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EXPERIMENTAL INVESTIGATION OF A MULTI-AIRCRAFT FORMATION

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Abstract

A wind-tunnel experiment was conducted by Bihrle Applied Research Inc. at the Langley Full-Scale Wind Tunnel to investigate the aerodynamic effects of a lead aircraft on a trail aircraft in close formation. Force, moment, and pressure data were collected on a 1/10 scale model of a modern military fighter configuration as a similar wing body configuration was positioned at various predetermined formation-leader positions. Lift-to-drag ratio increases exceeding 30% were measured. Results also revealed induced lateral-directional force and moment asymmetries. Pressure data reveal region of increased suction on the top surface accounting for the increased lift while in formation. The data also show asymmetric span-wise suction distributions on the top surface of the wing which verified the measured lateral-directional force and moment results.

Force and moment data from the wind-tunnel test were implemented into a six-degree-of-freedom simulation to study the effect of close formation on trim input. Results showed that the vehicle could be trimmed and in close formation and realize a decrease in trimmed thrust required. These results correlated well with informal flight tests conducted by NASA Dryden.

Introduction

Migratory birds have taken advantage of the benefits of close formation flight for thousands of years. Man is finally catching up. During the last several years, interest in the use of formation flight to improve mission effectiveness and range, has increased in the military aviation community. Close formation flight is being discussed for use with transports, fighters, and conceptual uninhabited combat aerial vehicles (UCAV). It is postulated that two or more vehicle flying in close formation will benefit from increased range and endurance. Unfortunately this benefit does not come without a cost. The resulting aerodynamic forces and moments adversely affect flying qualities presenting a difficult control situation. Therefore, control-law designers must be provided with representative aerodynamics models of the formation flight situation to ensure the system robustness required for tasks such as station keeping or collision avoidance. An experimental investigation was proposed to study the formation flight scenario with two main goals. The first was to establish experimental techniques for investigating multi-vehicle aerodynamic interactions. The second was collect data for use in a six-degree-of-freedom simulation to model and study the effects of a lead vehicle on a trail aircraft.

As part of the first phase of an Air Force Research Laboratory Small Business Innovative Research (SBIR) effort, AF98-175, Bihrle Applied Research Inc. of Hampton, VA conducted an experimental investigation of a two aircraft formation in the Langley Full-Scale Wind-Tunnel and developed an incremental effects model based on the results.

Nomenclature

b	Span (ft)
CD	Drag coefficient (+aft parallel to free stream)
CL	Lift Coefficient (+up normal to free stream)
Cl	Rolling moment coefficient (+right wing down)
Cm	Pitching moment coefficient (+nose up)
Cn	Yawing moment coefficient (+nose right)
CY	Sideforce coefficient (+right)
X	Longitudinal distance of lead aircraft from trail aircraft (+ forward)
Y	Span-wise distance of lead aircraft from trail aircraft (+ left)
Z	Vertical distance of lead aircraft from trial trail aircraft (+ down)

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α	Angle of attack (deg)
β	Angle of sideslip (deg)

Wind-Tunnel Test

Test Facility

The test was conducted at the Langley Full-Scale Tunnel, which was operated by Old Dominion University. The tunnel is powered by two 4,000 hp electrical motors, each driving a four-bladed propeller positioned side by side downstream of the test section's ground plane. Drawn from the return passages on both sides of the tunnel, the air stream is accelerated in the converging nozzle prior to entering the 30-ft x 60-ft open test section.

The test section was equipped with a main model support located on the test-section centerline. The tunnel also featured an overhead carriage that has been used for flow surveys and was capable of translating in three directions, parallel, and perpendicular, both horizontally and vertically to the tunnel's freestream.

Test Articles, Apparatus, and Setup

Force, and moment data were measured with an SPT-2 six-component strain gauge balance from a 1/10-scale model of a modern military fighter in close formation with representative wing-body geometry having an identical wing planform and area. Pressure data were also collected from 256 ports on the trail vehicle during the test using ESP32 transducers and a PSI780B data acquisition system. Figure 1 contains a photograph of the two models in the wind tunnel in a lead-trail formation.

The lead aircraft was mounted on an "L" sting extending from the overhead carriage (Figure 2). The trail aircraft, considered the test aircraft, was mounted on the tunnel's main model support. To minimize sting interference from the lead rig, both models were mounted inverted. To investigate the effects of the lead aircraft on the trial aircraft, relative distances between the 25% MAC reference points of the two aircraft were set by moving the lead aircraft, with X, Y, and Z distances referenced from the 25% mean aerodynamic chord of the test aircraft. The coordinate system origin was stationary at the reference point of the test aircraft, and its axes were parallel to earth-fixed axes. The sign convention of the measured distances was defined as:

X positive forward
Y positive toward the left wing
Z positive down.

The carriage motion allowed a normal (Z) variation of approximately ±1.5 semi-spans, lateral variation (Y) of ±8.0 semi-spans, and longitudinal (X) variations of 3.0 to 4.5 semi-spans

Conditions

At each of the designated X, Y, and Z locations, force, moment, and pressure data were collected from the test aircraft at a tunnel dynamic pressure of 5 psf and a free-stream Reynolds number of approximately 411,000/ft. The test aircraft was set at angles of attack ranging from 0 to 10 degrees and at sideslip angles of ±5 degrees. The lead-aircraft angle of attack was fixed at 10 degrees.

Data were collected with the leader at relative distances from the test aircraft as listed.

