and agree well with the semiempirical expression previously determined.

Most encouraging results were obtained from an experiment performed on the elliptical airfoil of 18% thickness ratio with dual symmetrical jets. These results indicate that the leading-edge jet does not disturb the flow and actually furnishes some additional reaction force to the lift. Hence, the important application of the elliptical airfoil (or oval airfoil) with dual jets to the retreating blade of a helicopter rotor is evident.

Furthermore, the results of aerodynamic response measurements of the model to cyclic changes in the blowing jet are surprisingly encouraging. The cyclic valve was tested at frequencies equivalent to twice that of the rotational speed of a conventional helicopter blade, and the response of the lift was found to be excellent with negligible delay. The response of the drag as well as the chordwise pressure distribution to the cyclic changes in the blowing jet were also found to be very good. These results clearly indicate that the periodic variation of lift on the airfoil can be fulfilled by cyclic variation of the jet momentum; hence, the circulation control problem is reduced to simply the problem of pressure control inside the model.

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SEPT.-OCT. 1970 J. AIRCRAFT VOL. 7, NO. 5

A Review of Para-Foil Applications

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Numerous tests of various para-foil designs have been carried out by the University of Notre Dame, the U.S. Air Force, the U.S. Navy, the U.S. Army, NASA, and industry. These tests include wind-tunnel studies of models ranging in size from 0.2 to 300 ft² and free-flight tests of units ranging in size from 8 to 864 ft². Unmanned free-flight tests of certain units have included deployment tests to 350 fps, guidance and control tests with payloads to 2000 lb, and glide performance tests with payloads to 2000 lb. Manned jumps and manned ascending flights have been made with units ranging in size from 165 to 360 ft². Manned flights using propeller powered carts have been made with a 360-ft² unit. The various para-foil application programs will be discussed and a summary of results obtained from various wind-tunnel and free-flight tests will be given.

Nomenclature

AR = aspect ratio (AR = span divided by chord), dimensionless
C_L = coefficient of lift, dimensionless
KIAS = knots indicated airspeed
L/D = lift-to-drag ratio, dimensionless
MSL = mean sea level
ND$x.x(yy)$ = Notre Dame para-foil of aspect ratio $x.x$ and area of yy ft² [e.g., an ND 2.0 (90) para-foil has AR = 2, S = area = 90 ft², span = 13.4 ft, and chord = 6.7 ft]
q = dynamic pressure, psf
S = canopy area (S = span times chord)
α = angle of attack of bottom surface of para-foil, deg

Introduction

THE para-foil§ is a true flying wing made entirely of nylon cloth with no rigid members, (Figs. 1, 4–7). Like a rigid wing, it has an upper and a lower surface, and an airfoil section. The leading edge is open to permit inflation by the ram air pressure. The para-foil is composed of numerous cells which give this cloth wing its unique rigid shape.

It is fabricated of a low porosity nylon cloth and can be packed and deployed in a manner similar to a conventional parachute. Pennants are distributed along the bottom surface to which the suspension lines are attached. These pen-

Presented as Paper 68-968 at the AIAA 2nd Aerodynamic Deceleration Conference, El Centro, Calif., September 23–25, 1968; submitted December 17, 1968; revision received January 14, 1970.

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§ The para-foil is a proprietary product (patent 3285546) of Space Recovery Research Center Inc. The University of Notre Dame has a license for research and design of para-foils.

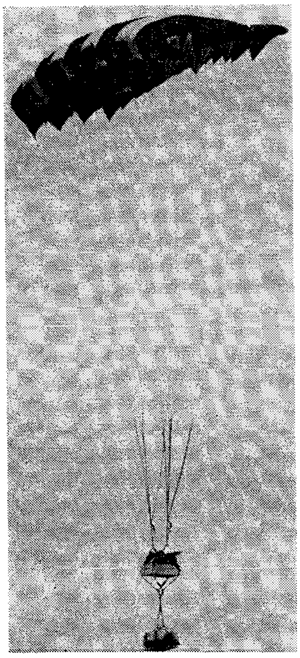

Fig. 1 Para-foil cargo delivery system.

nants serve three purposes: 1) they distribute the aerodynamic forces to the suspension lines, 2) they partially channel the flow into a two-dimensional flow pattern which reduces tip losses and improves the aerodynamic efficiency, and 3) they provide side area which aids in obtaining directional flight stability.

