AIAA Atmospheric Flight Mechanics Conference
13 - 16 August 2012, Minneapolis, Minnesota

AIAA 2012-4802

An Initial Flight Investigation of Formation Flight for Drag Reduction on the C-17 Aircraft

Joe Pahle[1] and Dave Berger[2]
NASA Dryden Flight Research Center, Edwards, CA, 93523

Mike Venti[3], Chris Duggan[4], Jim Faber[5], and Kyle Cardinal[6]
Tybrin Corporation, NASA Dryden Flight Research Center, Edwards, CA, 93523

Many theoretical and experimental studies have shown that aircraft flying in formation could experience significant reductions in fuel use compared to solo flight. To date, formation flight for aerodynamic benefit has not been thoroughly explored in flight for large transport-class vehicles. This paper summarizes flight data gathered during several two-ship, C-17 formation flights at a single flight condition of 275 knots, at 25,000 ft MSL. Stabilized test points were flown with the trail aircraft at 1,000 and 3,000 ft aft of the lead aircraft at selected cross track and vertical offset locations within the estimated area of influence of the vortex generated by the lead aircraft. Flight data recorded at test points within the vortex from the lead aircraft are compared to data recorded at tare flight-test points outside of the influence of the vortex. Since drag was not measured directly, reductions in fuel flow and thrust for level flight are used as a proxy for drag reduction. Estimated thrust and measured fuel flow reductions were documented at several trail test point locations within the area of influence of the lead's vortex. The maximum average fuel flow reduction was approximately 7-8%, compared to the tare points flown before and after the test points. Although incomplete, the data suggests that regions with fuel flow and thrust reduction greater than 10% compared to the tare test points exist within the vortex area of influence.

Nomenclature

AFF	=	autonomous formation flight
AWODS	=	advanced wireless open data system
F	=	engine thrust, lbf
FFS	=	formation flight system
HUD	=	heads up display
KCAS	=	knots calibrated airspeed
NASA	=	National Aeronautics and Space Administration
N2	=	engine core rotor speed, percent RPM
SKE	=	station keeping equipment
USAF	=	United States Air Force
V	=	velocity
w_f	=	fuel flow, pounds per hour
Y_{offset}	=	cross-track distance between vehicle fuselage centerlines, ft
Z_{offset}	=	vertical distance between vehicle fuselage waterlines, ft
δ_a	=	aileron deflection, deg
δ_s	=	spoiler deflection, deg

[1]Aerospace Engineer, Flight Controls and Dynamics Branch, P.O. Box 273, MS 4840, Senior AIAA Member.
[2]Aerospace Engineer, Aerodynamics and Propulsion Branch, P.O. Box 273, MS 4840, Senior AIAA Member.
[3]Senior Research Engineer, Propulsion Systems, P.O. Box 273, MS 115, AIAA Non-Member
[4]Student Intern, contact information currently unavailable, AIAA Non-Member.
[5]Aerospace Engineer, Aerodynamics and Propulsion Branch, P.O. Box 273, MS 4840 B, Senior AIAA Member.
[6]Student Intern, contact information currently unavailable, AIAA Non-Member.

I. Introduction

A significant body of research already exists discussing the aerodynamic benefits of formation flight (for example, Refs. 1-8). Many of these studies were inspired by observing geese, pelicans, cranes, and other birds that exploit the benefits of formations to accomplish extraordinary feats of endurance during migration. In 1970, Lissaman and Shollenberger showed that theoretically, individuals within a flock of 25 birds would have up to a 70% range increase over birds flying alone.[1] Hummel showed that the total flight power reduction of the formation depends strongly on the lateral separation between members of the formation.[2] King used ideally loaded wings to show that the optimum lateral separation corresponds to approximately a 10% span overlap of wing tips.[3] Weimerskirch et al reported experimental results that indicate great white pelicans flying in formation, had heart rates that were up to 14.5% lower than birds flying alone or in ground effect.[4] Although there are likely behavioral reasons for bird formations as well,[5-7] the energy reduction from aerodynamic benefit in formation flight has been shown theoretically and observed experimentally.

Theoretically, aircraft flying in formation benefit in a similar way as bird formations. Upwash created by the wingtip vortices of the lead aircraft results in a forward rotation of the lift vector on the trailing aircraft decreasing the total drag, and thus decreasing the power and fuel flow required for sustained flight of the trail aircraft.[9] At typical commercial transport aircraft utilization rates, a 1% reduction in drag may result in saving between 30,000 lb and 100,000 lb of fuel per year per aircraft depending on the size and type of aircraft.[10] Thus the benefit from even a small drag reduction can be significant. The potential drag reduction from formation flight is sizeable. Theoretical studies[11-13] estimate that formation flight could reduce the overall drag of the trail aircraft by 15-28%. In order to address one concern that formation flight might only be used in the cruise portion part of the flight regime, and that another aircraft must be present and in the optimal location to derive any benefit, several recent reports have looked at the application of formation flight to transport class vehicles in realistic operational scenarios. Nehrbass showed that formation flight and morphing wing technology could be used to make a point-to-point service more efficient than the existing hub and spoke system.[14] Bower et al examined the use of formation flight on cargo aircraft originating from different airports. For a two aircraft formation, the maximum fuel savings was approximately 10% with a wing-tip overlap of 10% span.[15] Ning examined “Extended” formation flight (aircraft separated longitudinally by more than 10 spans), and showed an induced drag reduction of 38-45% for several different three-ship formation geometries including uncertainties in relative position within the formation.[16]

In addition to theoretical results, several flight research programs in the last two decades have validated the predicted drag reduction and fuel savings benefit from formation flight. In 1995, Hummel documented a 15% power reduction for the trail aircraft of two Dornier (Dornier Technologie GmbH Co. & KG, Uhldingen-Mühlhofen, Germany) Do-28 aircraft.[9] An 18% fuel flow reduction was demonstrated in flight for two National Aeronautics and Space Administration (NASA) F/A-18 (McDonnell Douglas, now The Boeing Company, Chicago, Illinois) aircraft in cruise configuration.[17] An 8.8% fuel savings was shown for two T-38 (Northrop-Grumman Corporation, Los Angeles, California) aircraft with a lateral spacing of approximately 86% wingspan, while the results from a three-ship T-38 formation were inconclusive.[18]

Many aircraft currently fly in formation for a variety of reasons, yet rarely for aerodynamic benefit. Flying clubs, civil and military aerobatic demonstration teams, and massed military airdrops all make use of formations. There is some evidence that sailplane pilots use formation flight for aerodynamic benefit,[19] but the technique does not appear to be widespread.

A relevant application to the context of this investigation is the current use of formation flight avionics on air mobility aircraft. Speer described the development of formation flight technology (also called station-keeping equipment) applied to military cargo aircraft performing aerial delivery missions.[20] Station-keeping equipment (SKE) is used throughout the United States Air Force on most air mobility aircraft, allowing aircraft to fly in formation even during low visibility conditions. The C-17 (McDonnell Douglas, now The Boeing Company, Chicago, Illinois) has an advanced SKE capability, called the Formation Flight System (FFS), allowing formation flight of a large number of vehicles. Some researchers have proposed the use of military-style formations as a way to increase civilian airspace capacity and throughput.[21-22]

For at least the last four decades, the primary focus of understanding the wake vortex of transport vehicles has been to avoid, rather than exploit, the wake of a preceding aircraft.[23-26] To date, formation flight for transport-class aircraft has been largely unexplored experimentally, and challenges still remain in the understanding of the complex aerodynamic phenomenon of formation flight and how best to exploit the potential benefits.