X b/2	Y b/2	Z b/2
3.0	0	0.0, +0.3,+0.6,±1.2
	±1.0	0.0, +0.3,+0.6,±1.2
	±2.0	0.0, +0.3,+0.6,±1.2
	±3.0	0.0, +0.3,+0.6,±1.2
4.5	0	0.0, +0.3,+0.6,±1.2
	±1.0	0.0, +0.3,+0.6,±1.2
	±2.0	0.0, +0.3,+0.6,±1.2
	±3.0	0.0, +0.3,+0.6,±1.2

Results

Baseline force and moment data were collected with the test configuration in the absence of a lead configuration and were used to reduce the parametric data into aerodynamic increments. Aerodynamic effects of span-wise formation position were found to be symmetric therefore, data from corresponding span-wise positive and negative positions were averaged with attention paid to lateral and directional orientation and convention. This procedure lead to a complete incremental effects model for a single span-wise direction. For model implementation purposes, zero values were placed at all span-wise distances for Z distances equal to ± 2 b/2 and ± 4 b/2.

Figure 3 through Figure 6 contain contour plots of the formation effects model created from data collected in the wind-tunnel for the two X distances tested at 5 and 10 degrees angle of attack for zero sideslip. Each figure contains individual plots of changes in lift-to-drag ratio, CL, CD, Cm, CY, Cl, and Cn. The Plots contain lines of linearly interpolated constant change from the baseline. Normalized Y and Z positions are placed as the abscissa and ordinate of each plot respectively. For presentation purposes, all data were mirrored across the Y = 0 b/2 plane of symmetry. Care was taken to ensure that the proper orientation of lateral-directional data was maintained.

Figure 7 contains surface plots of the pressure data collected on the test vehicle for three different span-wise distances along with baseline aircraft (out of formation) data. These plots represent data interpolated for chord-wise and span-wise position from on the top surface of the test aircraft.

Discussion

Lift and Drag

In Figure 3 through Figure 6 the X = 3.0 b/2 and X=4.5b/2 distances have similar regions of lift and drag increase. The regions of improvement are well defined at the Y = ±2 b/2 span-wise location. At 10º degrees, in both longitudinal positions, larger lift increases were measured than in the 5º cases. However the 10º case the drag increased by an order of magnitude over the 5º cases. This resulted in the 5º angle-of-attack case experiencing a much larger lift-to-drag ratio than the higher angle-of-attack cases.

Looking at the results for 5º angle-of-attack, Figures 3 and 5, the region of benefit to L/D is relatively large, extending span-wise from one semi-span to three semi-spans and reaching over a vertical positioning range of +1 semi-span to –2 semi-spans. The greatest benefit of over 30% in the X = 3.0b/2 and 20% in the X=4.5b/2 case being achieved at the two semi-span-wise location, slightly above the leaders' reference plane.

The 10º angle-of-attack cases had L/D increases one order of magnitude less than the 5º cases in regions that were approximately the same location.

Longitudinal position of the trail configuration had a small but pronounced effect. As expected, the further away from the lead aircraft, the smaller the effects from the formation. This can be seen in the L/D increases for both angle-of-attack.

For all cases of angle-of-attack and X position, the region on the leader's centerline showed decreases in excess of 50% in L/D for the 5º angle-of-attack case and much smaller decreases for the 10º angle-of-attack cases. The region of performance reduction increases in both vertical and span-wise distances as the trail aircraft is positioned further from the leader. For the 5º angle-of-attack at X=4.5b/2, L/D gradients are steep in the ±1.0 to ±1.5 b/2 region. This emphasizes the importance of station keeping when attempting to benefit from formation flight.

Pitching Moment

Formation effects on the pitching moment of the trail aircraft were close to zero in the regions of best L/D benefit for all angles-of-attack and X distances. All angle of attack cases show increased nose up pitch moments as trail aircraft span-wise position moves inboard on the leader. The pitching moment effect at 5º angle of attack reduces to nearly zero at the leader's centerline. In the 10º cases, the effect of trail position causes a nose-down pitching moment increment as the trail aircraft approaches the centerline of the leader. The span-wise location of this transition varied with vertical position.

Rolling Moment

The effect of position on rolling moment is largest when the trail aircraft is positioned at the one semi-span span-wise location. In this position, the trail aircraft's nose is in line with the leader's wing tip. At this position the outboard wing of the trail aircraft is impinged on by the leader's tip vortex causing asymmetric suction on the top surface of the wing and inducing a rolling moment toward the centerline of the lead configuration. This can be seen in the pressure data plotted in Figure 7.

In the X=3.0b/s longitudinal position, as the trail aircraft moved to outboard span-wise positions it experienced a rolling moment reversal with the transition occurring near the two semi-span position. This happens to be the region of greatest benefit. At this position little or no roll trim is required, but station keeping may be difficult due to divergent nature of the gradients. At the X=4.5b/2 position, no reversal takes place, but the region of little or no effect on roll existed at the two semi-span lateral position. As the trail aircraft position moves outboard from the two-semi-span position, the effect increases in the inboard wing direction. This effect was less pronounced at the 5° angle-of-attack case than it was for 10° case.

As with lift and drag, effects on rolling moment decreased with increase longitudinal distance from the lead.

Side Force and Yawing Moment

Trail aircraft position effects on side force and yawing moment were greatest at the one – semi span location and varied with Z position. The magnitudes and directions of the side forces and yawing moments are consistent with lead aircraft's wing vortices impinging on the trail aircraft's vertical tails.

