Validation of a numerical simulation tool for aircraft formation flight.

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Abstract

The use of formation flight for increased fuel efficiency has received a lot of attention in the last couple of years.

This paper covers a numerical simulation of a NASA test flight utilizing a formation of two F18A Hornet aircraft. The numerical simulation was made using an adapted version of the vortex lattice method TORNADO, allowing for several aircraft to be simulated in a trimmed condition. The numerical results showed good agreement with the flight test data. Some discrepancies due to the numerical model not covering viscous diffusion was found as expected but not quantified or analyzed.

1 Background

The physical phenomenon behind the drag reduction encountered in formation flight has been understood for a long time, but formation flight has never seriously been employed in civilian airline traffic. On the military side, formation flight has been extensively used for tactical considerations such as navigation or suppressive fire coverage and only exceptionally as a fuel saving measure. The increased fuel efficiency is due to the decrease in induced drag caused by the upwash formed by the vortex system of a lifting wing. The formation flight then becomes a virtual extension of the span of the constituent aircraft thereby increasing the aspect ratio.

Several studies have been performed showing large potential savings in fuel consumption; The NACA study supplying the flight test date used in this paper reported a reduction in fuel consumption of 20% for a fighter type aircraft, the McDonnell Douglas (now Boeing) F/A-18 Hornet. This is a number significantly higher than the potential fuel savings from design changes.

As an example of the systematic benefits of employing formation flight for fleet operations in the north Atlantic, a conservative stance on what the in-operation fuel savings would be to assume a 5% save, based on the NASA results. Just for the trans-Atlantic routes with 385 flights a day, each direction, each burning 50 tons of fuel this would mean that in absolute numbers a flight-in-formation scheme would save 2000 ton of aviation fuel saved, each day.

While Flight tests results are closer to a real situation, they are also prohibitively expensive for mapping out a large array of tests, and some data may be inaccessible for measurement. This paper aims at showing the validity of using a Vortex Lattice Method (VLM) to assess benefits and drawbacks of employing formation flight in fleet operations and to explore what types of results would be beneficiary for future studies, such as autopilot controller design or aircraft formation movement procedures.

The numerical study was set up using the VLM implementation Tornado, modified to cater for multiple aircraft computational meshes. The code has been developed for linear aerodynamic wing design applications in conceptual aircraft design. By modeling all lifting surfaces as thin plates and modeling the flow as a potential flow, Tornado can solve for most aerodynamic derivatives for a wide range of aircraft geometries. With a very high computational speed, Tornado gives the user immediate feedback on design changes, making quantitative knowledge available earlier in the design process.

The aircraft geometry in Tornado is fully three dimensional with a flexible, free-stream following wake. Tornado allows a user to define most types of contemporary aircraft designs with multiple wings, both cranked and twisted with multiple control surfaces. Each wing may have taper of both camber and chord.

Based on the polar equation (eqn 1), a simple model of maximum achievable induced drag reduction for a multi aircraft formation would simply be based on a virtual increase of the aspect ratio.

$$C_{Di} = \frac{C_L^2}{\pi e \cdot AR} \tag{1}$$

By assuming that the Oswald factor, e, remains constant the induced drags of the formation ($C_{Di,2}$) can be written as a function of the single ship induced drag, ($C_{Di,1}$) and the corresponding aspect rations, as in eqn 2:

$$C_{Di,2} = C_{Di,1} \frac{AR_1}{AR_2} \tag{2}$$

Plotting this relation for up to a ten aircraft formation, as in figure 1, it becomes evident that that the marginal benefit of adding one more aircraft when already having 4 in formation diminishes.

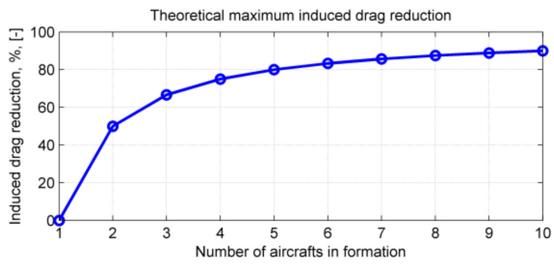

Fig. 1 Expected theoretical maximum induced drag reduction from formation flight, based on increased virtual aspect ratio.