To address some of these challenges, the purpose of this investigation was threefold:

1) gather qualitative flight data and pilot comments during formation flight of two C-17 aircraft, with the trail aircraft in the area of influence of the vortex from the lead aircraft,

2) assess the ability of the C-17 FFS and auto-flight system to stabilize at trail locations with predicted fuel flow and thrust reduction, and

3) assess the feasibility of using fuel flow and thrust measurement from the production C-17 instrumentation system with application to measuring the performance benefit of formation flight.

II. Test Vehicle Description

The United States Air Force (USAF) C-17 Globemaster III is a heavy, four-engine military transport manufactured by Boeing. Figure 1 shows a 3-view of the C-17 test aircraft.

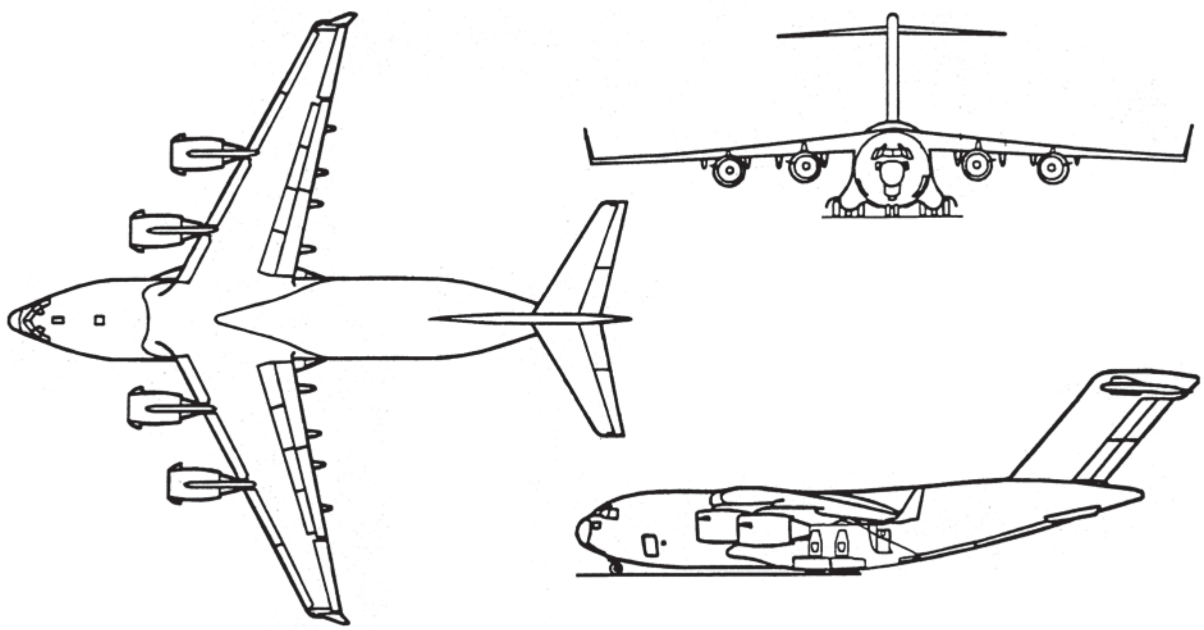

Figure 1. C-17 aircraft three view.

The C-17 aircraft is well suited for this investigation because it is a robust, four-engine transport-class aircraft already equipped with an advanced formation flight system. The engines on the C-17 aircraft are military versions of the Pratt & Whitney (East Hartford, Connecticut) PW2000 engine family. The PW2000 engine family is also used on the Boeing 757. The similarity of the C-17 engines to those used on commercial aircraft coupled with the technology level of the engine controller made this an ideal engine for this study.

In this investigation, the C-17 formation flight system was used to control the position of the aircraft for some of the test points, to calculate the relative position of the trail aircraft with respect to the lead, and to provide the relative position information to the pilot display. The two C-17 aircraft used in this study were production aircraft. All flights were flown in visible conditions. Because of the flight research nature of this investigation, the pilot of the trail aircraft was required to be a test pilot school graduate and current in formation-flight procedures. The bulk of the flight data shown in the paper was obtained through the production C-17 Advanced Wireless Open Data System (AWODS) recorded on board and processed post-flight.

III. Flight–Test Approach

In order to conduct this flight research, engineering staff from the Air Force Flight Test Center (Edwards Air Force Base, Edwards, California) assisted NASA in the safety assessment, test documentation, flight preparation, and conduct of the actual flight test. NASA engineering staff flew on board the C-17 aircraft for real-time data assessment and safety monitoring during the test. A laptop display with selected engine parameters, aileron and rudder deflections, and FFS parameters was developed by NASA in order to monitor the performance of the aircraft in real-time. The display is shown in Fig. 2. Using this research display, a NASA engineer aboard the trail aircraft was able to simultaneously observe the trail aircraft position relative to the lead, assess performance and stability of the engines, and monitor the primary lateral-directional flight control surface deflections.

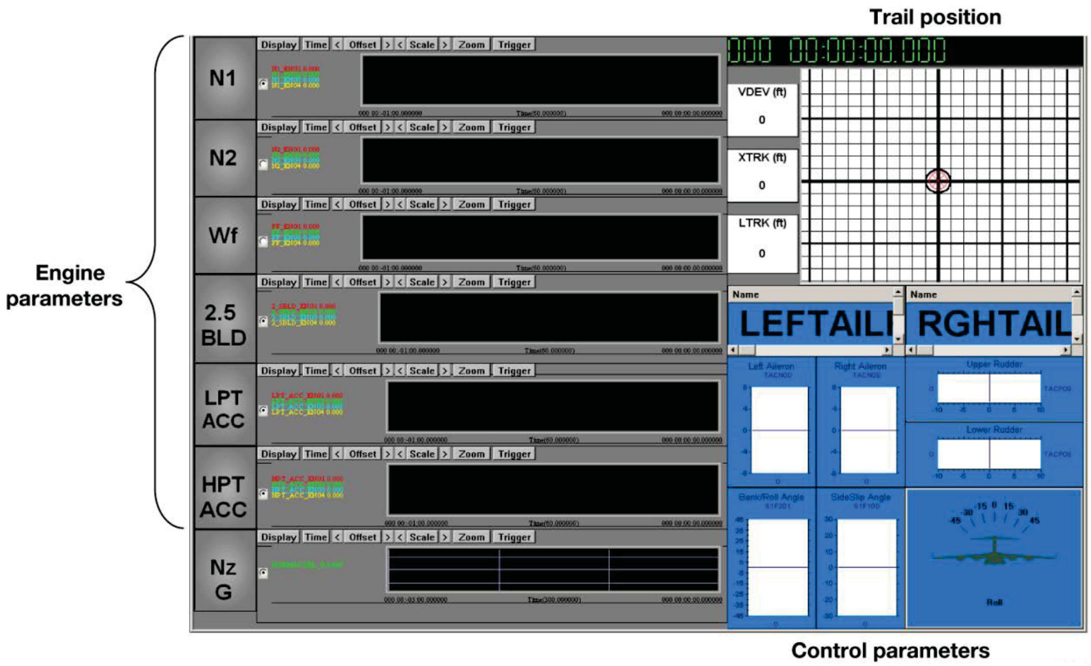

Figure 2. NASA formation flight real-time display.