For both angles of attack, at both longitudinal positions, while near the one-semi-span-wise location and approximately one semi-span below the lead configuration, the trail aircraft experienced a yawing moment pushing the nose inboard. This yawing moment was coordinated with the roll caused by the position. The effect on yaw decreased to zero as the trail aircraft moves outboard or inboard. This effect also decreased as the trial aircraft approaches the reference plane of the lead configuration. As the trail aircraft Z position increased, for the 5° angle-of-attack case at X=4.5b/2, steep yawing moment gradients were evident near the one–semi-span position. These resulted in a yawing moment reversal becoming uncoordinated with roll caused by position. The X=3.0 b/2 case experienced decreasing yawing moment with increasing Z position, but no reversal. Yawing moment increased in the same direction as Z position reached the leader wing plane leaving a region of little or no effect on yawing moment The 10° angle-of-attack cases experienced the same trends as the 5° cases, but there was little or no yaw reversal.

In the region of largest performance increase, yawing moment decayed as the trail aircraft moved outboard and vertical. Only the X=4.5b/2 at 5° angle of attack where the yaw reversal occurs presents potential problems for station keeping.

As expected, side force and yawing moment decreased with increased longitudinal distance.

Subsequent Work

As part of the Phase I effort mentioned above, a supplemental task was performed to evaluate the use of the data collected during this experiment in a simulation. A preliminary evaluation of the simulation modeling of the interaction effects and their influence on flying qualities was conducted and permitted the analysis of the trim requirements during operation in the flow field of another aircraft.

Simulation Model

A complete six-degree-of-freedom nonlinear flight model was used for this evaluation. The simulation contained representative aerodynamics, flight control, and engine models of the modern military aircraft tested in this research. This model is hosted in BAR's D-Six simulation environment in support of Navy activities and provided the interface needed for the addition of the incremental effects. Incremental effects on aerodynamic coefficients were functions of position and angle of attack, and incorporated into the aerodynamics model.

To simplify the execution of this study, the lead vehicle was assumed to be at a constant distance from the trail aircraft. The main goal of this effort was to perform a preliminary assessment of a trimmed formation situation. Holding formation distances constant made piloting tasks easier in the absence of a station keeping control law. These positions were variable and set at the start of a simulation run.

Simulation Results

Attempts were made to fly the simulation in real time at identical trim conditions in and out of the virtual formation in the region of highest L/D benefit, position XYZ. As expected, the in-formation flight case required much more pilot workload than the out-of-formation case. Lateral and directional coordination was the most difficult task. Because of significant sideslip influence on drag, the pilot's goal was to minimize sideslip angle. Attempts to fly the aircraft in this region of L/D benefit required substantial lateral trim input and proved particularly difficult to maintain trim, especially as directional input and angle of attack changed.

More attempts at a second formation location were made, $\Delta x = 3.0$ b/2, $\Delta y = 2.7$ b/2, $\Delta z = .7$ b/2 position. This position is where the test data revealed a relatively high L/D benefit requiring inducing minimal lateral and directional asymmetries.

A comparison of percent of full control deflection in and out of formation is provided in Figure 8. During the formation flight, the trailing aircraft experienced an 8% increase in L/D, allowing the trim at a lower angle of attack thus reducing thrust required for trim, as indicated in Figure 8. Since the simulation accounted for surface effects in the estimation of drag, simulated L/D values were lower than wind tunnel measured results.

Recent informal testing at the Dryden Flight Research Center a similar test aircraft have also shown apparent improvements in the thrust requirements for a two-aircraft configuration.[1] While the test results are preliminary for a two aircraft formation, flight extracted results indicate reductions of trimmed thrust required during formation flight of approximately 10%. These results compare favorably to the results shown in this study.

Concluding Remarks

The investigation of a two aircraft formation has shown that effects of formation flight can be measured experimentally using scale models. The test results have shown that a performance benefit can be achieved on a trail configuration by maintaining a lateral position of a approximately one span from the leader, while keeping the trail aircraft's wing in plane with the lead aircraft's wing. Though data were collected at only two longitudinal distances, data revealed that effects on the aerodynamics decreased with increases longitudinal distance from the lead configuration. Future investigations should expand the study of longitudinal position effects. The investigation also revealed roll and yaw asymmetries that must be considered during station keeping control law design. These asymmetries were identified using the pressure data collected during the test. The data reveal regions of increased suction on the top surface of the wing resulting from upwash caused by the wake vortices of lead aircraft.

A simulation study provided an example of the implementation of data from a multi-vehicle wind-tunnel test. Even with the simplification of a static formation, results emphasized the difficulty of achieving trimmed flight. The accounting of drag resulting from deflected surfaces is an important issue to consider when modeling a formation flight scenario. As seen in this study, realized benefit in L/D during trimmed formation flight was 17% lower than ideal the test predicted value of 24.5%. This decrease was most caused by sideslip effects on drag and increased drag due to trim surface deflections.

Future Work

Bihrle Applied Research Inc. will continue this research in an SBIR Phase II effort. During this effort, wind-tunnel test capability will be expanded to allow simultaneous measurement of force and moment data on both the lead and trail configuration. This will allow for the study of dynamic formation flight and the effect of lead vehicle wing loading on a trail vehicle. Hardware modifications will also be made to expand the range of formation position that can be attained. Future tests will also include force and moment measurements of configurations with deflected control surfaces. In addition to the enhanced test capability, BAR intends to further develop its D-Six simulation environment to better accommodate dynamics formation flight simulation.