1.1 Formation flight code modifications

The VLM code needed some modifications before a formation of aircraft could be modeled. In the single aircraft case, the lattice, or mesh is a list of coordinates describing vortex lines, collocation points, normal and panel corners. When adding one or more aircraft to the lattice, the connectivity is based on the number of panels on each aircraft. The coordinate system of secondary aircraft placement is shown in figure 2, were the origin is placed at the apex of the main wing of the lead AC and one half-span outboard.

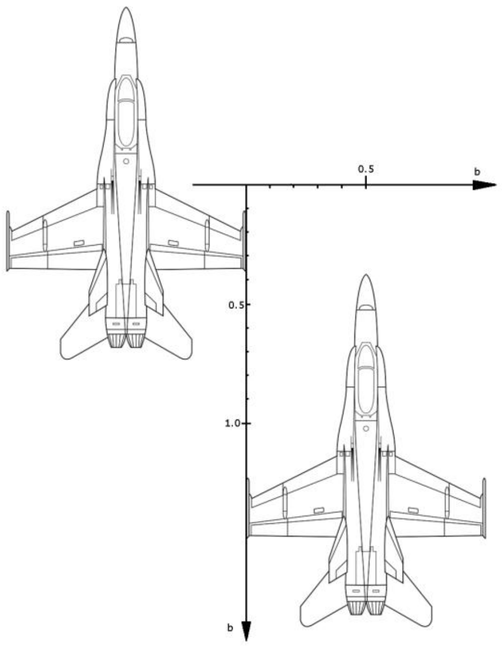

Fig. 2 Coordinate system. When the aircraft are line abreast, wing tips touching, they are at origin position. [0 0 0].

The aerodynamic state of the aircraft: angle of attack, sideslip angular rotations and so on, becomes properties of the formation in the multi aircraft case. This means that instead of changing the angle of attack to achieve heave trim, the code instead rotates the individual aircraft sub lattice for heave trim. In order to achieve useful drag reduction results, all aircrafts in the formation were trimmed in heave and pitch, while partial trim drag components from roll and yaw trim were estimated from a single ship control derivatives.

The result vector contains forces on each panel, and by using the same connectivity as for the lattice, forces and moments can be distilled out and an integrated for forces on each aircraft used for generating the individual aerodynamic coefficients.

1.2 Experiments

A NASA study performed in 1998 [2],[3] Used two F18A aircraft flying in close formation to evaluate the drag reduction. What was actually measured was the fuel consumption, which via an advanced thrust model could be equated to drag decrease. Maximum recorded value was decrease in overall drag by approximately 20%, see figure 3, corresponding to a decrease in induced drag by around 40%, close to the theoretical maximum of 50% for a two ship formation.

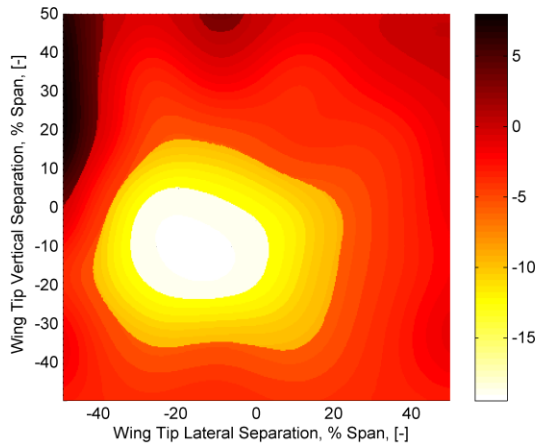

Fig 3: Overall drag reduction. in %, as a function of wingtip separation as reported by [3].

As these tests were performed under a certain timespan, the weight of the fuel remaining, thus aircraft weight varied throughout the experiment. This in turn means that the lift required for heave trim is unknown, thus the actual drag due to lift is unknown.

When evaluating the drag from the flight tests in this study, it was assumed that the weight of the aircraft was the average weight of the aircraft during the flight tests. As start and stop weight were available, the errors of this approach could be quantified.

1.3 Numerical model

The flight test parameters were modeled with the following accuracy:

The aircrafts, the F18A was modeled in Tornado as a system of lifting surfaces, according to figure 4. The geometrical data was compiled from a list of resources [5],[6],[7]

A grid convergence study was performed to ensure good grid quality. The convergence was performed on a single aircraft geometry. The cutoff level for changes between iterations was set to 0.01 delta in Lift-, Drag- and pitching moment coefficients. The grid convergence history can be seen in figure 5.