Thrust was not available in real-time during the flight, but computed off-line using flight data to drive a high fidelity engine simulation. The simulation model was the steady state performance computer simulation for the F117-PW- 100 engine (Pratt & Whitney, East Hartford, Connecticut) used on the C-17 aircraft.[27]

All flight data was gathered at a single flight condition of 275 KCAS +/- 2 knots, and 25,000 ft MSL +/- 200 ft. Because flight within the wake was expected to be dynamic and the turbulence level was unknown, for safety reasons, the test condition was selected to be below the maximum gust penetration speed of the C-17 aircraft (280 KCAS).

In order to estimate the performance benefits from formation flight using the C-17, a similar (but simplified) flight-test approach to the NASA Autonomous Formation Flight (AFF) Program[28] was used. Stabilized test points outside of the vortex influence, referred to as tares, were flown before and after each horizontal or vertical test sequence. The tare flight conditions are representative of the trail aircraft flying solo. Research test points are shown in Table 1.

Table 1. Desired formation flight test point locations.

Test point	Long-track offset, ft	Cross-track offset, ft	Vertical offset, ft	Note
T1	3,000	400	200	5 minute dwell after stabilized
H1	3,000	240	0	3 minute dwell after stabilized
H2	3,000	220	0	3 minute dwell after stabilized
H3	3,000	200	0	3 minute dwell after stabilized
H4	3,000	180	0	3 minute dwell after stabilized
H5	3,000	160	0	3 minute dwell after stabilized
T2	3,000	400	200	5 minute dwell after stabilized
V1	3,000	180	20	3 minute dwell after stabilized
V2	3,000	180	-20	3 minute dwell after stabilized
V3	3,000	180	-40	3 minute dwell after stabilized
V4	3,000	180	-60	3 minute dwell after stabilized
T3	3,000	400	200	5 minute dwell after stabilized

Figure 3 shows the test point matrix for the trail on the left side of the lead, looking forward from behind both aircraft. In Fig. 3, the trail aircraft is shown at test point V4, with the fuselage centerline of the trail aircraft offset to the left of the lead aircraft by 180 ft, and the wingtip of the trail aircraft 60 ft below the wingtip of the lead aircraft.

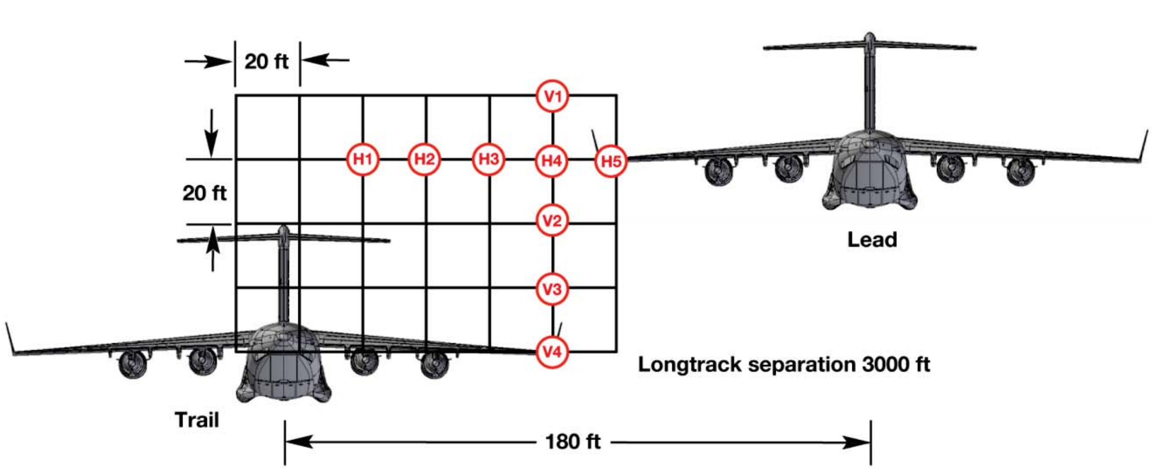

Figure 3. Formation flight test point matrix. Trail shown at test point V4 on left side.

Figure 4 shows the sign convention for the vertical, cross-track, and long-track separation between the two aircraft used throughout the paper. A trail aircraft flying above, to the left side, and aft of a lead aircraft would have positive vertical offset, positive cross-track offset, and negative long-track offset. Also shown in Fig. 4 is an example upwash velocity profile[29] as a function of distance from the two primary vortex cores produced by the lead aircraft.

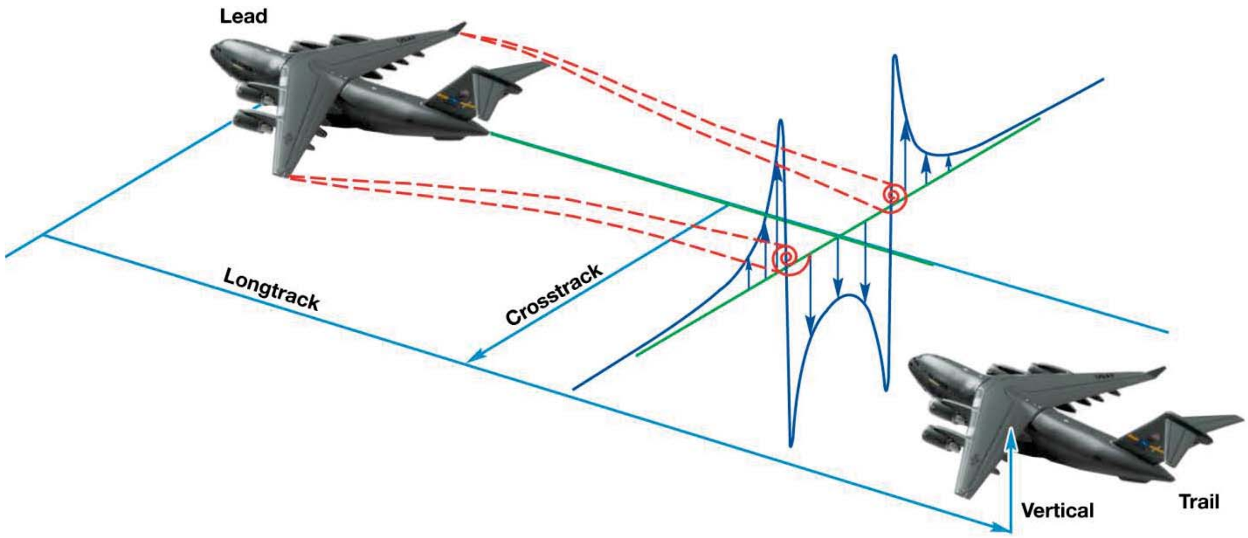

Figure 4. Long-track, cross-track, and vertical separation between two aircraft.