The para-foil is based on a unique kite design discovered by D. Jalbert. The term para-foil, which denotes the combination of parachute and airfoil, was selected by the University of Notre Dame, to describe various redesigns of the original Jalbert kite.[1,2]

The first studies of the para-foil by Notre Dame concentrated on wind-tunnel tests of small models where the smoke flow could be studied and the various aerodynamic coefficients measured. Concurrent with these wind-tunnel tests various tethered and gliding flight tests were carried out on numerous para-foil designs.[1-5]

Following these early wind-tunnel and free-flight tests, the University of Notre Dame contractually furnished para-foils and para-foil design and performance criteria to various organizations for test and evaluation against potential applications such as cargo delivery,[6] sounding rocket payload recovery,[7] tethered flight,[8] and manned flight. Progress on these various para-foil programs will be summarized in the following sections.

Cargo Delivery¶

The capability to accurately air-drop cargo under adverse weather conditions and at large stand off distances can provide an operational unit with a decisive tactical advantage. To achieve this, however, requires precise trajectory control. One method of obtaining this trajectory control is through use of a radio controlled automatic homing steerable parachute. During 1964 under Project Homing Pigeon, the Air Force Flight Dynamics Laboratory (AFFDL) successfully demonstrated the feasibility of such an approach using a para-sail steerable parachute. This 2000-lb capacity system had a glide ratio of about 1:1. This glide ratio coupled with a sink rate of less than 30 fps provided a limited offset capability.

With the introduction of higher glide devices such as the para-wing, sail-wing, and para-foil, the capability for trajectory control in winds of 30 knots or higher became technically feasible. In January 1967, the AFFDL initiated Project Pin Point to demonstrate the feasibility of using the para-foil for such an application.

The Project Pin Point objective was to provide a system with the following characteristics: payload, 500 and 2000 lb; glide ratio, 2.6:1 in no wind; sink rate (MSL, stable glide), less than 30 fps; airdrop aircraft, any cargo aircraft with capability of air-dropping payload; airdrop velocity, up to 130 KIAS; airdrop altitude, up to 15,000 ft (MSL); guidance system, automatic homing with manual override. Figure 1 shows the resultant 500-lb payload para-foil system in controlled gliding flight.

System Design

The para-foils being utilized in this program have evolved from a 165-ft^2 AR 1.5 para-foil design provided by the University of Notre Dame as part of an earlier analysis on the feasibility of the para-foil for a 500-lb payload cargo delivery application.[6] The 500-lb payload system utilizes a 300-ft^2 AR 1.5 para-foil and the 2000-lb system utilizes an 864-ft^2 AR 1.5 para-foil. These para-foils are of low-porosity coated nylon, incorporate shaped individual overlapping flares, an inlet extending the curvature of the first flare up to an intersection with the top surface and use of cross-flow ventilation ports in each interior rib.

The shaped flare and inlet design was arrived at through use of the static structural testing rig shown in Fig. 2. The airfoil/flare section was loaded with aluminum weights representing an assumed pressure distribution. Various flare shapes and material orientations were tested to determine that combination which would transmit and distribute suspension line forces while maintaining a straight chord line** and a smooth upper lifting surface. The radial lines extending from the flare tips to the chord line represent reinforcing ribbons which were included to assist in distribution of the suspension line forces. The dotted rectangles represent cross-flow ventilation ports incorporated into each interior rib to assist the inflation process and reduce potential overpressurization of individual cells during the inflation process.

The 24-v electro-mechanical guidance and control subsystems weigh about 150 lb for the 500-lb system and about 250 lb for the 2000-lb system. The para-foils with their rig-

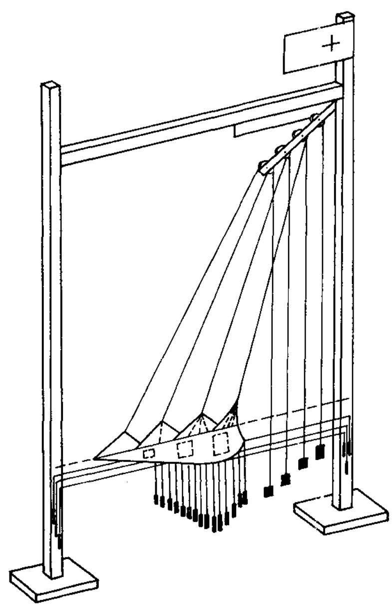

Fig. 2 Airfoil/flare static test rig.