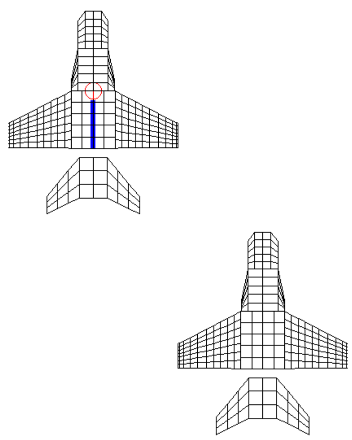

Fig 4: Mesh distribution of the numerical simulation with the following aircraft in position [1.3 0 0].

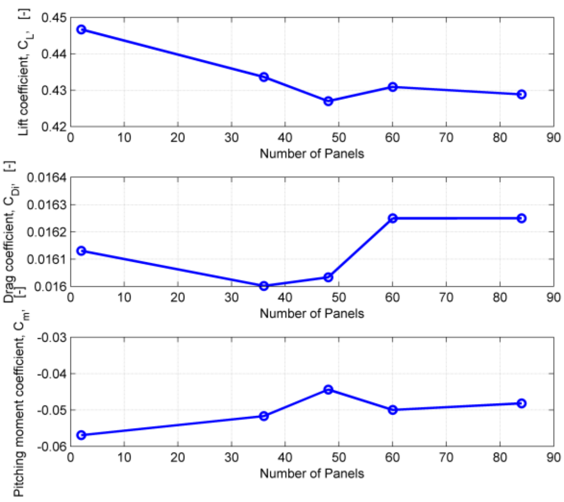

Fig 5: Grid convergence history. Number of panels in the entire geometry.

The converged grid had 18 panels semi-span wise on the main wing, and 4 panels chord wise.

The horizontal tail was modeled as an all-moving tail. The nosecone of the aircraft was not modeled at all, as the angles of attack and sideslip in this study were low enough to prevent detached vortex formation from the nose.

The solver was set to give both aircraft a prescribed C_L by changing their individual angle of attack in an iterative loop. Once heave convergence was found, the horizontal taileron was deflected in an inner loop to achieve pitch trim. When this was done, the heave loop was entered again to ensure that heave convergence was still valid. When exiting the loop, rudder and aileron deflections were computed form the control power derivatives, and the associated trim drag increase was computed from a single aircraft computation.

2 Results

There was good agreement between the simulated and experimental results; Figure 6 shows the numerical induced drag reduction at flight level 250 with a 2.75 span longitudinal separation. The cruise C_L was 0.42. The box shows the region of available flight test data.

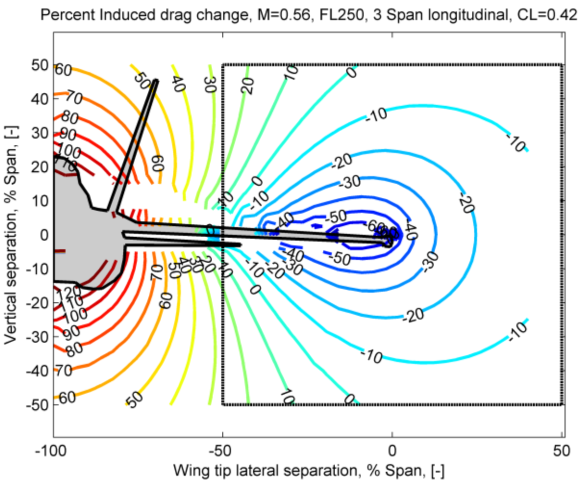

Fig 6: Iso curves of induced drag reduction., showing the F/A 18 outline.

Figures 7 and 8 shows the induced drag reductions in the test space available from the flight test, for the numerical and for the experimental results, respectively. The numerical results show a higher drag reduction which is more centered on the trailing edge. This is to be expected as the numerical model does not take any viscous losses into account, nor employs any wake relaxation schemes.

Furthermore, the induced drag reduction in the numerical results is slightly higher than the theoretical maximum, but as these areas are also coupled with a large condition number in the numerical solver, hence a larger error is expected.

