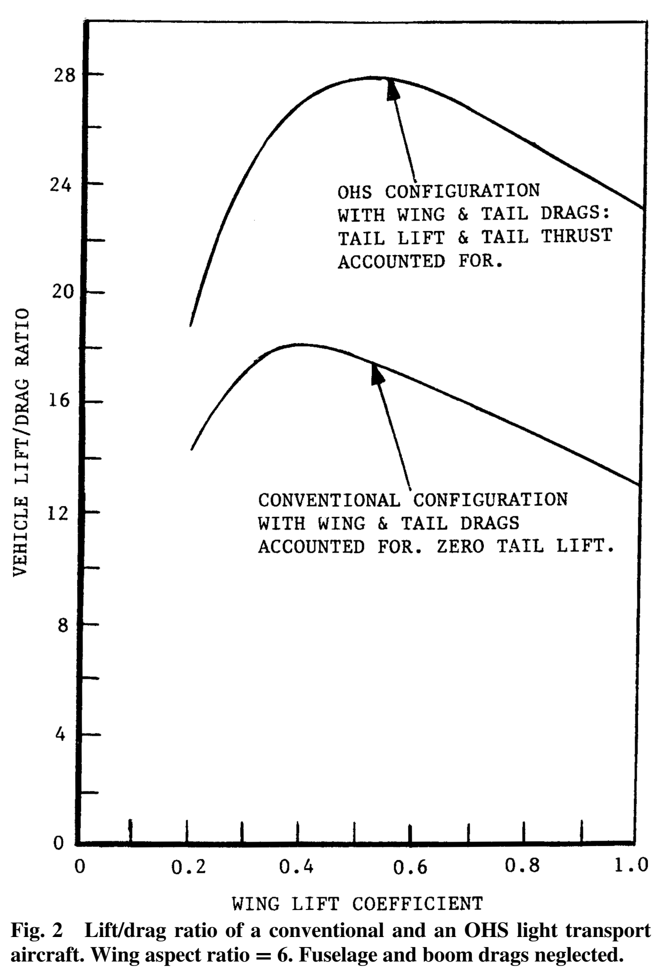

Fig. 2 Lift/drag ratio of a conventional and an OHS light transport aircraft. Wing aspect ratio = 6. Fuselage and boom drags neglected.

high subsonic Mach number cruise conditions [6]. Kentfield [6] also provides an outline of basic structural considerations.

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