¶ The information on this program was provided by R. J. Speelman III, Project Engineer, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.

** By convention the lower surface of the para-foil is the chord line.

ging and reefing hardware weigh about 55 lb for the 500-lb system and about 75 lb for the 2000-lb system. These weights should not be considered as representative of an optimum design but merely as the resultant weight of a design utilizing readily available hardware. It is felt that these weights could be reduced by 25–50% in an optimum system design. The combined weight of the payload, the guidance and control box, and the para-foil give system weights of 705 lb and 2325 lb or canopy loadings of about 2.4 and 2.7 psf.

The 500-lb payload system sequence of events is as follows: gravity extraction of the payload; static line deployment of a pilot chute; pilot chute deployment of the reefed para-foil; para-foil disreef, full inflation, and load stabilization. The 2000-lb payload system sequence is as follows: 15-ft ring slot parachute extraction of the payload; transfer of extraction line force to deployment of the reefed para-foil; para-foil disreef, full inflation, and load stabilization.

Free-Flight Performance

The objective of free-flight testing has been to demonstrate and verify the performance and functional characteristics of the para-foil system and system components. System performance was determined by on-board self-recording oscillographs and by cinetheodolite space position data corrected for wind conditions.[10,11] Free-flight testing conducted at release velocities from 18 to 135 KIAS and altitudes to 15,000-ft MSL can be categorized into three general areas: deployment/inflation, turn control, and glide.

Deployment Inflation

Theoretical calculations, wind-tunnel tests using 20-ft² AR 1.5 para-foil, and free-flight tests using para-foil ND 1.5 (145) at a canopy loading of 2.3–2.4 psf revealed a requirement to reduce force levels and indicated that a practical reefing technique was a combination of suspension line rigging to provide near zero angle attack and reduction of the inlet area during the deployment-inflation process.

Figure 3 illustrates the results of these reefing tests by showing the opening force coefficients obtained with the unreefed configuration, after incorporation of riser reefing (initial zero angle of attack rigging) and after incorporation of riser reefing and closure of about 30% of the inlet area. For the 300-ft² para-foil at a canopy loading of 2.4 psf, the unreefed opening force at a release velocity of 130 KIAS was estimated at 11,000 lb. Incorporation of the inlet reefing for 2 sec after aircraft release and the riser reefing for 4 sec results in reducing this to a force peak of about 3000 lb occurring at initial reefed inflation and then again at riser reefing release.

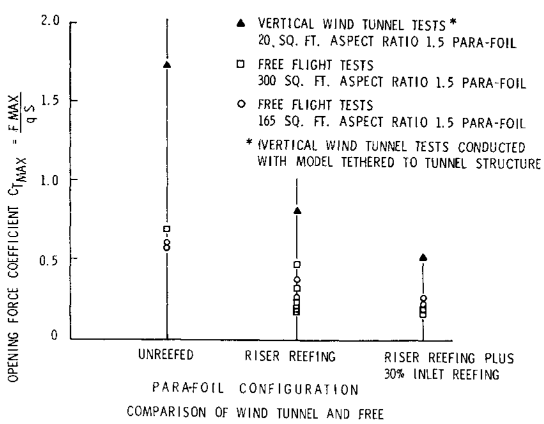

Fig. 3 Comparison of wind-tunnel and free-flight opening force coefficients.

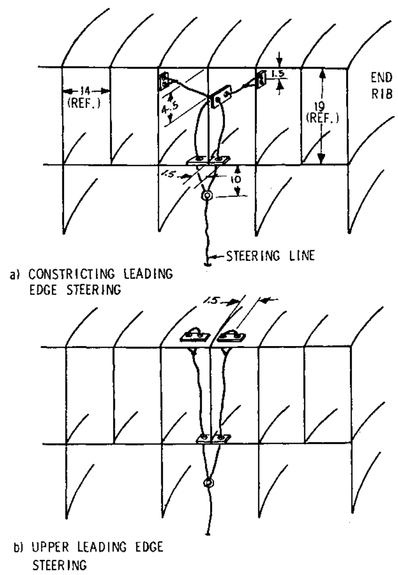

Fig. 4 Leading edge steering techniques.

Turn Control

The following techniques for distorting the para-foil to obtain turning moments sufficient to provide positive control were qualitatively evaluated during truck tow tests of a 165-ft² para-foil and a 300-ft² para-foil at speeds of 30–60 fps: 1) warping the para-foil by pulling on various suspension line attachment flares in the two aft rows and 2) deflecting one of the forward outboard corners by collapsing or constricting the cell inlets. Figure 4 illustrates two techniques of accomplishing this deflection.

