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Development of the C-17 Formation Airdrop Element Geometry

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The analysis and tests that established a three-ship C-17 element geometry suitable for formation airdrop operations at night are discussed. The objective is to avoid jumpers encountering vortices generated by aircraft upstream. Candidate formation geometries were judged using a vortex tracking code that estimated the closest lateral proximity between a vortex and a jumper for a given wind condition. The initial formation geometry underwent two changes during the course of the test as a result of the introduction of tolerance boxes for aircraft position and vortex encounters that occurred during mannequin trials. An echelon geometry 6000 ft long and 1500 ft wide was ultimately adopted. In 101 passes over the drop zone, 1349 mannequins and 1251 personnel were dropped from this formation geometry without a vortex encounter.

Nomenclature

b = wingspan
C_D = parachute drag coefficient
k = vortex strength reduction factor
r = radial distance from vortex core
r_c = vortex core radius
t_d = vortex decay time
t_l = parachute opening time
V = aircraft velocity, ft/s
V_C = crosswind, ft/s
V_θ = vortex-induced radial velocity
v_k = lateral component of vortex-induced velocity
W = aircraft weight, lb
W_P = paratrooper weight, lb
w_k = vertical component of vortex-induced velocity
X = downstream distance between aircraft, ft
Y = lateral distance between aircraft, ft, positive to starboard
δ = drift angle, angle between aircraft heading and longitudinal axis, positive if aircraft pointed to the left of the groundtrack; for zero sideslip, equals wind drift angle
Γ = vortex strength
Λ = wing quarter-chord sweep angle
ν = air viscosity
ρ = air density

Introduction

LARGE-SCALE airborne assaults have proven to be one of the most effective military tactics developed over the last 50 years. The 1941 German invasion of the island of Crete was mounted entirely from the air and was successful in spite of heavy defenses on the island and control of the surrounding waters by the British Navy. Modern military transports have realized a factor of 5 increase in both payload (paratroopers) and range relative to their earliest predecessors. One consequence of this capability, an increase in span loading by a factor of 10 (Table 1), exacerbates an operational problem for formation airdrops. High-span loads result in large, strong wake vortex systems that can cause serious problems for parachutes dropped from aircraft downstream in a formation[1,2] (Fig. 1).

Airfield seizure, a modern military objective for mass airdrop, requires waves of multiship elements in a low-altitude tight formation. Elements having as many as nine ships were used during World War II and Korean operations. Modern employment uses two or three ships per element. Different approaches are used to avoid vortices within an element and between elements. This paper will only address vortex avoidance within an element; the multielement problem is still being studied and will be discussed at a future date. Within an element, the requirement is to totally eliminate the possibility of an encounter because of the strength of the vortex and the resultant severity of the encounter. Operational considerations disallow obvious solutions such as aircraft flying side by side. The paper will review the results of flight tests conducted on the C-5[3] and C-17[4] and show the methodology that resulted in the ultimate C-17 formation geometry.

Parachute Vortex Interactions

Progress has been made in the understanding and computational replication of parachute opening and the effects of the wake of the delivering aircraft.[11] The interaction of a parachute and fully rolled-up wingtip vortex from an aircraft upstream is not well understood. However, systematic tests have been conducted[1,2,12] to investigate the type, frequency, and severity of the reactions. In these tests, two aircraft flew directly in trail into the wind, and mannequins were dropped from the trail aircraft. Smoke was used in an attempt to mark the vortices. The tests have determined the following facts:

1) A vortex encounter before the parachute has opened (generally in the first 4 s after aircraft exit) is not considered hazardous. The jumper initially falls very rapidly, making any encounter difficult to see. This may explain why vortex encounters have not been identified as a serious problem in previous generations of aircraft such as the C-130 and C-141. The slower descent rate of the vortices from these aircraft (3–4 ft/s) means that the probability is high that the jumpers fall past the vortices in the first 4 s. The higher descent rate of C-5 and C-17 vortices (roughly 6 ft/s) gives the parachute time to inflate prior to an encounter.

2) Three types of potentially hazardous reactions can occur once the parachute has opened. The first is an increase in descent rate that may not return to normal prior to ground impact.

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Table 1 Aircraft and drop zone data from selected combat airborne operations and current tests[4–10]