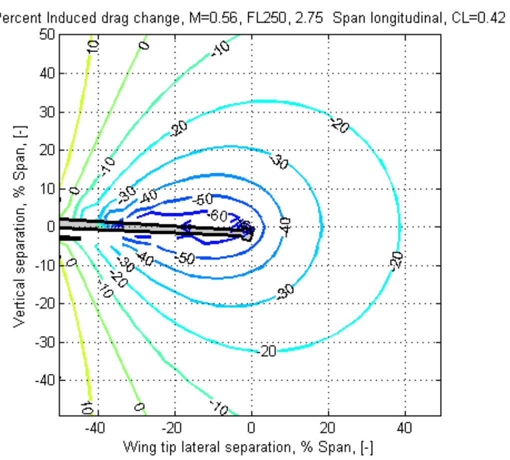

Fig 7: Iso curves of induced drag reduction from the numerical simulation.

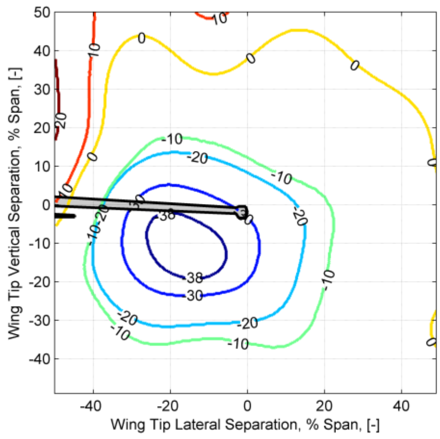

Fig 8: Iso curves of induced drag reduction from NASA flight tests.

When assessing the similarity between the incremental rolling moment on the wing aircraft caused by the tip vortices of the lead aircraft a relation similar to the drag reduction comparison. Figure 9 show the numerical results and figure 10 show the experimental results. Both methods have the maximum influence zone at around -10% wing tip offset. In the numerical results, the data for zero vertical offset were omitted as it contained large numerical errors due to badly conditioned matrices. The numerical results were also more closely centered on the zero offset vertical position. As with the drag this is due to the numerical methods inability to model wake relaxation.

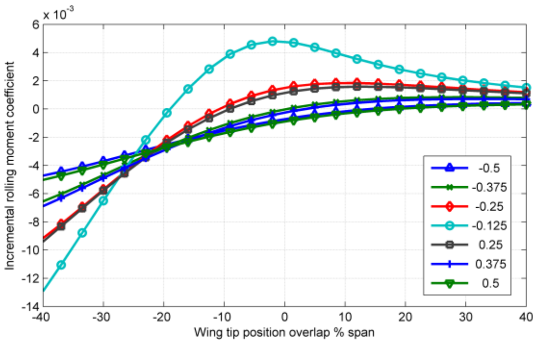

Fig 9: Incremental rolling moment coefficient at different wing tip overlaps and height offset, numerical results.

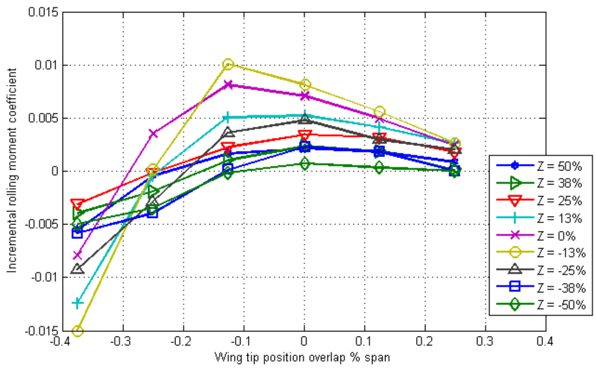

Fig 10: Incremental rolling moment coefficient at different wing tip overlaps and height offset, numerical results.

Figure 11 show the numerical data for the incremental rolling moment coefficient in iso-curve format. Interestingly there are two iso lines valued zero approaching the wing from the top and bottom. These paths could serve as approach vectors when joining a formation in order to minimize the need for excessive control input during formation forming.