The truck tow tests revealed that the leading edge deflection techniques required less steering line travel and less force than did those techniques using various rear suspension lines and they did not result in the control reversal characteristic which was observed when using the rear suspension lines. Control reversal occurs when the para-foil turns to one side for a certain amount of steering line travel and then reverses itself and turns to the other side after any further steering line travel.

For the 500-lb system, the constricting technique was selected and in conjunction with the available steering motor torque/travel/speed operating envelope, has resulted in turn rates of from 5 to 25°/sec.

The present breadboard automatic guidance and control subsystem for the 500-lb payload system operates such that upon sensing that it is of course by a predetermined amount, the proper steering line is pulled full and is not released until the unit senses that it is again back on course. This results in the system flying somewhat of a sine wave flight path towards the transmitter. To compensate for the relatively slow speed of the available servo motors and this overcontrol dictated by the available guidance electronics an automatic homing mode turn rate of 13 to 15°/sec was selected and has proven successful in winds of up to 50 fps.

When the 500-lb payload system flys over the transmitter it assumes an orbit pattern generally resembling a figure eight. Impact accuracies of 200 yd or less are obtained depending on where in this figure eight pattern the unit is when it runs out of altitude. A more realistic impact accuracy, representative of that attainable with a guidance and control subsystem properly designated for this application, is that obtained with manual control inputs. With this present hardware, an operator can insert manual override commands as the system nears the ground and can easily increase impact accuracy to less than 50 yd.

Glide Performance

The system glide ratio for the entire flight is computed from space-time data as the ratio of horizontal velocity (wind

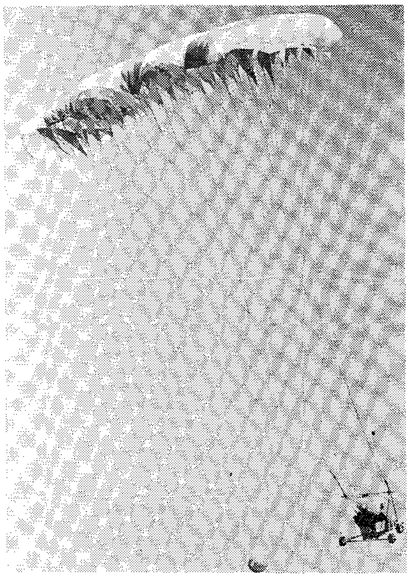

Fig. 5 Towed cart manned ascending flight.

corrected) to vertical velocity. The system glide ratio is affected (reduced) during turns by the steering technique utilized and it is also affected during periods of nonturning flight by wind gusts. System glide ratios ranging between 1.5 and 2.4 (Fig. 13) for the 300-ft^2 para-foil at canopy loadings from 0.77 to 2.4 pfs were obtained. Utilizing the following selection criteria to review the wind corrected space position data: 1) minimum sink rate variation, 2) low wind or relatively constant wind magnitude and direction, 3) equilibrium nonturning gliding flight, i.e., a straight line ground plane plot and a constant total velocity, 4) derived left coefficient values, and 5) minimum attack angle variation and near zero roll angle.

Based on wind-tunnel research conducted since the present system design was frozen (see following section), it is felt that the system glide performance could be improved by rerigging to a new angle of attack or by use of a higher aspect ratio design. However, in light of the objective to build a demonstration type system around the para-foil rather than to obtain maximum performance, improved designs were not introduced.

Sounding Rocket Payload Recovery††

Since the mid 1940's, sounding rocket flights have been conducted to investigate the Earth's upper atmosphere. The normal payload recovery method is to use conventional parachutes. However, due to high winds at altitude, such a technique can cause large dispersion in the final impact area of even complete loss of the payload.[7]

Since 1961, the Sandia Corp. has been interested in application or radio controlled, automatic homing steerable parachutes as a means of obtaining trajectory control of the returning payload.[12] In 1966, a project was initiated to investigate the para-foil's potential in this area. The specific objective of the program was to provide a system with the following characteristics: payload, 150 lb; glide ratio, 3.5:1 in no wind; sink rate (MSL, stable glide), less than 30 fps; deployment velocity, up to 180 KIAS; deployment altitude, 70,000–100,000 ft (MSL); guidance system, automatic homing.