Date	Location	Aircraft (number)	Span load, lb/ft	Troops	Drop zone $L \times W$, yd	Paratrooper unit
5/20/41	Crete	Ju-52 (493)	210	8060	4 DZs	German 7th Airborne Division
9/17/44	Nijmegen, Holland	C-47 (135)	260	2031	~3080 × 1760	US 82nd Airborne Division
		C-47 (135)	——	2281	~3000 × 1320	——
		C-47 (132)	——	1922	~3000 × 1320	——
9/17/44	Eindhoven, Holland	C-47 (135)	260	2200	4000 × 1400	US 101st Airborne Division
		C-47 (154)	——	2391	4000 × 1400	——
		C-47 (135)	——	2050	~3520 × 2000	——
9/17/44	Arnhem, Holland	C-47 (177)	260	2283	~2000 × 900	British 1st Airborne Division
2/3/45	Luzon, Philippines	C-47 (143)	260	2665	4000 × 2000	US 11th Airborne Division
3/26/45	Wesel, Germany	C-47 (119)	260	1920	~2640 × 2640	British 6th Airborne Division
		C-47 (121)	——	1917	~2640 × 2640	——
		C-47 (181)	——	2469	2000 × 1500	US 17th Airborne Division
		C-46 (70)	370	1995	2500 × 1000	——
10/20/50	Sukchon, Korea	C-46 (40)	370	2860	——	US 187th Airborne Regiment
		C-119 (71)	535	Total	——	——
2/22/67	Vietnam	C-130 (13)	780	780	——	US 173rd Airborne Brigade
10/25/83	Grenada	C-130 (10)	780	400	3400 × 1400	US 75th Ranger Regiment
12/20/89	Panama	C-141 (20)	1485	2176	5100 × 700	US 82nd Airborne Division
10/17/96	Ft Bragg, NC (Holland DZ)	C-17 (3)	2333	306	3220 × 1750	US 82nd Airborne Division
1/31/97	Ft Bragg, NC (Sicily DZ)	C-17 (6)	2333	612	4750 × 1000	US 82nd Airborne Division

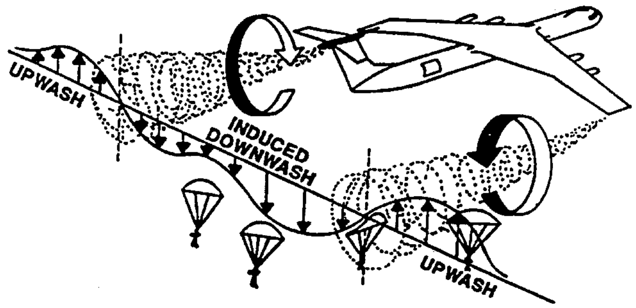

Fig. 1 Wake vortex flowfield.

This occurs if the parachute falls through the high downwash region between the vortex cores. The second is a partial or complete collapse of the canopy, which may not fully reinflate prior to ground impact. This is presumed to occur if the parachute is very close to or contacts the vortex core. The third reaction is a lateral oscillation of the parachute/jumper system that may not dampen prior to ground impact, resulting in a significant lateral impact velocity. This is also presumed to result from close proximity to the core.

Operational Restrictions

To better understand the ground rules for establishing an element geometry, a summary of the pertinent operational restrictions for personnel airdrop will be given.

Drop Time

The minimum practical total time over the drop zone is needed to maintain the element of surprise. This precludes the vortex avoidance tactic of spacing individual aircraft far enough apart that the vortices have dissipated. On the other hand, a minimum spacing between aircraft is needed to allow for room to maneuver and to avoid the possibility of collision. The minimum acceptable spacing on this basis under instrument flight rules (IFR) conditions is currently considered to be 3000 ft. The width required to allow safe side-by-side flight under IFR conditions would make the required drop zone too wide to be operationally acceptable.

Drop Altitude

The lowest practical drop altitude is needed to minimize the possible impact of ground fire on both the paratroopers and aircraft. Higher altitudes are used for training to minimize injuries and allow use of a reserve parachute. Current drop altitudes for training and combat are 800 and 500 ft, respectively, with all aircraft within an element at the same altitude.

Drop Zone Length

Drop zone length is determined by the number of jumpers dropped per aircraft. A single C-17 can drop 102 troops, 51 from each side. The minimum drop zone length for this size drop is over 4000 yd. As the drop zone length decreases, additional aircraft are needed to deploy a fixed number of troops, assuming each aircraft makes only one pass over the drop zone. Because this is true for any aircraft, drop zone length is not a critical parameter for establishing an element geometry. Drop zone sizes used during the present tests and in past combat operations are shown in Table 1.

Drop Zone Width

The number of possible drop zones in any conflict increases as the required drop zone width decreases, and so it is a tactical advantage to keep the required drop zone as narrow as possible. Narrow drop zones also minimize the time needed on the ground for the units dropped to assemble. The required drop zone width is determined by parachute dispersion during descent, position error of the element relative to the drop zone center, and the actual width of the element. An approximate rule for calculating the required drop zone width is to add 600 yd to the element width. Element width is determined by the vortex avoidance requirement, because lateral spacing between the aircraft is needed for jumpers to avoid vortices from upstream aircraft under low wind conditions. Thus, the narrowest possible element width is needed to minimize the total required drop zone width.

Analysis Technique

Analysis of the formation airdrop problem requires a model of the trailing vortex position coupled with a model of the paratrooper drop path. Several techniques for predicting vortex behavior behind large aircraft have been published.[13–15] All assume a fully rolled up vortex and use an elliptic load assumption for the initial vortex characteristics. Kurylowich[13] includes empirical models for the vortex core radius and strength decay. Greene[14] accounts for vortex decay, density stratification, and atmospheric turbulence in an approximate theoretical fashion. Kantha[15] accounts for ambient turbulence, crosswind shear, and ground effect including vortex bounce.