To begin the test sequence, the first tare point (T1) was flown at the same desired long-track position as the rest of the test points. All three tare test points (T1-T3) were flown at essentially the same long-track, vertical, and cross-track offset from the lead aircraft on either side of the lead aircraft. The duration for each tare test point was 5 min after the desired flight conditions were stabilized. Because of the large long-track separation between the two aircraft, pilots had to rely on the FFS displays, and verbal cues from the engineer monitoring the research display (Fig. 2) for precise relative position control. After completing the initial tare point, a horizontal step-wise profile (H1-H5) was flown with desired cross-track position shown in Fig. 3 at the same altitude as the lead aircraft. Desired cross-track test points were spaced every 20 ft. A 3 min duration was used for each of the test points flown within the vortex area of influence. After the horizontal sequence (H1-H5) was completed, another tare point (T2) was flown. If the pilot saw no safety issues with all the test points in the horizontal sequence, then a vertical step-wise profile (V1-V4) was flown at the same cross-track location as H4 (approximately +/-180 ft cross-track fuselage center-to-center). If the pilot did not like any of the horizontal test points during the build-up sequence, or if flight-test data indicated a safety issue, then the vertical profile was flown at the cross track at which the last “good” horizontal test point was flown.

Although automatic control of position using the C-17 FFS was desired, much of the flight data was manually flown. The pilot typically flew in “split-axis” mode with the long-track altitude and airspeed controlled by the C-17 auto-flight systems, while the pilot concentrated on controlling the lateral position minimizing the cross-track error from the desired position displayed in the C-17 heads-up display (HUD).

Stabilizing at test points for 3 min within the vortex area of influence using the existing FFS pilot displays did not consistently yield sufficient steady-state data for detailed comparative analysis between test points. Because of this, a “steady-state” criteria was developed to select data from each test point. The criteria were designed to be a combination of flight condition, trail test point position offset rate, flight control activity, and engine parameters all satisfied for a period of at least 10 s. The criteria is shown in Eq. (1). The summations shown in the engine criteria indicate that the parameters were included from all four engines (i=1 through 4). Figure 5 shows an example of the criteria applied to flight data from test point V2 (trail on left of lead) from flight 3. The figure shows that a large portion of the entire test point meets the criteria, but flight data where the aileron rate or fuel flow rate is large is not included in the subsequent steady-state data computations.

$$\text{Flight condition: } (273\ \text{KCAS} < V < 277\ \text{KCAS}) \text{ and } \left(|\dot{V}| < 4\ \frac{\text{knots}}{\text{s}}\right)$$

$$\text{Test point: } \left(|\dot{Z}_{\text{offset}}| < 4\frac{\text{ft}}{\text{s}}\right) \text{ and } \left(|\dot{Y}_{\text{offset}}| < 4\frac{\text{ft}}{\text{s}}\right)$$

$$\text{Control surface activity: } (|\delta_a| < 16\ \text{deg}) \text{ and } \left(|\dot{\delta}_a| < 10\ \frac{\text{deg}}{\text{s}}\right) \text{ and } (|\delta_s| < 2\ \text{deg})$$

$$\text{Engine: } \left(\left|\sum_{i=1}^{4} \dot{N}2_i\right| < 2\ \frac{\%}{\text{s}}\right) \text{ and } \left(\left|\sum_{i=1}^{4} \dot{F}_i\right| < 400\frac{\text{lb}}{\text{s}}\right) \text{ and } \left(\left|\sum_{i=1}^{4} \dot{w}_{f_i}\right| < 200\frac{\text{pph}}{\text{s}}\right) \tag{1}$$

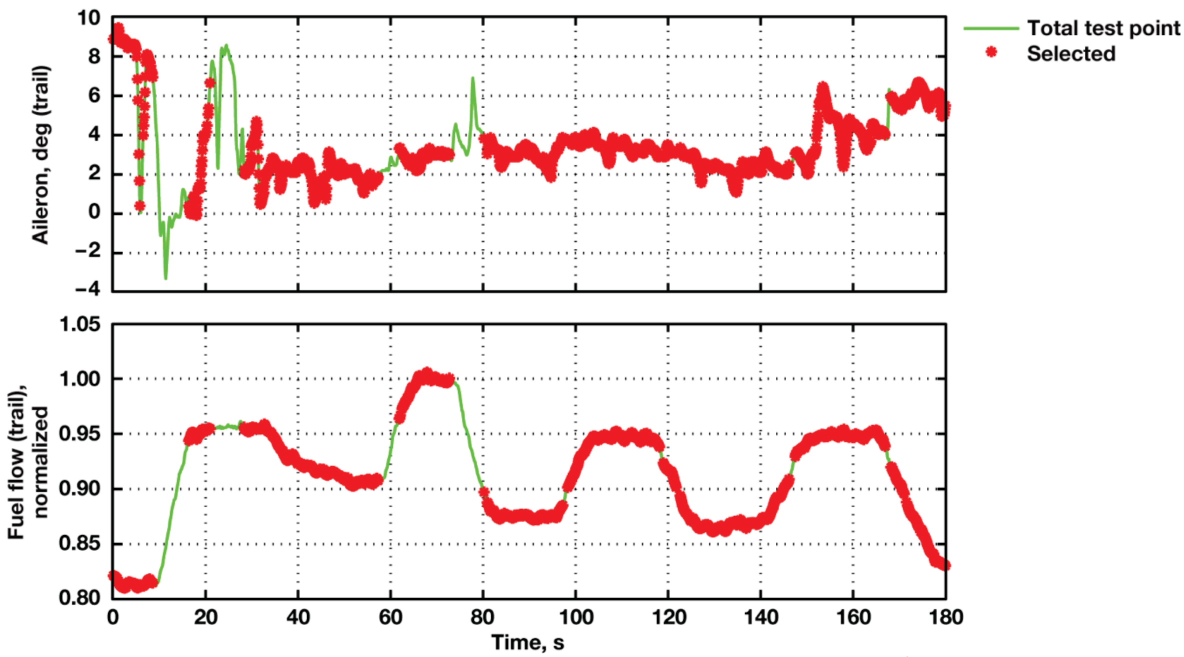

Figure 5. Steady state criteria applied to test point V2 on left side for flight 3.

IV. Results and Discussion

The test point sequence shown in Fig. 3 was attempted on three flights during cross country deployments of the C-17 test team from Edwards, California to Charleston, South Carolina. The first two flights were used to develop and mature the flight-test techniques, and validate that the proper data signals were available from the AWODS. Lessons learned from the first two flights were incorporated into the test matrix for the third flight. The first two flights were flown with a long-track separation of 1,000 ft, while the third flight was flown with a long track separation of 3,000 ft. Tares on flight three were flown farther away (larger vertical and lateral offset) from the estimated vortex location than on the first two flights, and the tare dwell time was increased from 3 min to 5 min. An additional tare (T2) was included in between the horizontal and the vertical sequence. Because of these changes, and the experience gained by the test team in the previous flights, all test points were safely and successfully completed on both sides of the lead C-17 aircraft during the third flight.

The remainder of the paper will focus on data analysis and results from the third flight. All test points were obtained in a test block at a single flight condition: 275 KCAS +/- 2 knots, and a pressure altitude of 25,000 ft +/- 200 ft.