An ND 2.0 (72) para-foil is used with this payload and weighs about 9 lb. The 28-v electromechanical guidance and control package weighs about 10 lb.[12] These weights are not optimum design weights but are the weight of a design utilizing available hardware. The combined weight of the para-foil, the guidance and control package and the payload is 169 lb giving a canopy loading of about 2.4 psf.

The sequence of events for the rocket payload recovery is as follows: drogue gun deployment of a pilot chute; pilot chute deployment of the para-foil and para-foil inflation.

Prior to selection of a particular para-foil for rocket payload recovery, deployment and gliding tests were carried out by Sandia on para-foils ranging in size from 8 to 313 ft^2. These tests validated a packing and deployment technique and provided lift-to-drag ratios ranging from 1 to 4[7] depending on the design used.

Based on the success of these early tests, a 9-lb ND 2.0 (72) para-foil was designed by Notre Dame and tested by Sandia at deployment velocities ranging from 30 to 200 KIAS and at altitudes to over 9000 ft. This para-foil has been successfully deployed with a canopy loading of 2.1 psf at a dynamic pressure of 120 psf (deployment velocity of 350 fps).

Additional tests on a similar sized unit at a canopy loading of 0.7 psf have yielded system glide ratios of 3.88.[13] This was obtained from a three station cinetheodolite camera network and is an average for the major portion of the flight as corrected for winds. Tests have also been carried out on a similar sized unit using a 10 lb, 28 v, electromechanical automatic homing subsystem which was able to guide the para-foil at a wing loading of 1.4 psf to the area of the ground transmitter with good control response. Control was obtained by using the 4 suspension lines in each rear corner.[7]

Tethered Applications

From the beginning, the para-foil has shown promise for kite type applications. Designs ranging in size from 8 to 864 ft^2 have been flown in the tether mode to flight altitudes well over a mile. Most para-foils in fact are first tested as kites to check rigging, trim, and general performance. Some of the various tethered applications are summarized in the following sections.

NASA Apollo‡‡

The tracking ship radars which are used to guide the Apollo Spaceship must be accurately aligned. In order to provide a high-altitude target for alignment calibration of two different radar tracking systems. Para-foil kites carrying 15-lb radar tracking devices were proposed. An ND 1.5 (165) para-foil for low wind (5–15 knots) and an ND 1.5 (120) for high wind (15–40 knots) were designed and flight tested at Notre Dame to altitudes of over a mile. To insure stable flight under extreme conditions a weight transfer type mass stabilization system was also provided in these systems supplied to NASA Goddard.

Army—White Sands§§

The U.S. Army in carrying out missile and rocket tests at the White Sands Missile Range must insure accurate warhead impact under various weather conditions. In order to determine the correct ballistic wind, temperature, and pressure at high altitude, an ND 1.5 (165) para-foil and an ND 2.0 (18) para-foil are being tested to carry weather instruments to 3000-ft altitude. Para-foils are also being investigated by this organization for application in gathering air diffusion data for toxic fuels and for gathering air pollution data.

†† The information on this program was provided by W. B. Pepper, Parachute Project Leader, Aerothermodynamics Dept., Sandia Corp., Albuquerque, N.M. This program was supported by the United States Atomic Energy Commission.

‡‡ This program is under the direction of J. McKenna, Navigational System, NASA Goddard Space Flight Center, Greenbelt, Md.

§§ This program is under the direction of J. Horn, Atmospheric Sciences Laboratory, U.S. Army, Electronics Command, White Sands Missile Range, N.M.

Colorado State University¶¶

As instrumentation platforms for high-altitude meteorological research an ND 2.6 (165) para-foil and an ND 2.4 (360) para-foil were provided to the Atmospheric Research Laboratory at Colorado State University. In conducting this research the ND 2.6 (165) para-foil has been flown from near the top of a 12,000-ft mountain to altitudes of 20,000-ft MSL.

Sandia Corporation***

An ND 2.6 (165) para-foil identical to the unit provided to Colorado State University was loaned to the Sandia Corporation for use as a meteorological monitoring instrumentation platform. For this application, Sandia has also constructed and tether flown a 176 ft^2 para-foil of AR 2.66, a 704 ft^2 para-foil of AR 2.66 and a Bifoil, or double deck para-foil, consisting of two 72 ft^2 AR 2.0 para-foils.