The vortex tracking code used during the present study, based on the Kurylowich model,[13] was used in a prior airdrop study[16] and will be summarized here. It computes the location of trailing vortices from a formation of up to 18 aircraft and an idealized paratrooper trajectory from a preselected aircraft. The flow behind each aircraft is modeled as a single pair of fully rolled up vortices (Fig. 1). Minimum formation spacing for airdrop (>1500 ft) is beyond the point of wake rollup, so this assumption is warranted. The vortex strength is given by

$$\Gamma = \Gamma_0 = 4kW/\pi\rho Vb, \qquad t < t_d$$
$$\Gamma = \Gamma_0(t_d/t), \qquad t > t_d \tag{1}$$

For the C-17, the values for the empirical constants k and t_d are 1.0 and 30 s, respectively, using the empirical equations developed by Kurylowich.[13] Unpublished analysis of LIDAR measurements[17] taken on the C-17 at Edwards Air Force Base indicates values of 0.8 and 60 s and provides a better match to the observed vortex trajectories and estimated strength using the present vortex tracking methodology. A modified Lamb model is used for the vortex-induced radial velocity:

$$V_\theta = \frac{\Gamma}{2\pi r}[1 - e^{-1.26(r/r_c)^2}] \tag{2}$$

$$r_c = 36.2\sqrt{\nu t/\cos^2\Lambda} \tag{3}$$

Calculations are done in an axis system fixed to the lead aircraft and aligned with the groundtrack (Fig. 2). Trailing vortex positions are found using a time-stepping analysis, solved in the y-z plane (vertical plane perpendicular to the ground) in longitudinal increments of 100 ft. The lateral and vertical components of the induced velocity at each vortex core are calculated by summing the velocity components caused by all other vortices:

$$v = V_C + \sum_{j=1}^{nv} \frac{\Gamma_j(z - z_j)}{2\pi r^2}[1 - e^{-1.26(r/r_{c,j})^2}] \tag{4}$$

$$w = \sum_{j=1}^{nv} \frac{\Gamma_j(y - y_j)}{2\pi r^2}[1 - e^{-1.26(r/r_{c,j})^2}] \tag{5}$$

$$r = \sqrt{(y - y_j)^2 + (z - z_j)^2} \tag{6}$$

The crosswind is assumed uniform for all aircraft at all altitudes. Once Eqs. (4) and (5) have been applied to all vortices, the vortex positions are shifted for the next time step. Ground effect is ignored for the present analysis. For the lowest-altitude drops studied (500 ft), ground effect does not alter the vortex trajectory within an element. For multiple-element analyses, ground effect must be considered.

The paratrooper trajectory is modeled using a constant deceleration to zero forward velocity while the parachute is inflating until it is fully opened and vertical. The mean time for this to occur for the T-10C parachute[18] currently used by the U.S. Army is 4.1 s, with a vertical drop of 127 ft. The lateral path follows the aircraft groundtrack until the parachute is fully opened and vertical. Once vertical, it drifts with the wind and descends with a vertical drag coefficient[18] based on a parachute area (953 ft^2) of

$$C_D = 0.73 + 0.06(W_p - 180)/180 \tag{7}$$

The paratrooper path is not adjusted because of the proximity of any vortices.

As experience was gained with this code during 1995 C-17 testing, a simple approximation for the lateral distance between the paratrooper path and trailing vortices from other aircraft was developed. This distance is termed the design margin (Fig. 2) and was selected as the measure of merit for the formations to be analyzed for the present tests. It is approximated as

$$\mathrm{DM} = |(Y \pm \pi b/8) - (X + Vt_1/2)\tan\delta| \tag{8}$$

where DM is the design margin. One result is given for each (left, right) vortex. If the sum of the two equals the initial vortex spacing, i.e.,

$$\mathrm{DM}_1 + \mathrm{DM}_2 = \pi b/4 \tag{9}$$

then the drop path is between the vortices. If the sum is greater than the initial spacing, then both vortices lie to the same side of the drop path. The term $Vt_1/2$ accounts for the additional groundtrack covered by the aircraft while the parachute is opening. With the parachute model discussed earlier and an aircraft speed of 135 Kn, this distance is 468 ft.

The key question is, what is the minimum necessary design margin? How close a vortex can come to a parachute before it has an undesirable effect is unknown. Attempts to define this threshold in terms of a maximum allowable vortex-induced radial velocity[1,2,16] remain guesses at best. A better criterion may be a maximum velocity gradient over a scale of perhaps one parachute diameter (24 ft). The design margin must also be large enough to account for uncertainties including nonuniform winds, lateral dispersion of the jumper path, natural variability of vortices, and position error of the aircraft. The design margin for the C-17 was ultimately determined empirically based on the results of thousands of mannequin drops.