Acknowledgements

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References

[1] Bowers, A. Ralston, J. and Gingras D. Electronic and telephone correspondence discussing unpublished formation flight-test results performed at NASA Dryden. October 1998.

Figure 1. Photograph of a two aircraft formation in the Langley Full-Scale Tunnel.

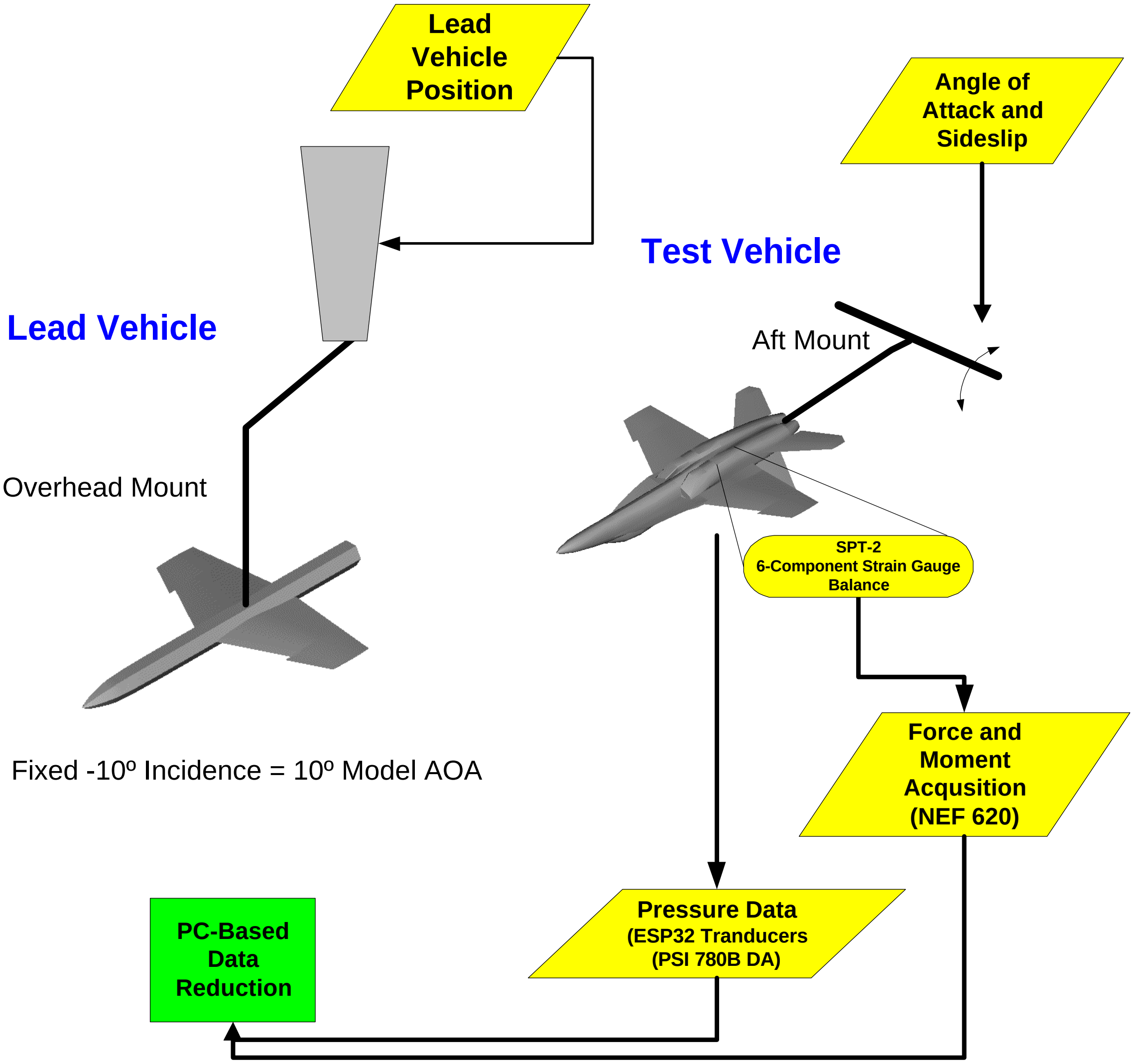

Figure 2. Diagram of test apparatus and set up.