The research test block took approximately 2.6 hr during the cross-country flight. The test block started with the trail aircraft to the left of the lead aircraft (positive cross track), and then proceeded to the right side. All test points and tares were flown with a target long-track separation of 3,000 ft +/- 200 ft aft of the lead. Because of the experience the test team gained during the first two flights and the initial test points conducted on the left side, the test point sequence with the trail to the right side of the lead was accomplished in about 70% of the time it took on the left side.

All fuel flow and thrust data shown in this paper are normalized by the maximum mean fuel flow and thrust required during the entire research test block for both the lead and trail aircraft. Flight dynamics experienced by the trail aircraft at the tare flight conditions differed significantly from the test points within the area of influence of the vortex from the lead aircraft. Figure 6 shows a comparison of the horizontal test point with a target cross track of 160 ft (H5) with the trail on the left side, and the tare (T2) flown immediately afterwards. Because of the close proximity in both location and time, vehicle weight and general atmospheric conditions are assumed to be nearly identical for these two test points. From the figure it can be seen that both H5 and T2 are flown within the same airspeed band (275 KCAS +/- 2 knots), but the total aileron deflection (left–right) indicates the two test points clearly represent different local atmospheric conditions. At test point T2, the vehicle requires almost no aileron trim to maintain wings level flight, while the same vehicle requires an average of approximately 7 +/- 3 deg to remain wings level during H5. The aileron required to remain wings level at H5 is opposing a left wing down rolling moment, consistent with the hypothesis that the right wing is in the upwash region of the vortex from the lead. Also shown on this plot are the mean (data symbol *) and standard deviation (error bars) of all of the data that met the steady-state criteria (Eq. (1), described previously) for both test points. The normalized total fuel flow during T2 is fairly steady with a low frequency oscillation evident during the 5 min tare point. The normalized fuel flow for test point H5 is much more oscillatory during the 3 minute test point. This is in part due to the fact that the trail aircraft is not stationary at H5, but is moving about the test point location in a region where the upwash gradient from the vortex is assumed to be high. Although much more oscillatory, even the maximum peaks of the fuel flow during H5 are generally less than the average fuel flow during T2, with almost all of the fuel flow at H5 significantly less than the fuel flow at T2.

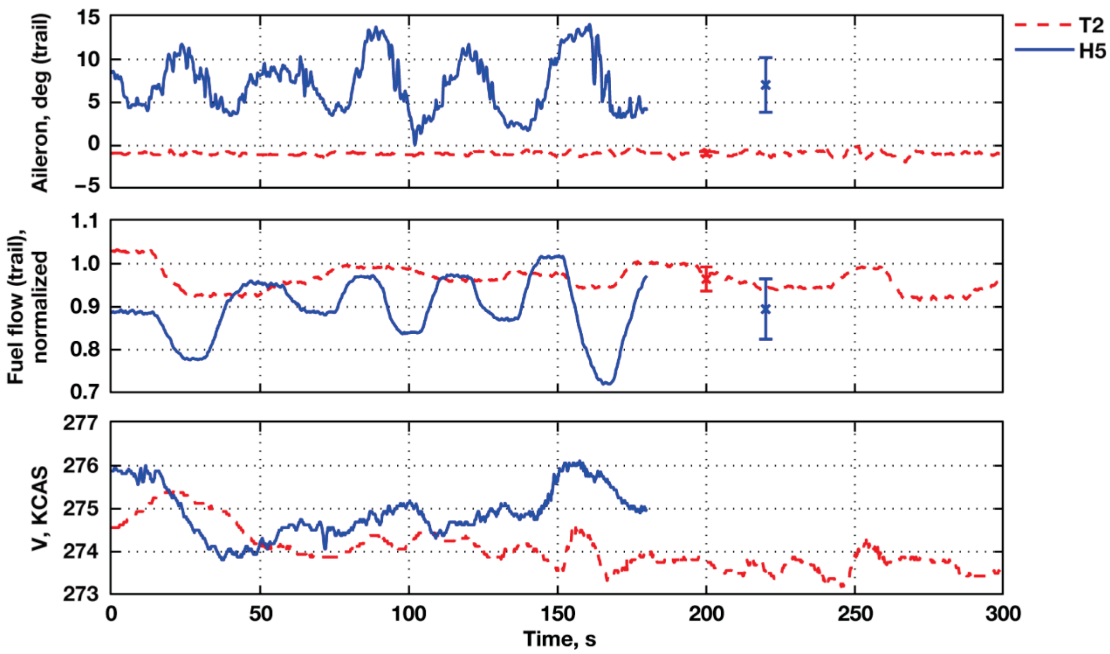

Figure 6. Comparison of test point H5 with tare T2. Mean is shown as an asterisk, and standard deviation as the error bars about the mean.

Applying similar analysis across all the test points, Fig. 7 shows a summary of the mean and standard deviation for the aileron, normalized total thrust, and normalized total fuel flow for all the test points. Also shown in the figure is a linear fit of the mean total fuel flow (green line) computed as a function of total vehicle weight (trail aircraft) averaged over each test point. In this figure, the flight data is organized by test point, shown along the x-axis. Normalized total fuel flow and normalized total thrust show nearly identical trends across all of the test points. This is an important confirmation of the results, since total fuel flow is a measured quantity, while total thrust is estimated from engine parameters that do not include fuel flow. Thus, total thrust is a completely independent measure from total fuel flow. Additionally, aileron deflection shows a related trend in that increased mean aileron is required for those test points with increasingly greater reductions in fuel flow and thrust. The test points with larger fuel flow and thrust reductions also tend to have a larger standard deviation. Most of this is due to the oscillatory nature of the test points, as shown previously in Fig. 6. The increased standard deviation is likely a result of the dynamic environment within the area of vortex influence, and the difficult manual piloting task of maintaining tight position control using the existing FFS displays.

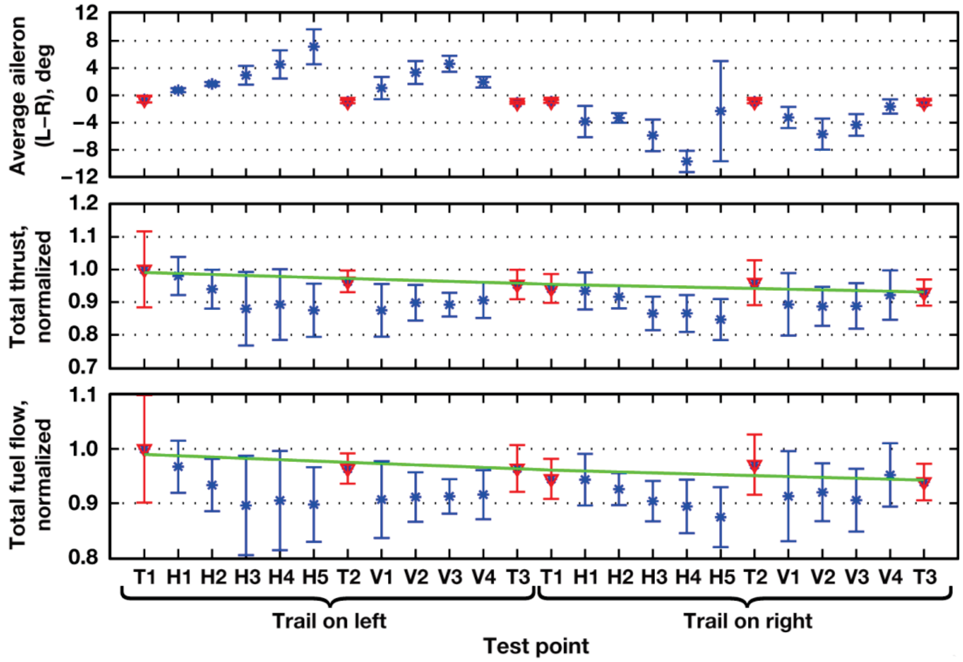

Figure 7. Mean and standard deviation for aileron, thrust, and fuel flow for all test points. Tares are shown as red diamonds, test points as blue asterisks, and the linear fit of the tares as a green solid line.