Discussion

Figure 3 shows different arrangements for three-ship element geometries. The V formation, used for daytime mass air-

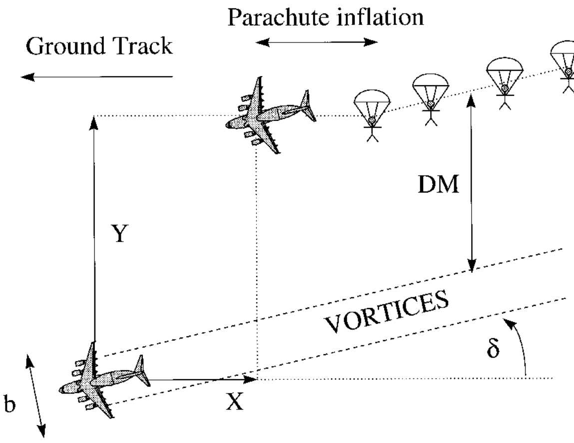

Fig. 2 Geometry for vortex tracking analysis.

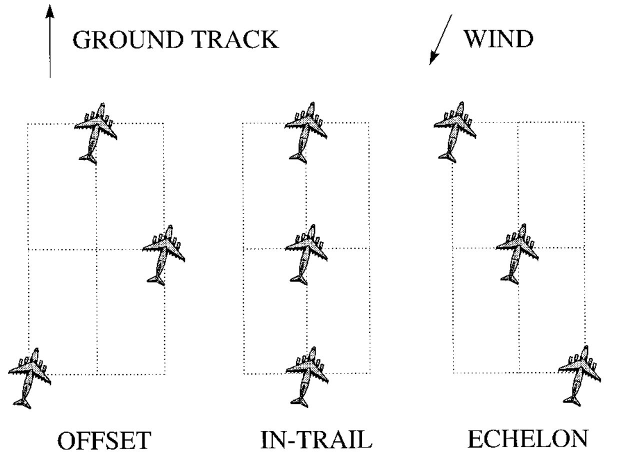

Fig. 3 Element geometry classification.

Table 2 Summary of IFR formation geometry/mannequin test data prior live drops

Aircraft	Element type	Design drift	Element position	Axial spacing, ft	Lateral spacing, ft	Design margin, ft	Test date	Encounters/ total drops
C-141	Offset	$\|\delta\| < 3$	2	4000	500	200	——	——
			3	8000	−500	0	——	——
	In-trail	$\|\delta\| \geq 3$	2	4000	0	170	——	——
			3	8000	0	170	——	——
C-5	Offset	$\|\delta\| < 3$	2	4000	500	180	12/94	0/22
			3	8000	−500	0	12/94	6/22
	In-trail	$\|\delta\| \geq 3$	2	4000	0	150	12/94	0/22
			3	8000	0	150	12/94	0/22
C-17	Offset	$\|\delta\| < 3$	2	3000	500	250	6/96	0/232[a]
Phase I			3	6000	−500	100	6/96	2/231
	In-trail	$\|\delta\| \geq 3$	2	3000	0	120	——	——
			3	6000	0	120	6/96	[b]
C-17	Offset	$\|\delta\| < 3$	2	3000 ± 500	600 ± 200	150	7–8/96	0/84
Phase II			3	6000 ± 500	−900 ± 200	300	7–8/96	1/374
	Echelon	$\|\delta\| \geq 3$	2	3000 ± 500	350 ± 200	270	7–8/96	0/303
			3	6000 ± 500	900 ± 200	270	7–8/96	0/246
C-17	Echelon	$\delta < 2$	2	3000 ± 500	650 ± 200	260	9/96	0/71
Phase III		Downwind	3	6000 ± 500	1500 ± 200	260	9/96	0/461
C-17	Offset	$\|\delta\| < 3$	2	3000 ± 500	700 ± 200	250	——	——
Phase III			3	6000 ± 500	−1100 ± 200	500	——	——
Alternate	Echelon	$\|\delta\| \geq 3$	2	3000 ± 500	350 ± 200	270	——	——
			3	6000 ± 500	900 ± 200	270	——	——

[a]6/72 not counted because of position error.
[b]3/72 not counted because of position error.

drops in World War II and Korea, is not considered viable for night operations. The C-130 and C-141 use the offset and in-trail geometries for formation airdrop, depending on the relative wind. Under crosswind conditions, the aircraft point into the wind as indicated in Fig. 3.

The starting point for this study was an assessment of the existing IFR formation flown by the C-141 (Table 2). At low crosswind conditions ($\delta < 3$ deg), the offset geometry is used, with the assumption that the lateral spacing is large enough to avoid the vortices from the lead aircraft. At high drift angles ($\delta \geq 3$ deg), the in-trail geometry is used, with the assumption that the high wind blows the vortices away from the trail aircraft. In both cases, the lead aircraft flies to the center of the drop zone.

The C-141 is equipped with the SKE (stationkeeping equipment) position feedback system. SKE uses a data link system with time slots for each aircraft to measure the distance between trail and lead aircraft and the angle between the longitudinal axis of the trail aircraft and the SKE signal direction. Longitudinal and lateral position data provided by SKE are along and normal to the aircraft longitudinal axis, respectively. To maintain proper ground track in a crosswind, data from pre-established drift tables are input into the SKE computer. If an aircraft is sideslipping, the actual lateral spacing will be different from that indicated by the SKE. Sideslip error is assumed to be one of the factors to be accounted for in the design margin.