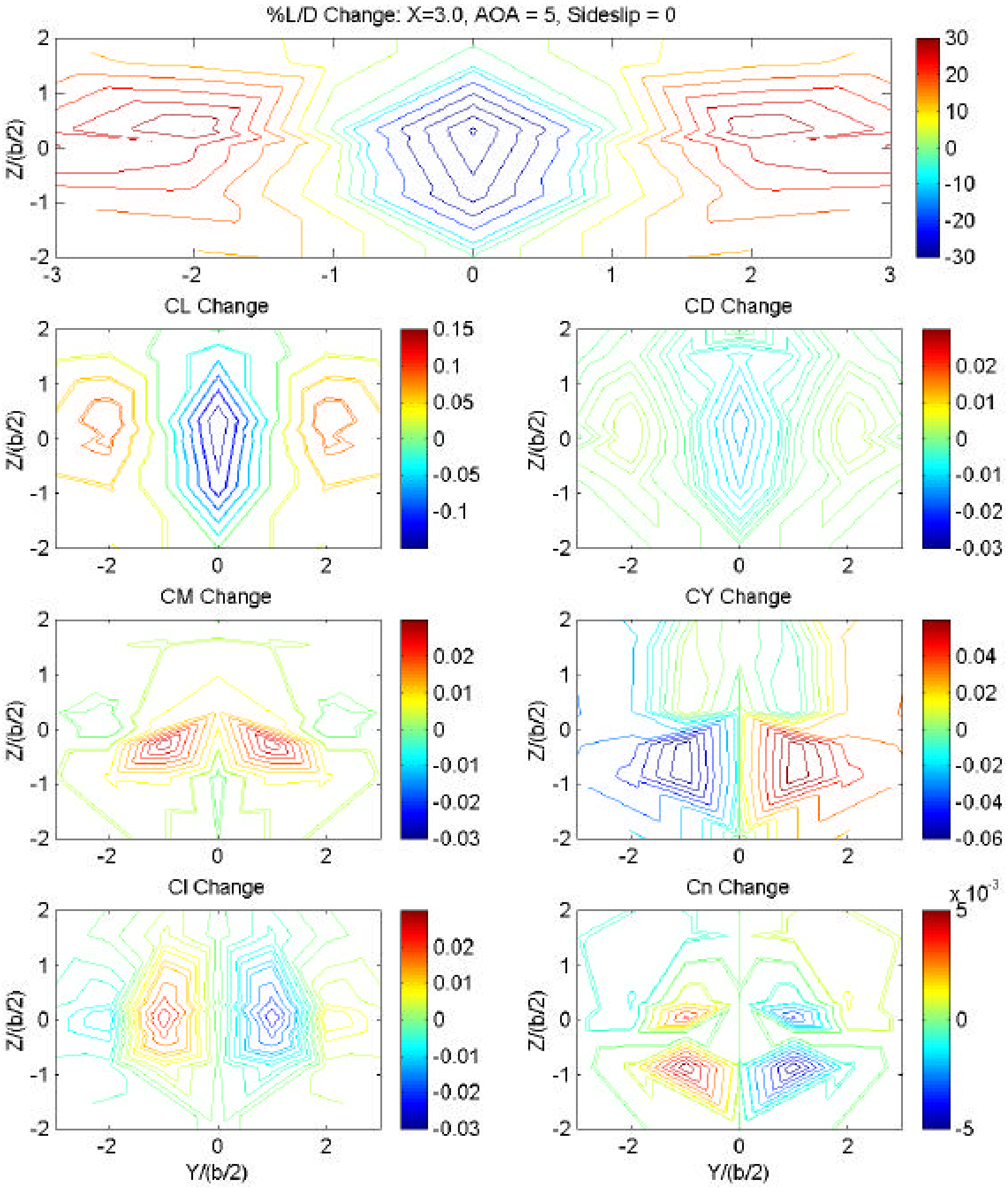

Figure 3. Aerodynamic effects on the test configuration at X position 3.0b/s, $\alpha = 5^{o}$ and $\beta = 0^{o}$ resulting from formation position.