One significant outlier from the other aileron deflection data shown in Fig. 7 is test point H5 on the right side. Looking closer at the data, the test point was flown significantly more inboard than the desired cross-track location, and actually required control surface commands that appeared at times similar to the test points flown on the left side. Pilot comments also indicated that this was the most difficult point to fly overall. Under pilot control, spoilers are only used when large roll moments are commanded. H5 on the right side had the largest spoiler commands of any of the test points flown on either side. One possible explanation for the large spoiler commands is that this test point was flown too far into the vortex structure, with the left wing in an area of downwash.

In order to reduce the uncertainty introduced by variations in test condition and aircraft weight as the cross-country flight progressed, and to compare results with a nearly identical aircraft not flying in the wake of another aircraft, similar measurements were made on the lead aircraft using the same data sources and analysis techniques applied to the trail aircraft. Figure 8 shows the mean and standard deviation of total fuel flow for both the trail and lead aircraft during all of the test points flown on flight 3. As in Fig. 7, the flight data is organized by test point (blue asterisks), tare points are shown as red diamonds, and a linear fit of the mean total fuel flow computed as a function of total vehicle weight is shown in green. Fuel flow reduction for the trail vehicle from the tares can be seen in the bottom plot of Fig. 8 for 17 of the 18 test points flown in the area of influence of the vortex.

The top plot of Fig. 8 shows normalized total fuel flow from the lead aircraft during the same time segments that correspond to the test points flown by the trail aircraft. All fuel flow and thrust data for both the lead and trail aircraft are normalized by the mean of the results from the trail aircraft during test point T1. Because the lead aircraft began the test block approximately 5% lighter than the trail aircraft, the normalized fuel flow for the lead aircraft was less than the normalized fuel flow for the trail aircraft. As expected, the normalized total fuel flow results for the lead aircraft at all the test points generally follow the linear fit of the tare results, since the lead vehicle is essentially flying the tare point continuously. The average tare data varies from the linear fit of all the tare data by 1-2% for both fuel flow and estimated thrust. Because of the consistent results from the tare test points from both the lead and trail aircraft, the production fuel flow measurement and the estimated thrust (driven from parameters obtained from the C-17 instrumentation system) were judged to be of sufficient data quality for this comparative investigation.

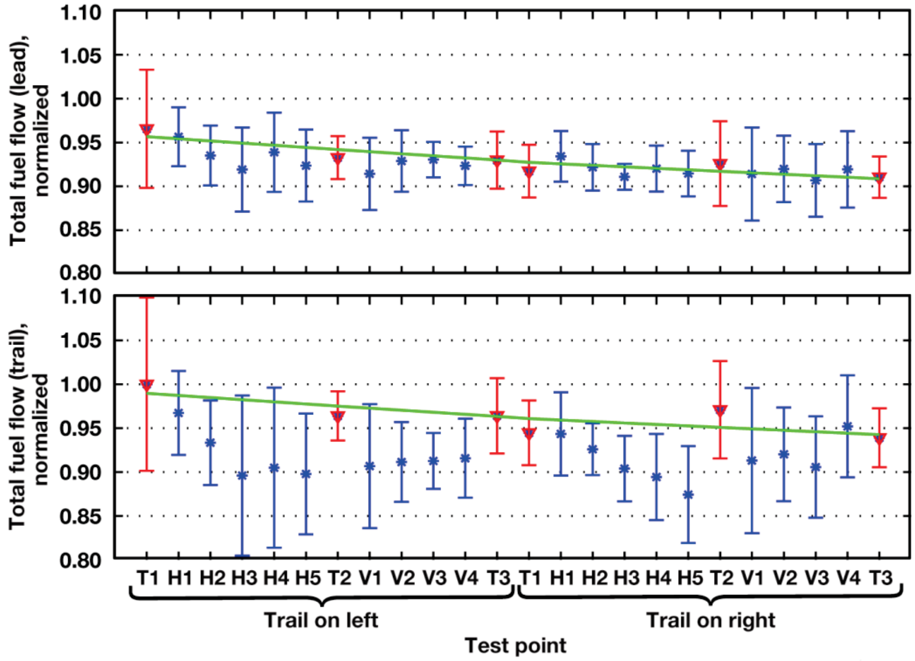

Figure 8. Comparison of fuel flow for lead and trail aircraft at all test points. Tares are shown as red diamonds, test points as blue asterisks, and the linear fit of the tares as a green solid line.

From Fig. 8, there appears to be a bias showing a fuel flow reduction from the tare conditions for the lead vehicle, particularly in the horizontal sequence (H2-H5) and part of the vertical sequence (V1-V2) on the left side. This may be due to variations in the test conditions between the tares and the test points, since the effect appears in results from both the lead and trail aircraft. In order to minimize any effect that would bias both the lead and trail aircraft from the tare results, the percentage change from the linear fit of the tares for the lead aircraft fuel flow and thrust results were subtracted from the trail results as shown in Eq. (2) and suggested by previous authors.[28]

$$\%\Delta w_{f\,\mathrm{corrected}} = \%\Delta w_{f\,\mathrm{trail}} - \%\Delta w_{f\,\mathrm{lead}} \tag{2}$$

Figure 9 shows the percent change in total fuel flow and total estimated thrust of the trail aircraft as compared to the tare conditions, corrected for the percent variations from the tare in the corresponding parameters for the lead vehicle. The results for the horizontal sequence (H1-H5) on both the left and right side show a nearly linear trend in performance benefit (fuel flow and thrust reduction) as the desired cross-track separation decreases from 240 ft (H1) to 160 ft (H5). The maximum average fuel flow reduction was 6.8% (H4) on the left side and 7.8% (H5) on the right. The vertical sequence (V1-V4) did not appear to indicate a clear linear trend in fuel flow or thrust reduction with vertical position on either side. The maximum corrected fuel flow reductions for the vertical sequences were 5.3% and 3.7% for the left and right sides respectively. The average thrust reduction shows very similar trends to the average fuel flow reduction for the horizontal and vertical sequences, but biased by several percentage points. The maximum average thrust reduction was 9.2% (H5) on both the left and right sides. The average tare data varies from the linear fit of all the tare data by approximately one percent for both fuel flow and estimated thrust.