In low-wind conditions, the para-foils are truck towed to altitude of about 1000 ft where the winds are generally sufficient to maintain flight from a stationary tether point. On one tow test after reaching an altitude of 400 ft with the 704-ft^2 unit, the tether line was cut and the unit was allowed to free glide. The horizontal glide range crosswind, with a high drag 400-lb payload, was approximately 1000 ft.

U.S. Air Force Targetry†††

During both tethered tests and free-flight tests, it has been found that para-foils are able to fly well with numerous holes and broken suspension lines. Accordingly it appeared that the para-foil might have application as a target and the following three phase program was established: 1) para-foil as a tethered target, 2) para-foil as a deployed and gliding target, and 3) para-foil as a towed target. The test program has included flights of para-foils ranging in size from 8 to 864 ft^2 and has included aerodynamic loadings in excess of 3 psf on some of the tests. The first two phases have been completed and while numerous tow tests have been carried out, aircraft tow tests have not yet been attempted.[8]

Manned Flight

During tethered tests of an ND 0.7 (313) para-foil at the University of Notre Dame in 1965, two graduate students were inadvertently lifted into the air. Manned flight soon became standard practice. In the resulting ascending flight test program students were towed to altitudes of 500–1000 ft, first with and then later without the cart as shown in Fig. 5, released from the tow line, and allowed to glide freely back to earth (Fig. 6). By pulling on suspension lines attached to the trailing edge, the student was able to conduct a flare-out maneuver and practically eliminate his horizontal and vertical velocity components and simply step down to a one-foot landing.

The confidence gained through these early manned ascending flight experiences, and extensive unmanned deployment tests lead to the first manned aircraft jumps of the para-foil in 1966 at the University of Notre Dame and later for key Department of Defense personnel at Quantico, Va. Para-foils ND 1.5 (165) and ND 1.8 (360) were used in these early manned jumps. Subsequent extensive live jump operations have been successfully carried out.

U.S. Navy Personnel Recovery‡‡‡

In 1963, the U.S. Navy initiated a program to develop a parachute assembly which would be more maneuverable than the currently approved military types and capable of employment as a single-parachute assembly for premeditated static line and free-fall personnel parachuting operations. As part of this program, the U.S. Naval Aerospace Recovery Facility is currently evaluating the para-foil to determine its feasibility and potential for employment: 1) as a recovery parachute assembly in aircraft ejection seat escape systems; 2) in premeditated static line and time delay/free-fall live jump operations. The program was designed to provide information and data on para-foil deployment, inflation, stability, reliability, and aerodynamic and flight performance characteristics, including the rate of descent, horizontal velocity, oscillation, opening forces, lift-to-drag ratio, and drag area.

Fig. 6 Notre Dame student in gliding flight.

It is planned to use ND 2.0 (360) para-foil assemblies weighing about 48 lb to conduct approximately 68 torso dummy tests at gross weights of 200,250, and 300 lb (canopy loadings of 0.55, 0.70, and 0.83 psf). No live jumps were programed for this initial phase of the investigation. These tests were to be made with indicated airspeeds at launch varying from 60 to 300 KIAS and from altitudes ranging from 1500 to 20,000 ft. The number of tests were predicated on the employment of 5 para-foil assemblies. At the completion of these tests, it is planned to conduct additional tests, if the condition of the para-foils permits. A total of 31 torso dummy tests have been completed at gross weights of 200, 250, and 300 lb at airspeeds varying from 60 to 175 KIAS and from altitudes of 1500- and to 15,000-ft MSL.

The sequence of events in these torso dummy tests are as follows: gravity launch of the dummy; static line opening of the para-foil container; pilot parachute extraction of the deployment sleeve and deployment of the para-foil; para-foil inflation.

There were normal deployment and opening in 23 of the 31 tests. During 25 of the tests, the para-foil had an acceptable rate of descent, i.e., within the performance specified for a 300-lb parachutist. These 25 tests include two tests where damage was incurred resulting in delayed inflation, however, in both instances, the para-foil did inflate, recover, and descend in a steady-state condition.

The para-foils, as originally furnished, had the control lines attached to the trailing edge. During deployment the control

¶¶ The tests are under the direction of L. Grant, Associate Professor, Department of Atmospheric Sciences, Colorado State University, Ft. Collins, Colo.

*** These tests were under the direction of W. Pepper, Aerothermodynamics Dept., Sandia Corp., Albuquerque, N.M.

††† This program is under the direction of A. C. Cobb, Headquarters Air Proving Ground Center, Eglin Air Force Base, Fla.