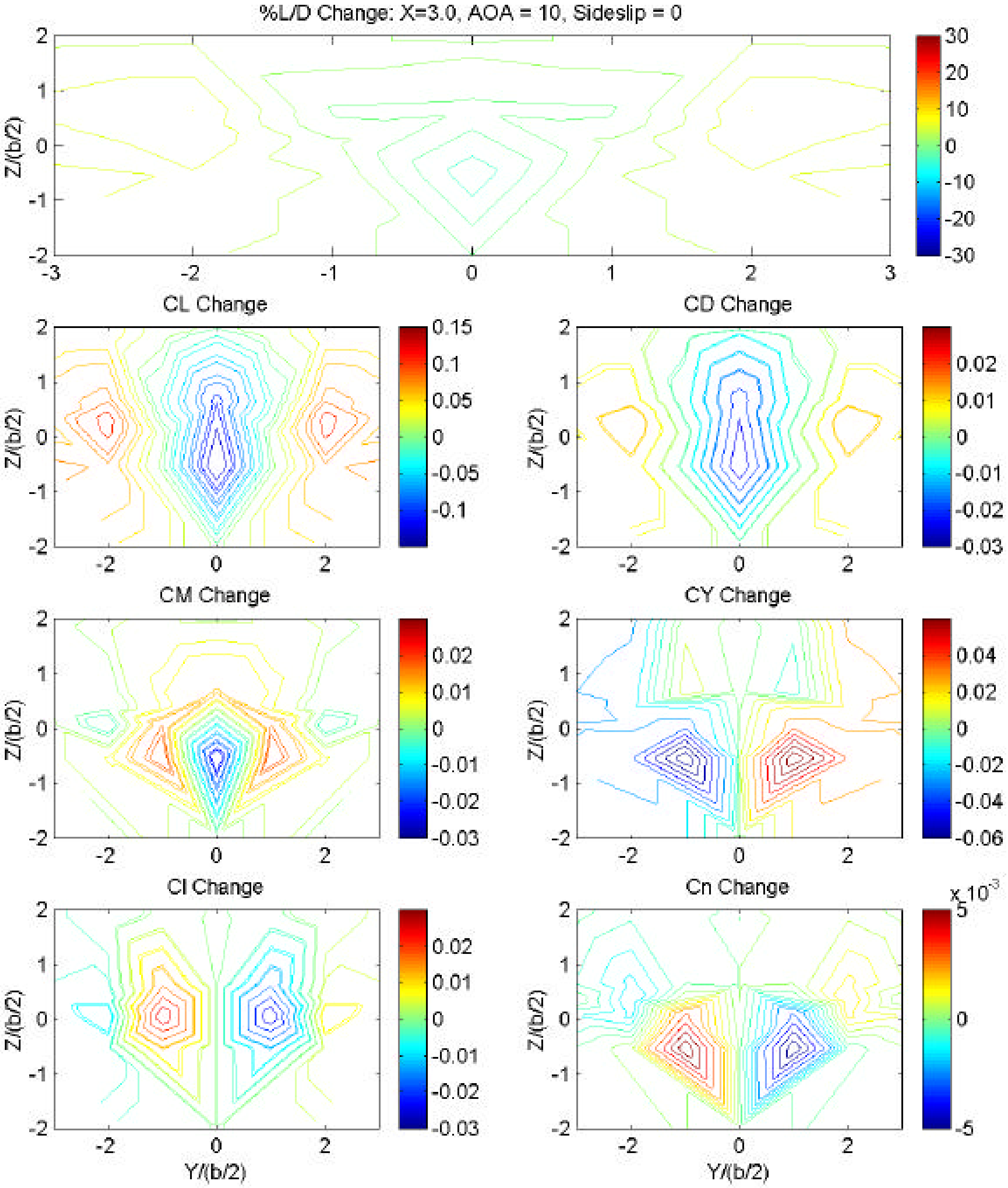

Figure 4. Aerodynamic effects on the test configuration at X position 3.0b/s, $\alpha = 10^o$ and $\beta = 0^o$ resulting from formation position.

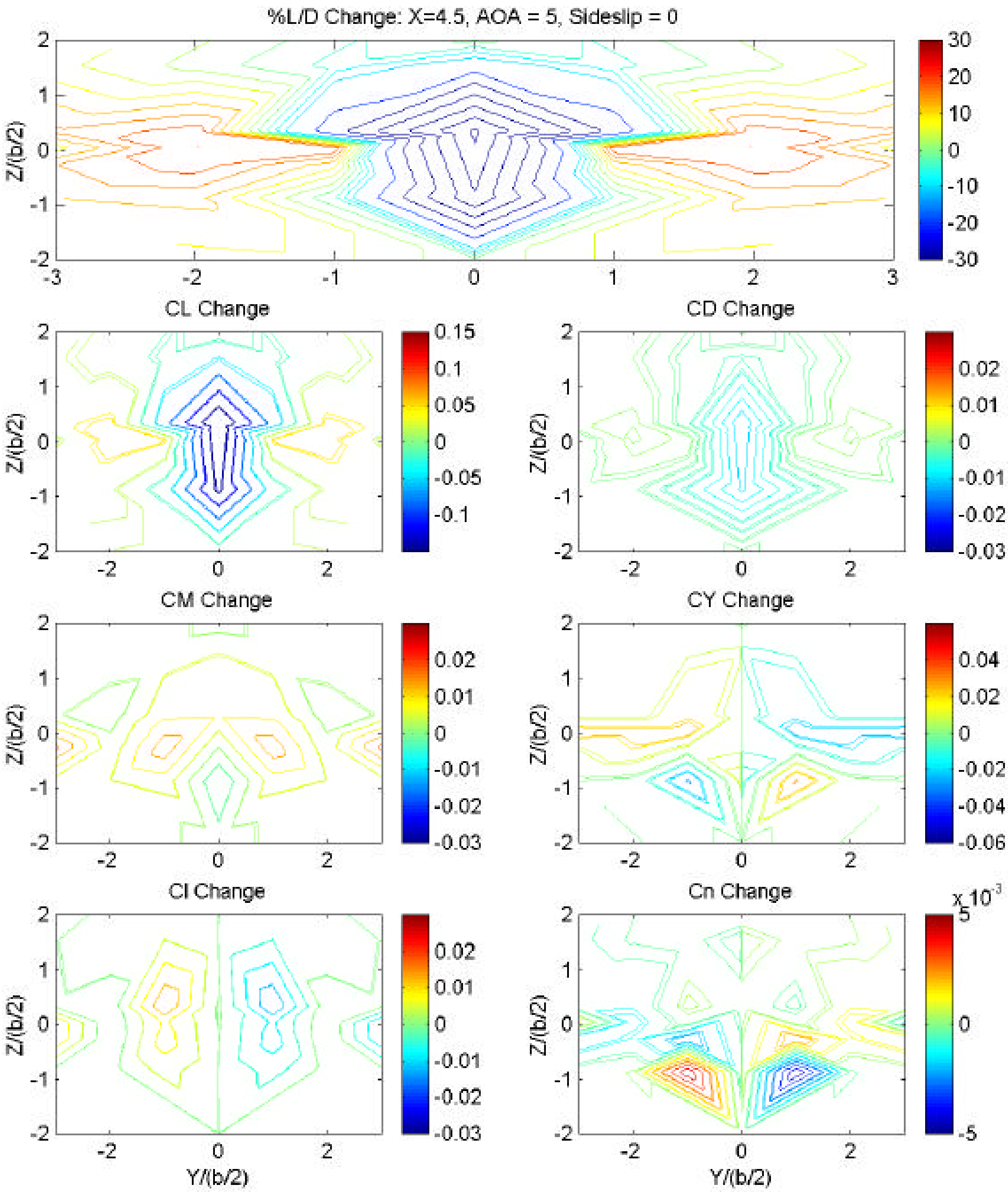

Figure 5. Aerodynamic effects on the test configuration at X position 4.5b/s, α = 5° and β = 0° resulting from formation position.