Analysis of the C-141 formation (Table 2) using Eq. (8) gives a design margin of over 150 ft for the second ship position in both formations and for the third ship position in the in-trail formation. Drift table data input into SKE are rounded to the nearest 10 ft, so that the design margins shown have also been so rounded. In the offset formation, the third ship position has a zero margin for drift angles near 3 deg. Here, the drop path is directly above the left wing vortex from the lead ship, indicating a high probability of a vortex encounter. As noted earlier, however, the relatively low descent rate of the C-141 vortex may preclude many encounters with fully developed canopies. It may also be that encounters occur but they are not severe enough to be a problem. This is supported by tests[12] conducted at Edwards Air Force Base, in which two C-141s spaced at an operationally representative 6000 ft flew directly into the wind and mannequins were dropped from the trail aircraft. The trail aircraft was positioned sufficiently above the lead aircraft to ensure the parachute was opened prior to an encounter. A total of 240 mannequins were dropped in 21 passes over the drop zone, with 55 vortex encounters observed (23% rate). All encounters were classified as minor, meaning that there was sufficient altitude for the jumper to fully recover his main parachute. An identical series of tests on the C-17 with a larger aircraft spacing (15,000 ft) resulted in 39 encounters out of 240 drops (16% rate), with seven classified as major because of a probability that limited altitude would make full recovery difficult and result in potential injury or reserve parachute deployment.

Prior C-5 Tests

The C-5 was originally required to have personnel formation airdrop capability, but unrelated problems with the program in 1973 resulted in an extended delay of airdrop testing.[2] C-5 formation airdrop testing resumed in 1994 at Fort Bragg.[3] The tests were conducted using the three-ship C-141 IFR formation geometry. No adjustments to the formation were made during the test. Analysis of the C-5 formation using Eq. (8) gives the same result as the C-141 (Table 2). Positive design margins of about 200 ft are attained for all ship positions except ship three in the offset formation, where zero margin is indicated. Eleven passes each were made in the offset and in-trail formations, with one mannequin released from each side of both trail ships. The test results support the analysis. No encounters were observed for the positive margin conditions, while 6 out of 22 drops resulted in encounters for ship three in the offset formation. All six encounters were canopy collapses.

The C-5 was not equipped with an SKE system, so the formation geometry was maintained by visual reference. This is an extremely difficult task for the distances involved. GPS data taken during these tests have been processed to obtain the actual aircraft positions during the drops. These data, in addition to wind data from each pass, allow Eq. (8) to be used to estimate the lateral proximity of the parachute to the vortices from the lead ship. Each pass was analyzed with the assumption that the vortex from the lead ship was the closest to the drop path and was responsible for any encounter. The light wind conditions that were present indicated a very low likelihood that the vortex from the second ship was responsible for the encounters. The predicted proximity of the jump path to the closest vortex from the lead ship for all passes from the Dec. 15, 1994 tests are shown in Fig. 4. The predicted distance

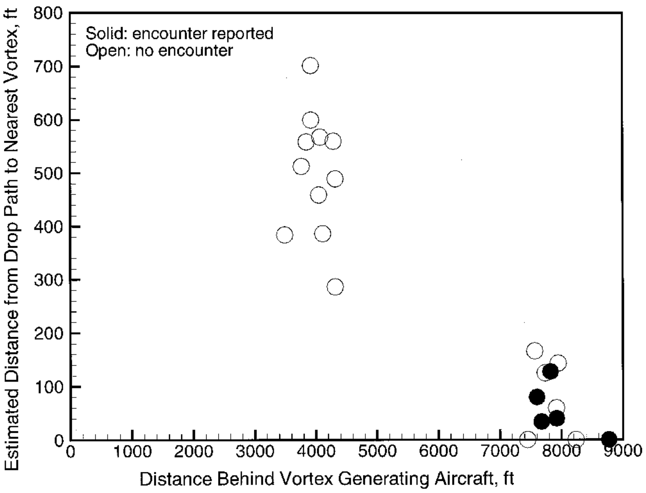

Fig. 4 1994 C-5 test results, each data point is one pass over drop zone (two mannequins dropped).

to the far vortex would be 175 ft greater for all but three cases where the prediction is between the vortices. It could not be established which vortex caused the observed encounters. A tentative conclusion from Fig. 4 would be that a design margin of 300 ft may be adequate 4000 ft from the vortex-generating aircraft, while a design margin of 120 ft is not adequate at 8000 ft from the generating aircraft.