‡‡‡ The material on this program was prepared by G. L. C. El Centro, Calif.

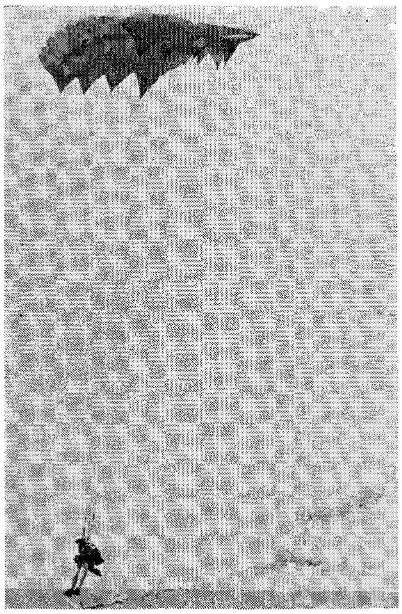

Fig. 7 U.S. Army Golden Knight in gliding flight.

lines would whip the canopy causing friction burns, lineovers, and frayed control lines, which either impaired or delayed inflation. Relocating the control lines to inboard suspension flares forward of the trailing edge eliminated this problem.

While conducting tests at 150 KIAS at a gross weight of 300 lb, one of the para-foils had one row of flares and single flares on two other rows torn off, a suspension line broken, and the deployment sleeve damaged. Although inflation was delayed and the para-foil was spiraling during descent, it did fully inflate and glide in a stable condition to impact.

During the 175 KIAS tests, one of the para-foils had two rows of flares torn off and three suspension lines broken; however, it did inflate and descended at a rate of 30 fps. Another para-foil had 5 rows of flares torn off, 17 suspension lines broken, and one of the cells split open. The canopy failed to inflate. Deterioration could have been a factor, since the para-foils had been used on several tests. While conducting these tests, no attempt has been made to control or steer the para-foil to determine its maneuverability and controllability during descent and prior to impact. Testing at pressure altitudes of 5000, 15,000, and 20,000 ft has been initiated, but there is insufficient data presently available to adequately assess the deployment and flight performance.

The tests indicate that this type of gliding parachute is very stable during descent with little or no oscillation. For an average of 4 tests at a gross weight of 200 lb, the rate of descent is 9.2 fps and the horizontal velocity is 27.4 fps (glide ratio about 3.0). For an average of 4 tests at a gross weight of 250 lb, the rate of descent is 9.6 fps and the horizontal velocity is 30.7 fps (glide ratio about 3.2). For an average of 15 tests at a gross weight of 300 lb, the rate of descent is 11 fps and the horizontal velocity is 34 fps (glide ratio about 3.0).

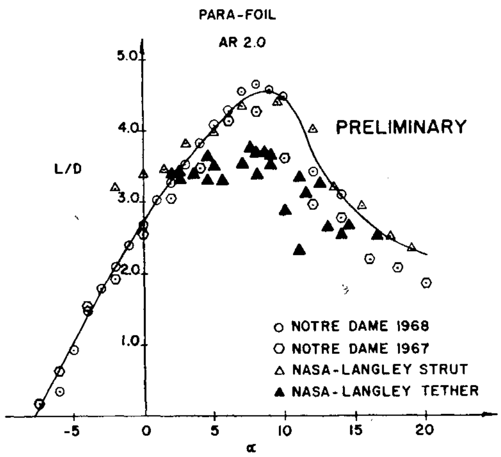

Fig. 8 Lift-to-drag as function of angle of attack (AR = 2).

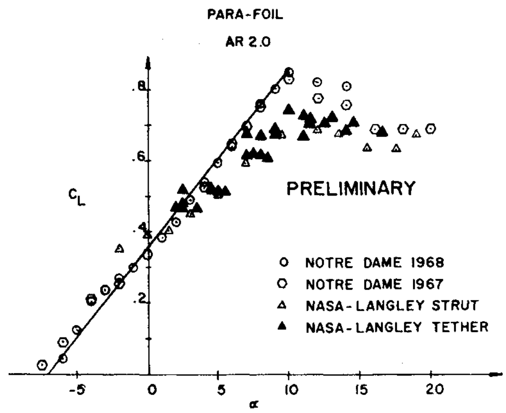

Fig. 9 Coefficient of lift as function of angle of attack (AR = 2).