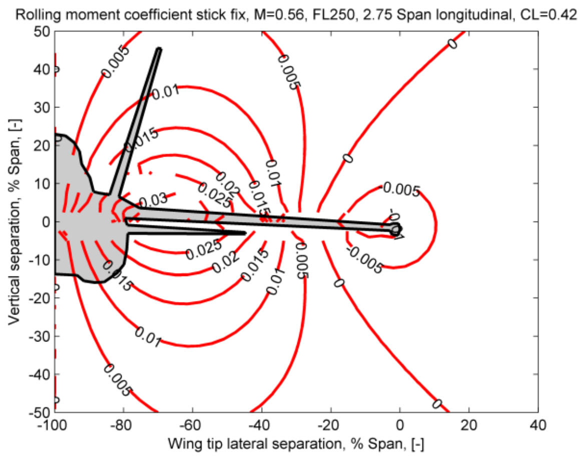

Fig 11: Incremental rolling moment coefficient

Other interesting results are shown in figure 12, where the rudder and aileron deflections needed for trim in yaw and roll are displayed. This data also shows the zero-influence approach paths as suggested by the rolling moment is also valid for the yawing moment., and as shown in figure 13 the side force coefficients.

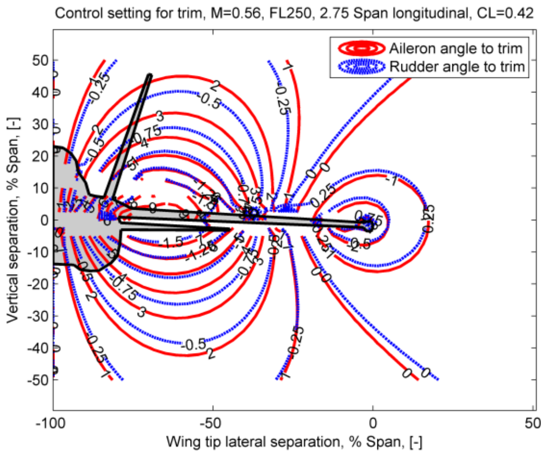

Fig 12: Incremental rolling moment coefficient

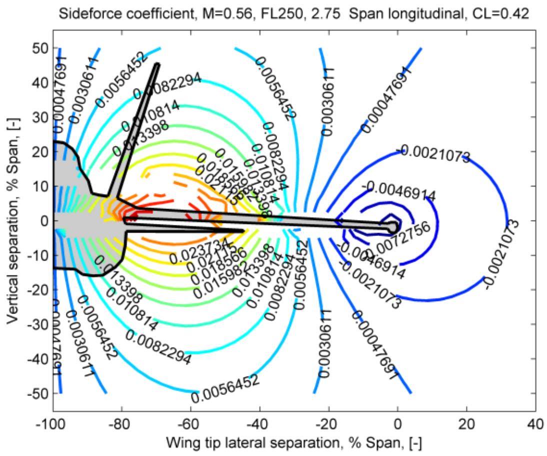

Fig 13: Incremental rolling moment coefficient

It appears as if there exists equilibrium point at [-20, 0] where rotational and translational derivatives are zero. The nature of this equilibrium point is dependent of the coupling derivatives of the individual aircraft. For example, an aircraft with no side-yaw coupling, and a very stiff roll axis, it would be a stable point with oscillations in spanwise overlap, with a frequency dependent on dynamic pressure. With a weaker roll inertia, the aircraft would start rolling out from the equilibrium pointafter disturbance.

3 Discussion

The numerical model did not cover the effects of vortex dissipation which will account for the indicated reduction of induced drag as computed numerically is slightly higher than the experimental data.

Furthermore, as no wake relaxation scheme is employed. The wake is static downstream and is not influenced by mutual interaction the vortex pair or by the vortices of the following aircraft. This in turn accounts for the misalignment of the position of the maximum drag reduction position in the y-z plane.

As no wake relaxation is done, the proposed method cannot be used to study the wake-aircraft interaction in detail.

The drag increments due to aileron and rudder deflections needed to attain trim in roll and yaw were computed using a single aircraft, therefore any effects on the drag increase due to the distorted flow field of the formation is not modeled. This effect though, is assumed to be small.

4 Conclusion

The validation study performed shows that the multi aircraft modification of Tornado can replicate flight test results with good accuracy. This means that further studies of other configurations will be encouraged.

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