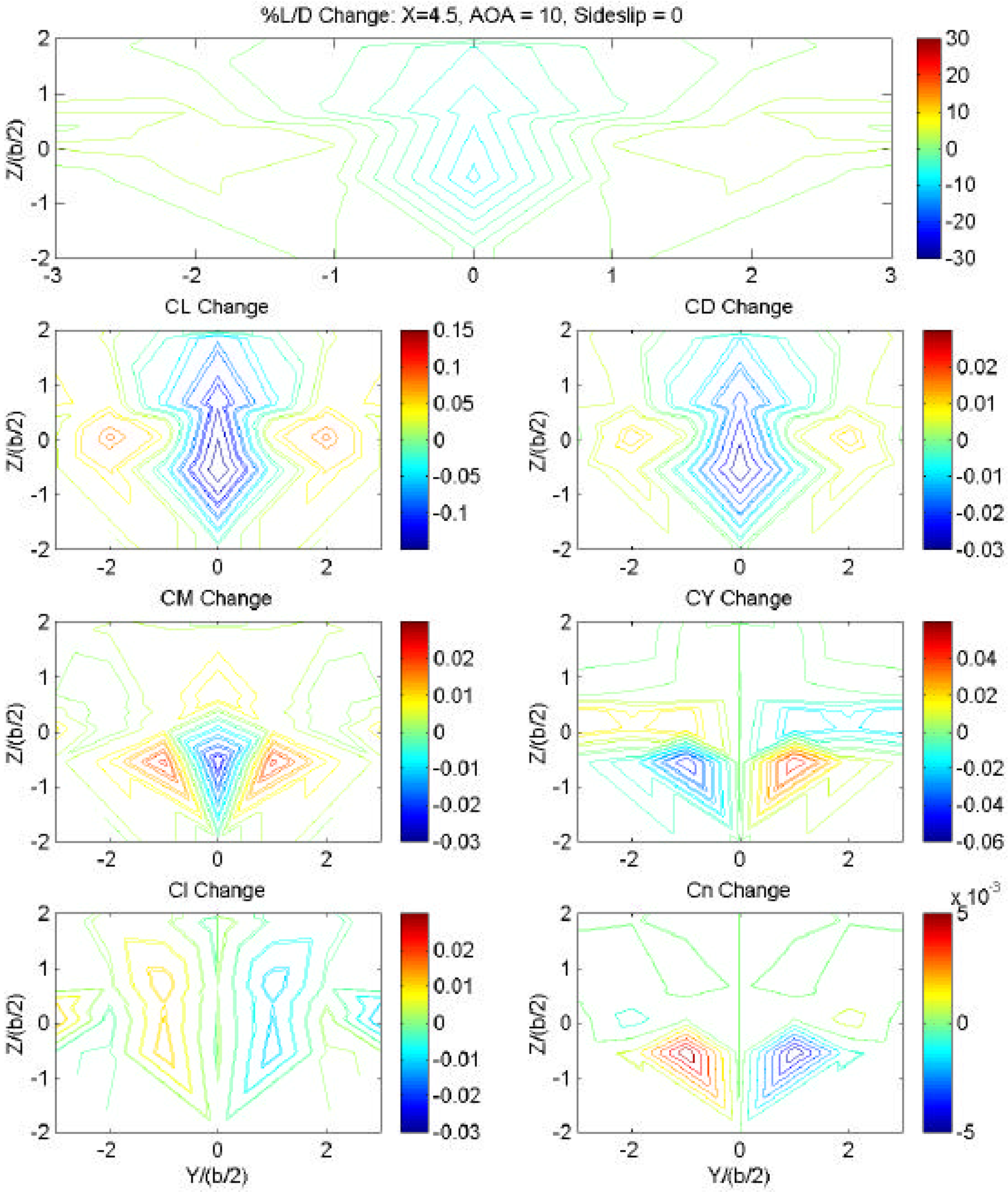

Figure 6. Aerodynamic effects on the test configuration at X position 4.5b/s, $\alpha = 10^o$ and $\beta = 0^o$ resulting from formation position.