Prior C-17 Tests

On Nov. 23 and Dec. 2, 1994,[19] drops from the trail ship of a two-ship C-17 formation were conducted at Edwards Air Force Base. Four passes were made over the drop zone with 47 mannequins and troops dropped without incident. The formation used was the C-141 visual flight rules (VFR) formation with the second ship 2000 ft aft of the first with wingtip spacing (165 ft between aircraft centerlines). Analysis of this spacing shows a zero design margin for almost all cases of the trail ship being downwind with less than 3 deg of drift. Testing using this formation was continued in June of 1995, as part of a planned six-ship demonstration. After successfully completing 72 mannequin drops, a live pass was made with 102 troops. Two jumpers encountered a vortex during this drop. It was at this point that the author became involved with the analysis of formation geometries. Analysis of the incident using the vortex tracking code gave the lateral distance from the vortices to the drop path as 30 and 160 ft. The direction of rotation of the canopy during the encounter (clockwise, viewed from the front) positively identified the right wing vortex as the culprit, indicating that the 30 ft value was correct. The vortex tracking code was used to assess alternate formations, and a shortened formation (1500 ft) with increased lateral spacing (500 ft) was selected for further tests. The design margin for this formation using Eq. (8) is 330 ft. A total of 585 drops were completed from this formation, without incident. However, only a two-ship element was demonstrated, and the longitudinal spacing was not considered operationally realistic for IFR operations.

Current C-17 Test

The objective of the current test[4] was to establish a C-17 capability suitable for the brigade airdrop mission under IFR (night) conditions. A three-ship element geometry was to be established. The tests were conducted by Detachment 1, 33rd Flight Test Squadron, Charleston Air Force Base, using aircraft based out of Charleston, South Carolina. Flight testing originated from Pope Air Force Base, with drops conducted on Holland and Sicily Drop Zones at Fort Bragg. Nominal aircraft gross weight was 385,000 lb.

The test plan called for a minimum of 460 successful mannequin drops from each trailing ship position prior to a safety release for live drops. Each aircraft was fitted with two 12-mannequin launchers with static line drop capability. Nominally, three passes over the drop zone were made with the aircraft alternating position within the element between passes. This resulted in 72 mannequin drops from a given ship position prior to return to base. On limited occasions, drops were conducted from the second and third ship positions simultaneously. Ground video coverage from multiple camera positions was provided for observation. These were reviewed for vortex encounters after each day of jumps by a review team consisting of jumpmasters, senior jumpers, and experts in parachute performance. Most of the review team members were participants in the parachute vortex interaction test[12] discussed previously.

Formations designed for the present tests used Eq. (8) to determine the lateral spacing required to maximize the design margin for a given formation width, longitudinal spacing, and worst-case wind condition. The vortex tracking code was then run to verify the predicted design margin. In all cases, the results were virtually identical because, by design, for a given wind condition the lateral distance between vortices from neighboring ships was maximized to the extent possible. This minimizes the effect of intraship vortex interference, which is the primary effect included in the tracking code and ignored in Eq. (8). Desired aircraft spacings were rounded to the nearest 50 ft for simplicity. Once testing began, if a vortex encounter occurred, the vortex tracking code was run with the conditions present during the drop. On each pass, a single recording of aircraft weight, airspeed, drift angle, and winds at altitude were made for each aircraft. Aircraft altitude and relative spacing were recorded at 10 s intervals. Engineering judgment was used to select the spacing for the analysis, based on an estimate of how long after the drop zone was reached the encounter occurred.

Phase I

The span loading and resultant vortex strength of the C-17 at airdrop conditions is nearly identical to the C-5, and 60% greater than the C-141. From this we would expect to duplicate the C-5 test result if the C-17 was flown using the C-141 IFR formation geometry. The goal of the initial formation was to maximize the design margin while maintaining the C-141 tactics of 1000 ft formation width, offset formation at low drift angle, in-trail formation at high drift angle, and lead aircraft centered over drop zone. These constraints allow two free variables, the longitudinal spacing between aircraft and the threshold drift angle for switching from the offset to in-trail formation. The formation selected had 3000- and 6000-ft longitudinal spacing, switching to in-trail at 3 deg drift or greater (Table 2). This formation increases the margin for ship three in the offset formation from 0 to 97 ft, while slightly decreasing the margins for the other cases. In light of the C-5 results, the 97-ft margin was still considered to be high risk.

Testing commenced with this formation on June 19, 1996. Early results indicated difficulty maintaining the formation under automatic control by coupling the SKE system to the autopilot. This resulted in vortex encounters on June 19 and 25 because of the trail ship being out of position. The tests were ultimately conducted under manual control with feedback from the positioning system used as a guide to the pilot to keep his aircraft in position. Over 500 drops were conducted under these conditions through June 28. On June 28, two mannequins from ship three encountered a vortex while flying the offset formation. All aircraft were in position when the encounter occurred. This constituted a test failure, which meant that a new position had to be established for the third ship.

The June 28 encounters involved canopy collapse and subsequent rotation (similar to the 1995 incident), which positively identified the left wing vortex from the lead ship as the cause. A top view of the predicted vortex trajectories and jumper path generated by the vortex tracking code for the June

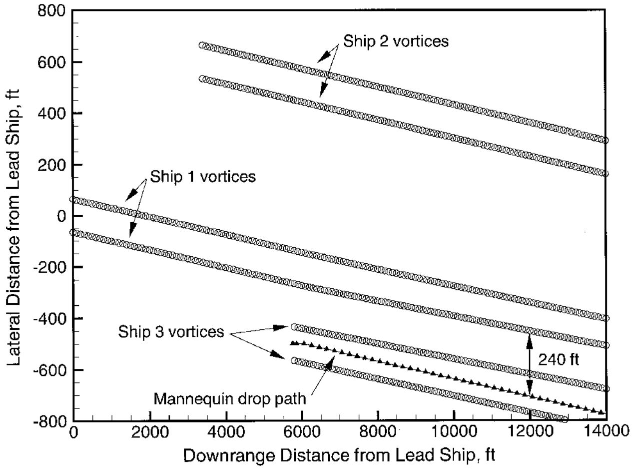

Fig. 5 Top view of predicted vortex trajectories for June 28, 1996 encounters.

