Inviscid Analysis of Extended Formation Flight

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Abstract: Flying airplanes in extended formations, with separation distances of tens of wingspans, significantly improves safety while maintaining most of the fuel savings achieved in close formations. The present study investigates the impact of roll trim and compressibility at fixed lift coefficient on the benefits of extended formation flight. An Euler solver with adjoint-based mesh refinement combined with a wake propagation model is used to analyze a two-body echelon formation at a separation distance of 30 spans. Two geometries are examined: a simple wing and a wing-body geometry. Energy savings, quantified by both formation drag fraction and span efficiency factor, are investigated at subsonic and transonic speeds for a matrix of vortex locations. The results show that at fixed lift and trimmed for roll, the optimal location of vortex impingement is about 10% inboard of the trailing airplane's wing-tip. Interestingly, early results show the variation in drag fraction reduction is small in the neighborhood of the optimal position. Over 90% of energy benefits can be obtained with a 5% variation in transverse and 10% variation in crossflow directions. Early results suggest control surface deflections required to achieve trim reduce the benefits of formation flight by 3-5% at subsonic speeds. The final paper will include transonic effects and trim on extended formation flight drag benefits.

Keywords: Formation Flight, Mesh Adaption, Cartesian Euler, Vortex Propagation, Inviscid

1 Modeling Approach

In close formation flight, aircraft are separated by only a few spans and there is a symbiotic relationship among the aircraft. Not only does the lead aircraft influence the trailing aircraft, but the trailing aircraft reduce the drag on the lead as well. Simulations of close formation flight, therefore require mechanisms for coupling the flight mechanics and aerodynamics of all the aircraft in formation. In extended formation flight, we consider aircraft separated by 15-40 spans. With such large separations, the influence of the trailing aircraft on the leader becomes negligible. This decoupling leads to a natural separation of the problem into three phases: (1) simulation of the lead aircraft in free air; (2) propagation of the lead aircraft's wake/vortex system using an augmented Betz method[1] and (3) simulation of the trailing aircraft with the aged wake/vortex at the inflow boundary. Figure 1 depicts a schematic of the procedure. All simulations used NASA's inviscid AERO package[2] to investigate a 2-craft extended echelon formation using both a subsonic wing and a transonic wing-body geometry.

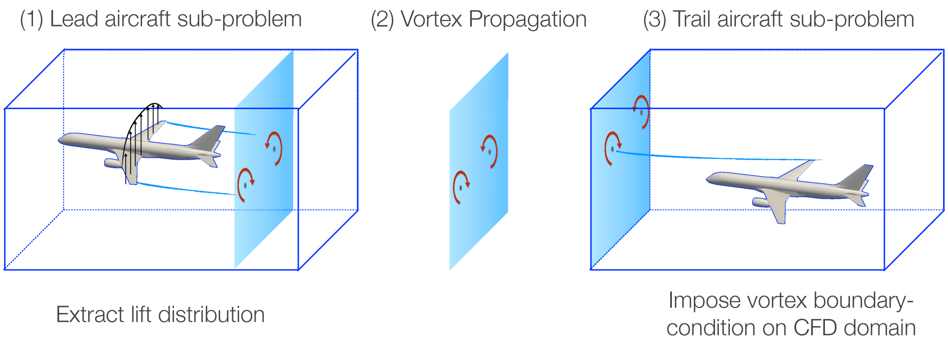
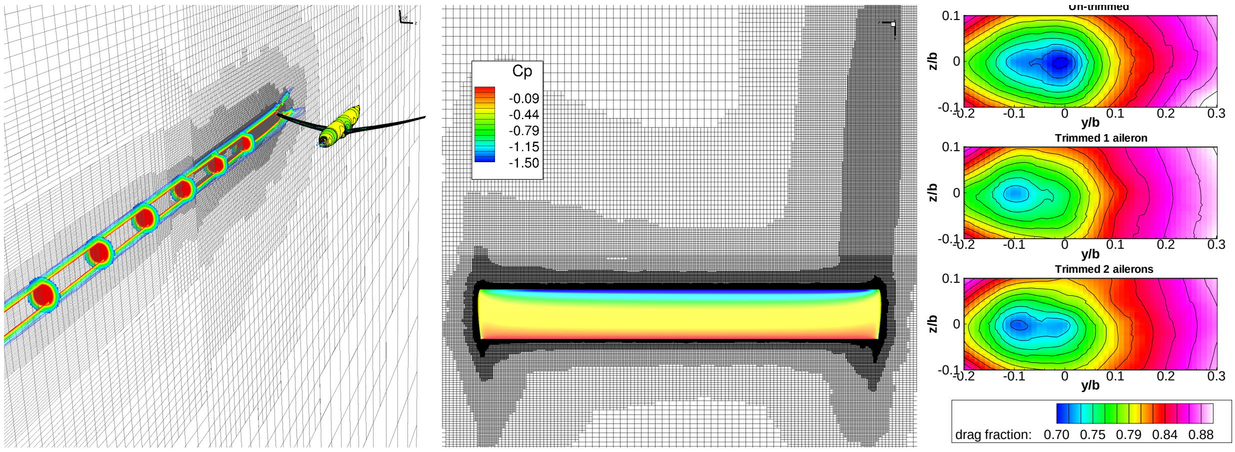