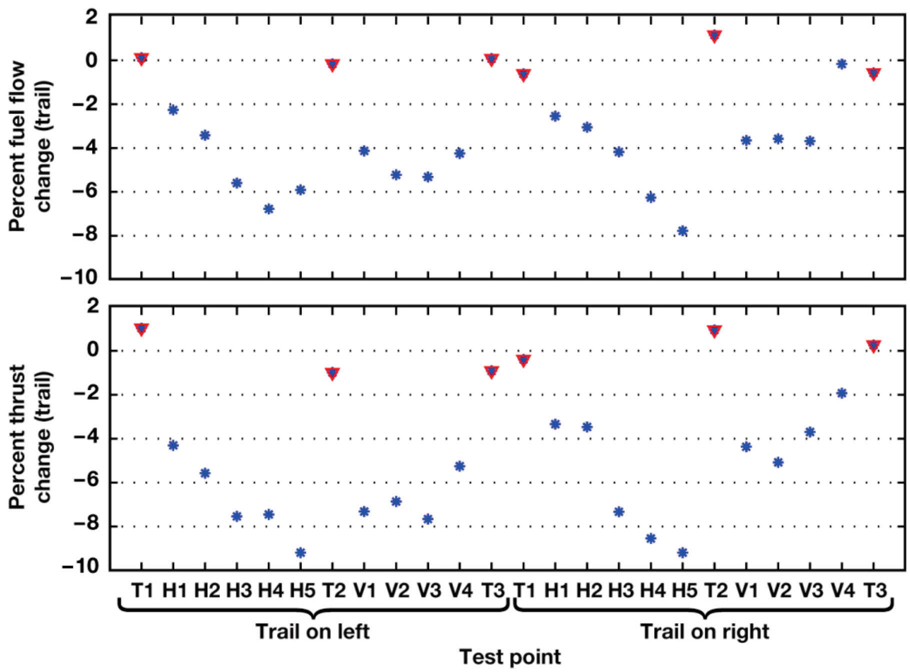

Figure 9. Percent reduction in total fuel flow and thrust (corrected for lead). Tares are shown as red diamonds, and test points as blue asterisks.

The test points were originally intended to be flown by the auto-flight systems, thus a formal pilot questionnaire was not developed for the test plan. Additionally, the pilot and crew were refining the test technique as the flight progressed. The pilot was able to consistently fly the FFS test points, but the workload was high and the task was judged as "not operationally representative" for the C-17 aircraft. However, limited pilot and crew comments were obtained from the flight cards and engineering notes taken during the flight. In general, piloting difficulty and turbulence noted by the crew appeared to increase during the test sequence as the cross-track separation decreased, that is, as the trail aircraft got closer to the estimated position of the vortex core. Unfortunately, there were no contrails, and no visible indication or other measurement of the vortex core location was available to validate this general observation.

After completing the horizontal sequence on the left side (H1-H5), the pilot noted that the concentration required was "similar to aerial refueling, but somewhat easier" because it was not "all three axes." The pilot also noted that test points conducted on the right side were "more difficult to maintain (position) than on the left." Crew comments ranged from "smooth ride, only 1.1 deg aileron" during V1 on the left side, to "ride seems very unsteady" during H5 on the right side. The flight-test engineer noted that during H4 on the left side, the "pilot was holding steady right stick (2-3 lb), no rudder." During that same test point (H4, left side) the FTE noted that there was "slight buffeting," that increased to "rougher ride quality – buffeting" during H5 on the left side.

Predicting the maximum benefit location, or "sweet spot" for the trail aircraft was significantly hampered by the lack of knowledge regarding the actual location, size, and velocity profile of the wake vortex. Additionally, the pilots were unable to maintain the very precise location desired for the entire duration of the test point. In order to determine if the location of the minimum fuel flow or "sweet spot" could be determined from the existing data, the data was organized by trail location rather than by test point as previously shown. All flight data that met the steady-state criteria was organized by actual test location, and then "binned" together into 5 ft by 5 ft blocks and averaged across the block. Figure 10 shows the mean percentage change from the tares for both fuel flow and thrust plotted as a function of cross-track and vertical offset from the lead aircraft. The percentage change from the linear fit of the tare for the trail aircraft has been corrected for the lead as described previously. Only blocks that contained a total composite of more than 10 s of steady state data are shown. The performance maps are obviously incomplete, but the data indicates that regions may exist within the vortex area of influence where the mean fuel flow benefit to the trail exceeds 10% compared to flying solo.

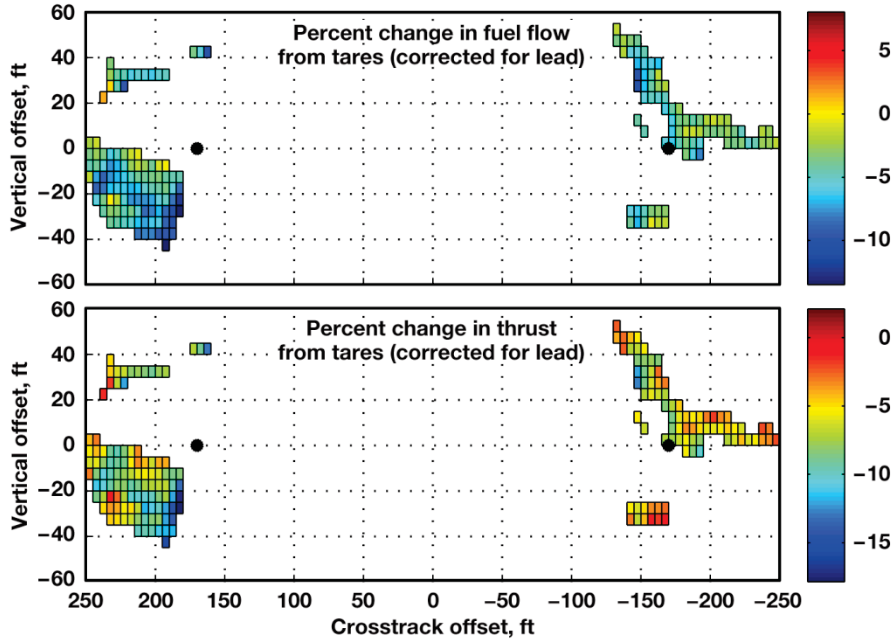

Figure 10. Percent reduction in total fuel flow and thrust as a function of the trail aircraft vertical and cross track offset position. Location for co-altitude wingtips aligned, on either side of the aircraft is shown as a black asterisk.

V. Summary

Flight data were gathered during several two-ship, C-17 formation flights at a single flight condition (275 knots, 25,000 ft). Stabilized test points were flown with the trail aircraft at 1,000 and 3,000 feet aft of the lead aircraft at selected cross-track and vertical offset locations within the estimated area of influence of the vortex generated by the lead aircraft. Most of the flight data was obtained with the pilot controlling the lateral axis and the autoflight systems controlling the remaining axes. The pilots were able to fly the formation test points, but the workload was high and the task was not operationally representative. Production fuel flow and inputs to an estimated thrust measurement from the C-17 instrumentation system were of sufficient data quality for this initial experiment.

Estimated thrust and fuel flow reductions were documented at most trail test point locations within the estimated area of influence of the lead's wingtip vortex. The maximum average fuel flow reduction was 6.8% to 7.8% (left and right side respectively), compared to the tare test points. The maximum average thrust reduction was 9.2% on both the left and right sides. Although quite incomplete, the data suggests that regions with fuel flow and thrust reduction greater than 10% compared to the tare test points exist within the vortex area of influence.