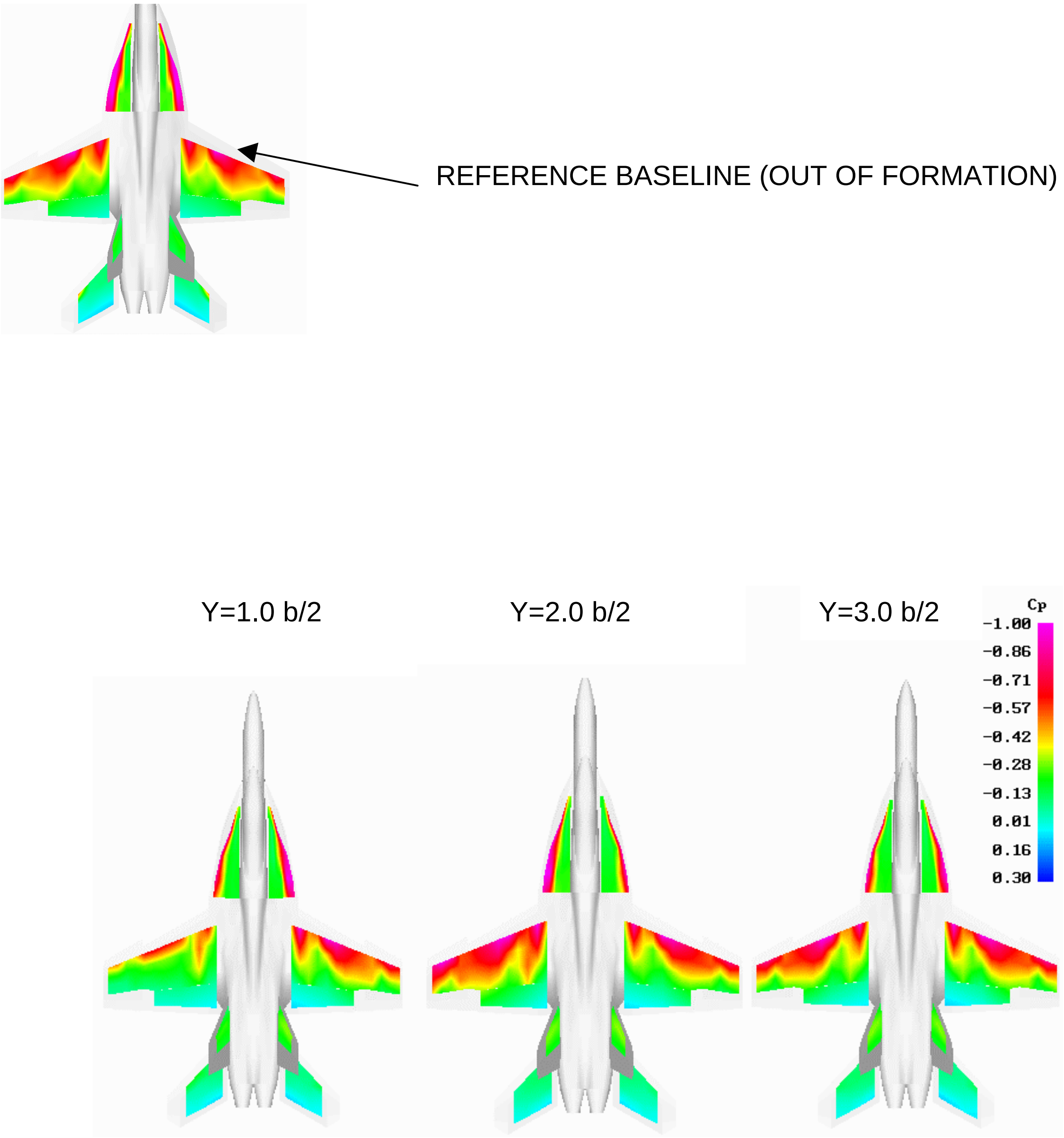

Figure 7. Top-surface pressure distribution of the test aircraft at $\alpha = 5^\circ$ and $\beta = 0^\circ$ for three span-wise formation positions.

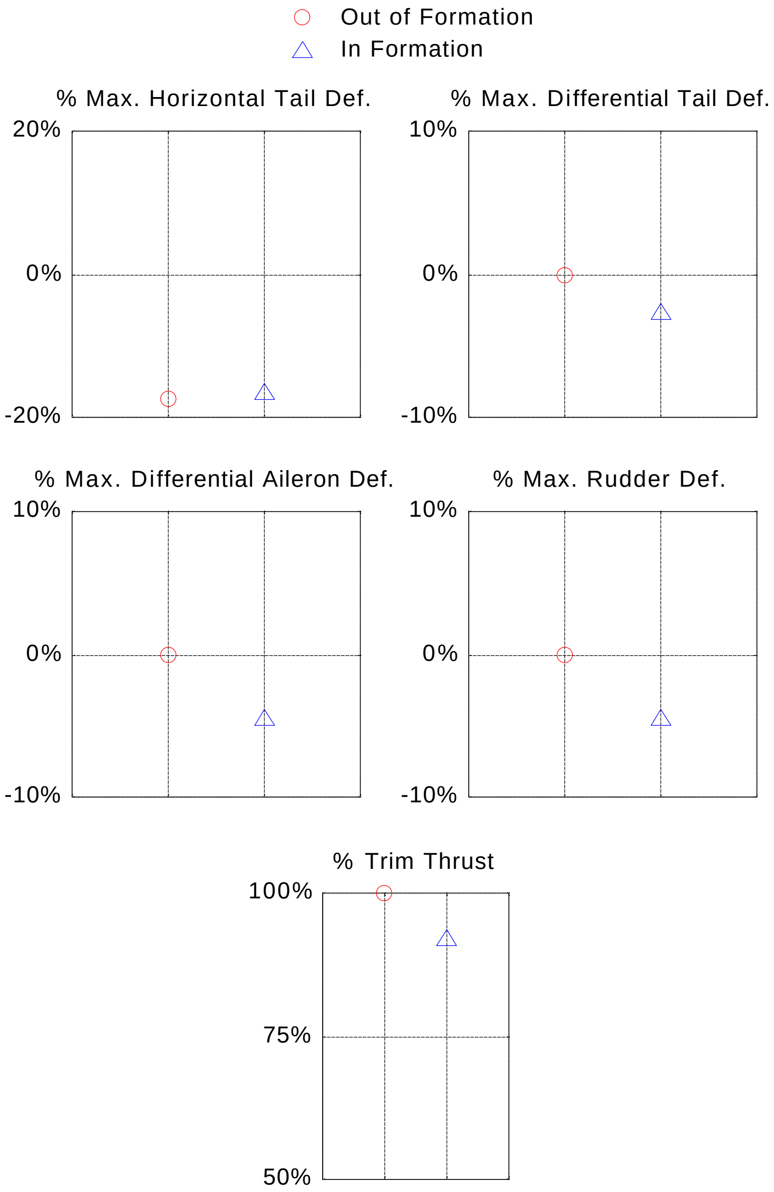

Figure 8. Trim control requirements for close formation flight.