Figure 1: Complete modeling procedure to extract lead aircraft CFD results, propagate vortex, and impose a modeled vortex as the inflow boundary condition for the trailing aircraft domain.

In contrast to previous work from Bower et. al.[3] which modeled trim with lower fidelity methods such as vortex-lattice schemes, the current work uses an iterative approach with the higher fidelity, NASA AERO package. Ailerons are deflected on the geometry, a new volume mesh is generated, and a new flow solution is computed iteratively until a specified convergence criterion is met.

2 Results

A vortex position study was examined to determine sensitivity of drag savings to the location of vortex core with respect to the wing. The spanwise domain extended from 20% inboard to 30% outbard of the wingtip. The vertical domain extended from 10% below the aircraft to 10% above the aircraft. Individual data points can be seen in the figure. A typical simulation used about 20 million cells. For this study, three trim configurations were examined each containing 25 data points for a total of 75 cases for each geometry. A few results are depicted in Figure 2. Figure 2 (a) depicts the vortex entering the trail wing-body aircraft domain. Cell stretching is used in the streamwise direction to reduce the computational costs. Figure 2 (b) displays a planform view of the subsonic wing in the presence of the vortex. The adaptive mesh refinement proceeds around the body as well as upstream to the inflow plane. Drag fraction, the sum of the induced drag of all the aircrafts in formation versus the sum of the induced drag of all aircrafts out of formation, is shown in Figure 2 (c) for the subsonic wing. Early results show that trimming results in a 3-5% increase in drag fraction.



(a) vortex inflow (b) top down view (c) drag fraction

Figure 2: (a) isometric view of incoming vortex on trail wing-body aircraft domain colored by x-vorticity magnitude (b) top down view of subsonic wing colored by pressure coefficient contours. Mesh refinement proceeds around the body as well as upstream to the inflow plane to capture the incoming vorticies. (c) Drag fraction contours for the three trim configurations studied; un-trimmed, 1 aileron used to trim, 2 ailerons used to trim. The wingtip is positioned at y=z=0 in the figure extending from left to right.

Summary

This paper examined the potential energy savings for extended formation flight quantified by span efficiency factor and drag fraction for a two-aircraft echelon formation separated streamwise by 38 spans. An Euler solver combined with adaptive mesh refinement, and a wake propagation model were used to study a two-aircraft echelon formation for both un-trimmed and trimmed configurations. Drag Fractions of at least 0.90 are found in a trail positioning sensitivity study that spanned 20% of the span inboard and 30% outboard in the span direction, and +/- 10% in the vertical direction. Of the two trim configurations tested, the conventional two aileron deflection cased proved to be most favorable in terms of induced drag reduction. Overall, early results show that trimming the aircraft results in a 3-5 % increase in drag fraction for the subsonic wing. This result is encouraging as it implys lower aileron deflection angles as well as a refrain from having to change current flight controls in order to fly in formation. In addition, regions of zero induced rolling moment were detected inboard around 10% of the wingtip indicating a theoretical point at which no control surface deployment would be needed to fly in formation and achieve close to optimal savings. The final paper will include a similar vortex sensitivity study for the transonic wing-body geometry yielding results for the effects of compressibility and trim on extended formation flight drag savings.

References

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