28 encounters is shown in Fig. 5. A time analysis of the video indicated that the parachute was approximately 12,000 ft downstream of the lead aircraft when it encountered the vortex. At this distance, the estimated lateral distance to the nearest vortex is 240 ft. For this case (as well as the June 19 and 25 cases) the vortex predicted to be closest to the drop path was confirmed to be the cause of the encounter based on the direction of the canopy rotation during collapse.

Phase II

Given the estimated distance of 240 ft for the June 28 encounter, a 300-ft design margin was selected for the new ship three position. It is reasonable to assume that the uncertainty in the vortex position increases linearly with distance behind the generating aircraft. This gave added confidence in the 300-ft value because the results as of June 28 from ship two (half as far back as ship three) with a 150-ft margin had been successful. Tolerance boxes for maintaining aircraft position were also defined: ±500 ft fore and aft and ±200 ft left and right, with no drop to be conducted if the aircraft was out of tolerance. At this point, design margins calculated from both Eq. (8) and the vortex tracking code assumed ship positions at the lateral edge of the tolerance box.

The new phase II formation, shown in Fig. 6, is 50% larger than the target width of 1000 ft. Three hundred ft of this additional width is a result of the introduction of the tolerance boxes; the additional 200 ft is attributable to moving the third ship out from 500 ft. The position of ship two is unchanged under the worst-case condition. The formation width was judged to be undesirable but still acceptable. A new feature of this formation is that for the high-wind case, the aircraft do not fly in-trail but in an echelon pattern, with the trail aircraft flying upwind. This is a consequence of the lateral tolerances that were established. An echelon formation for all winds was initially proposed for phase II but was rejected because it did not have the lead aircraft centered over the drop zone in the low-wind condition, which would have required changes in the C-17 mission computer.

After nearly 1000 successful drops from the phase II formations, a vortex encounter was reported for one mannequin from ship three on August 20. As with the June 28 encounter, the aircraft was within its defined tolerance box. The reported encounter was not characterized by any deformation of the canopy or increased oscillation. It can most easily be described as an increased rate of descent coupled with a slight coning motion. As a result, it was not possible to determine which (if any) vortex from the lead ship was the cause.

Analysis of the reported August 20 encounter using the vortex tracking code gave a predicted distance of 460 ft from the nearest vortex to the jump path. This distance should be too large to cause a visible disturbance to the canopy. It shows the magnitude of the combined uncertainties involved in the analysis. The encounter constituted a second test failure, which meant that a new position had to be established for the third ship.

Phase III

A required design margin of 500 ft was selected for the third ship position, which gives a corresponding margin of 250 ft for ship two, because it is only half as far back from the lead aircraft. The offset formation developed from these requirements has ship two 700 ft right and ship three 1100 ft left. The formation width of 1800 ft is almost double the original target width and immediately raised concern about its operational utility, both in training and combat. A three-ship, 600-yd-wide formation cannot be reliably flown over the Sicily Drop Zone.

At this point, the previously proposed echelon configuration was reassessed with the new uncertainty margin. Ideally, the echelon would form with the trail ships upwind under all circumstances. The determination of the wind direction and initiation of the formation is done several miles prior to the drop zone. Under light and variable wind conditions, it is possible for the trail ships to be downwind over the drop zone. To account for this possibility, the echelon spacing was designed to give a minimum 250-ft margin under an adverse drift of up to 2 deg. The resultant formation has 650- and 1500-ft lateral offsets (Fig. 7) and is the same overall width as the phase II formation. Air Mobility Command agreed to modify the C-17 mission computers to allow the formation to be used in all winds. This formation was successful, with 461 drops completed from the third ship position, without incident. Troop drops commenced on Sept. 27, 1996.

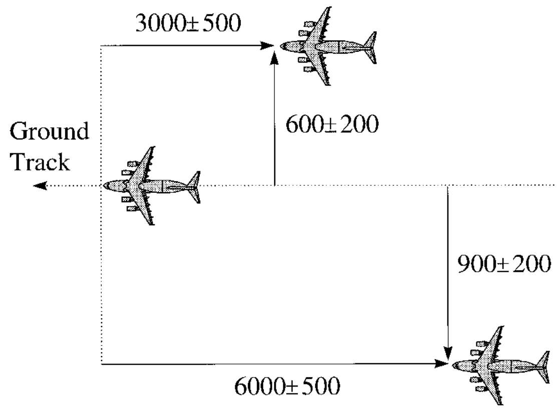

Fig. 6 C-17 phase II low-wind element geometry, $3 > \delta > -3$.