Acknowledgments

The authors would like to thank the 418th Flight Test Squadron (Edwards Air Force Base, California), and the C-17 Test and Integration IPT (Wright Patterson Air Force Base, Ohio) for their partnership and support.

References

[1]Lissaman, P. B. S., and Shollenberger, C. A., "Formation Flight of Birds," *Science*, Vol. 168, 22 May 1970, pp. 1003-1005.

[2]Hummel, D., "Aerodynamic Aspects of Formation Flight in Birds," *Journal of Theoretical Biology*, Vol. 104, 1983, pp. 321-347.

[3]King, R. M., and Gopalarathnam, A., "Ideal Aerodynamics of Ground Effect and Formation Flight," *AIAA Journal of Aircraft*, Vol. 42, No. 5 September-October 2005.

[4]Weimerskirch, H., Martin, J., Clerquin, Y., Alexandre, P., and Jiraskova, S., "Energy Saving in Formation Flight," *Nature*, Vol. 413, 18 October, 2001, pp. 697-698.

[5]Badgerow, J. P., "An Analysis of Function in the Formation Flight of Canadian Geese," *The Auk*, Vol. 105, October 1988, pp. 749-755.

[6]Hainsworth, F. R., "Induced Drag Savings From Ground Effect and Formation Flight in Brown Pelicans," *Journal of Experimental Biology*, Vol. 135, 1988, pp. 431-444.

[7]Cutts, C. J., and Speakman, J. R., "Energy Savings in Formation Flight of Pink-Footed Geese," *Journal of Experimental Biology*, Vol. 189, 1994, pp. 251-261.

[8]Hummel, D., "Formation Flight as an Energy-Saving Mechanism," *Israel Journal of Zoology*, Vol. 41, 1995, pp. 261-278.

[9]Hummel, D., "The Use of Aircraft Wakes to Achieve Power Reductions in Formation Flight," *Proceedings of the 1996 AGARD FDP Symposium on The Characterisation & Modification of Wakes from Lifting Vehicles in Fluid*, AGARD CP-584, Paper No. 36, Trondheim, Norway, 20-23 May 1996, pp. 1-13.

[10]Anderson, D., "Fuel Conservation - Airframe Maintenance for Environmental Performance," *Proceedings of the ICAO/Transport Canada Workshop on Aviation Operational Measures for Fuel and Emissions Reductions*, Presentation No. 6, Montreal, Canada, 20-21 Sept. 2006, [on-line presentation] URL: http://www.icao.int/icao/en/atb/ATBworkshops/2006/workshopfuelemissions/presentations.htm [cited on 19 May, 2011].

[11]Nangia, R. K., and Palmer, M. E., "Formation Flying of Commercial Aircraft, Variations in Relative Size / Spacing – Induced Effects & Control," AIAA 2007-4163, *25th AIAA Applied Aerodynamics Conference*, Miami, Florida, 25-28 June, 2007.

[12]Wagner, G., Jacques, D., Blake, B., and Pachter, M., "An Analytical Study of Drag Reduction in Tight Formation Flight," AIAA 2001-4075, *AIAA Atmospheric Flight Mechanics Conference*, Montreal, Quebec, August 2001.

[13]Blake, W., and Multhopp, D., "Design, Performance and Modeling Considerations for Close Formation Flight," AIAA-98-4343, 1998.

[14]Nehrbass, J. G., Frommer, J. B., Garison, L. A., Loffing, D. N., and Crossley, W. A., "Point to Point Commercial Aircraft Service Design Study Including Formation Flight and Morphing," AIAA 2004-6404, *AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum*, Chicago, Illinois, 20-22 September 2004.

[15]Bower, G. C., Flanzer, T. C., and Kroo, I. M., "Formation Geometries and Route Optimization for Commercial Formation Flight," AIAA 2009-3615, *27th AIAA Applied Aerodynamics Conference*, San Antonio, Texas, 22-25 June 2009.

[16]Ning, S. A., Flanzer, T. C., and Kroo, I., M., "Aerodynamic Performance of Extended Formation Flight," AIAA 2010-1240, *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, Orlando, Florida, 4-7 January 2010.

[17]Vachon, M. J., Ray, R. J., Walsh, K. R., and Ennix, K., "F/A-18 Aircraft Performance Benefits Measured During the Autonomous Formation Flight Project," AIAA 2002-4491, *Proceedings of the AIAA Flight Mechanics Conference and Exhibit*, August 5-8, 2002.

[18]Wagner, Maj. G., Jacques, Lt. Col. D., Blake, W., and Pachter, M., "Flight Test Results of Close Formation Flight for Fuel Savings," AIAA 2002-4490, *Proceedings of the AIAA Flight Mechanics Conference and Exhibit*, 5-8 August 2002.

[19]Reichmann, H., "Cross-Country Soaring," *Soaring Society of America Inc.*, Hobbs, New Mexico, 7th edition 2005.

[20]Speer, T. K., Mills, E. C., and Tate, J. L., "Formation Flight Technology," AIAA-1970-1337, *AIAA 7th Annual Meeting and Technology Display*, Houston, Texas, 19-22 October 1970.

[21]Jenkinson, L. R., Caves, R. E., and Rhodes, D. P., "Automatic Formation Flight–A Preliminary Investigation Into the Application to Civil Operations," AIAA 95-3898, *AIAA Aircraft Engineering, Technology, and Operations Congress*, Los Angeles, California, 19-21 September 1995.

[22]Haissig, C. M., "Military Formation Flight as a Model for Increased Capacity in Civilian Airspace," *IEEE Xplore 23rd Digital Avionics Systems Conference*, 24-28 October 2004.

[23]Federal Aviation Administration, "Vortex Wake Turbulence, Flight Tests Conducted During 1970," FAA-FS-71-1, AD724589, February 1971.

[24]Committee to Conduct an Independent Assessment of the Nation's Wake Turbulence Research and Development Program, "Wake Turbulence: An Obstacle to Increased Air Traffic Capacity," National Academies Press, Washington D.C., 2008.

[25]Rossow V. J., and Tinling B. E., "Research on Aircraft Vortex-Wake Interactions to Determine Acceptable Levels of Wake Intensity," *AIAA Journal of Aircraft*, Vol. 25, No. 4, 1988, pp. 481-492.

[26]Luckner, R., "Overview on Research in Wake Vortex Encounter Flight Tests and Flight Simulations," Wakenet2-Europe, 12 July 2004, [on-line draft] URL: http://www-mip.onera.fr/projects/WakeNet2-Europe/wg5/public/Wakenet2_WG5_Literature-Overview_v1d4.doc [cited on 19 May, 2011].

[27]*User's Manual For Steady State Performance Customer Computer Deck (CCD) D0652-15.1 F117-PW-100 C-17 DO-1 Post Flight Status Simulation*, 15 Sept. 1994, (available only from United Technologies, Pratt & Whitney, East Hartford, Connecticut).

[28]Ray, R. J., Cobleigh, B. R., Vachon, J. M., and St. John, C., "Flight Test Techniques Used to Evaluate Performance Benefits During Formation Flight," NASA/TP-2002-210730, August 2002.

[29]Burnham, D. C., and Hallock, J. N., "Chicago Monostatic Acoustic Vortex Sensing System, Volume IV: Wake Vortex Decay," DOT/FAA/RD-79-103, Vol. IV, July 1982, pp. 2-3.