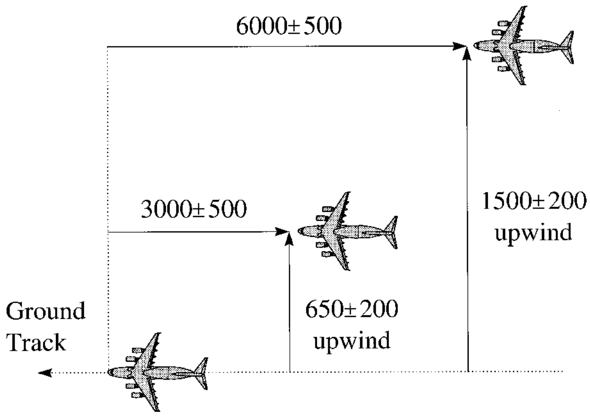

Fig. 7 C-17 phase III (final) element geometry, all winds (shown for $\delta < 0$).

Table 3 Total drops in final formation

Element position	Total passes	Mannequin drops	Troop drops
2	52	674	695
3	49	677	554
Total	101	1351	1249

Table 4 Effect of lateral position tolerance on element width

Tolerance	Two-ship	Three-ship	Four-ship
±200 ft	650	1500	2350
±150 ft	600	1350	2100
±100 ft	550	1200	1850
±50 ft	500	1050	1600
0	450	900	1350

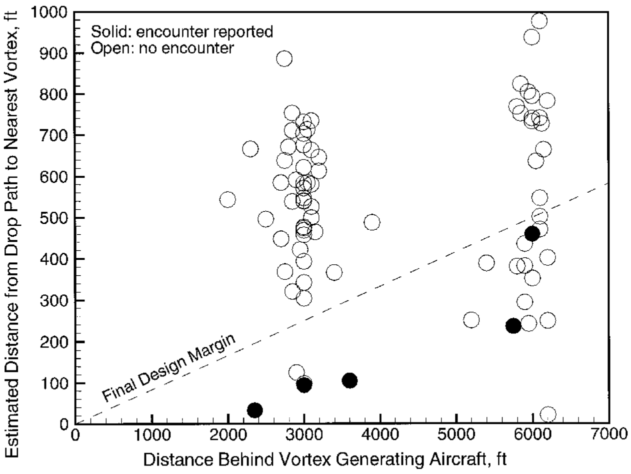

Fig. 8 1996 C-17 test results, each data point is one pass over drop zone (24 mannequins dropped).

Additional data for the element geometry were obtained from drops from the trail element during multielement tests. A summary of the total drops at the completion of the test (Jan. 31, 1997) is given in Table 3. This table includes 387 successful mannequin drops from phase II that the U.S. Army counted for validation of element position two. Total passes over the drop zone are shown in addition to total drops. The pass data indicate the number of distinct atmospheric conditions under which drops were conducted and are an alternate measure of the results.

The predicted proximity of the jump path to the closest vortex using Eq. (8) for all mannequin drops through Sept. 25, 1996 is shown in Fig. 8. The June 9, 1995 incident is also included. For the offset geometry cases, the lead ship is assumed to be the vortex-generating aircraft. For the echelon cases, the second ship is assumed to be the vortex-generating aircraft for drops from the third ship. For the in-trail cases, two points are given for each drop from ship three, representing the predicted distance from both the lead and second ships.

Application to Other Aircraft

The analysis methodology used for this study can be applied to any aircraft and has subsequently been used to develop an improved C-130 equipment airdrop formation. Gross weight, wing span, and sweep angle are the aircraft-specific variables in the analysis. For personnel airdrop, the 1500-ft-wide, three-ship echelon is applicable to any aircraft capable of maintaining lateral position within ±200 ft. For aircraft capable of more accurate positioning, the overall formation width can be reduced. This is shown in Table 4 for two-, three-, and four-ship elements. Axial spacing between adjacent aircraft is assumed to be 3000 ft.

Conclusions

A three-ship C-17 element geometry suitable for formation airdrop operations at night, which avoids jumpers from trail aircraft encountering vortices from aircraft upstream, has been developed and flight demonstrated. Candidate formation spacings were judged based on the closest predicted lateral proximity of a jumper and vortex using a vortex tracking code and a simplified engineering estimate. The starting point for the test was an offset geometry that was judged superior to one found unacceptable during previous testing on the C-5. The introduction of tolerance boxes for aircraft position and vortex encounters that occurred during mannequin trials increased the width of the offset geometry until it became operationally unsuitable. In the four cases where encounters were characterized by complete rotation of the canopy, the tracking code indicated that the vortex that caused the encounter was the closest vortex to the drop path. An echelon element geometry was finally selected that has been subjected to 2600 drops without vortex encounter. The echelon is based on a minimum lateral jumper-to-vortex proximity of 250 ft per 3000 ft of axial distance under the design (worst-case) wind condition. If a suitable positioning system is available, the formation can be used by other aircraft.

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