With a gross weight of 300 lb, the riser forces at opening were 1600 and 1.750 lb at 60 KIAS, and 3100 and 4825 lb at 175 KIAS. These are total forces obtained by attaching both risers to a single self-recording tensiometer.

In determining the glide ratio, an average is taken of the performance during the final 500 ft of descent as determined by cinetheolodite space position data which have been corrected for wind and other ambient conditions.[11] Upon completion of the testing, the acquired information and data will be analyzed and an assessment will be made of the potential, capabilities, and limitations of this type of gliding parachute in the light of current objectives and requirements. The test results will be presented in a technical report to be published by the Naval Aerospace Recovery Facility.

U.S. Army Manned Flight Tests§§§

In late 1967, a program was initiated to acquire definitive para-foil free-flight performance data through use of on board

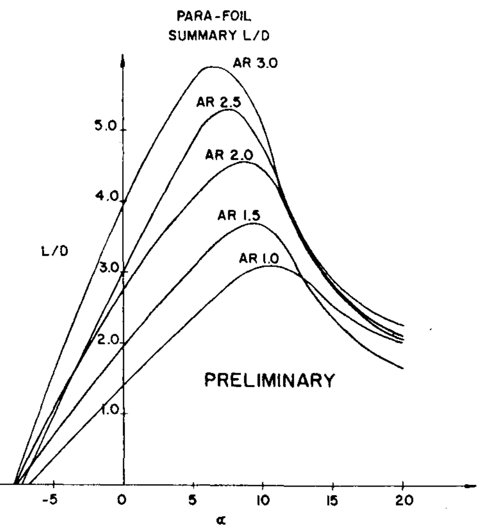

Fig. 10 Summary lift-to-drag as function of angle of attack.

§§§ This program is under the direction of S. Metres, Project Manager, U.S. Air Force Flight Dynamics Laboratory.

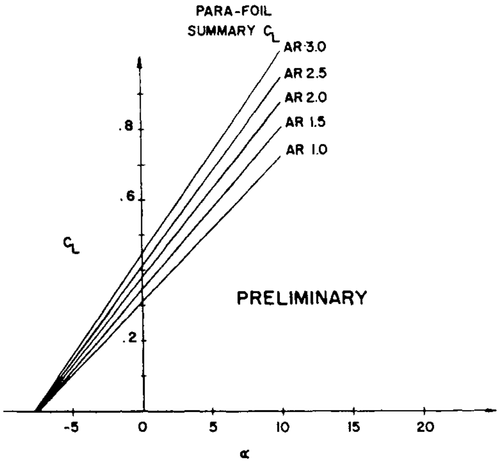

Fig. 11 Summary coefficient of lift as function of angle of attack.

instrumentation and the two station cinetheodolite range at Wright-Patterson Air Force Base.

Seven manned jumps¶¶¶ using the ND 2.0 (360) para-foil (see Fig. 7) and numerous manned ascending flight tests* using the ND 2.0 (360), ND 2.0 (242), and ND 2.0 (200), para-foils have been successfully carried out.

U.S. Army Manned Flight Tests†

The U.S. Army Golden Knight jump team expressed an interest in live jumping the para-foil ND 2.0 (360). Thirty jumps were carried out at Fort Bragg under the cognizance of the University of Notre Dame. Two of the turn control techniques which were used are discussed under the Navy personnel recovery program. The third technique was similar to the leading edge system used by the Air Force Dynamics Laboratory in the cargo delivery system. As a result of experience and confidence gained in these tests, the Golden Knights in cooperation with the University of Notre Dame conducted the above mentioned seven manned jumps on the instrumented test range at Wright-Patterson Air Force Base.

Following these and additional jumps the University of Notre Dame provided an ND 2.0 (242) para-foil suitable for deployment from a standard parachute pack. Following the usual checkout tether tests and ascending flight tests at Notre Dame, two dummy drops and three live jumps were carried out at Ft. Bragg. Excellent deployment, flight stability, control and landing flare were achieved.‡

Wind-Tunnel Tests

From the original Notre Dame para-foil studies in 1964 until the present day, continued wind-tunnel tests of various para-foil designs have been carried out.

The U.S. Air Force Flight Dynamics Laboratory has sponsored University wind-tunnel tests on para-foil designs having aspect ratios of 1.0, 1.5, 2.0, 2.5, and 3.0. The rigid model for these tests had a chord of 5 in., a cloth upper and lower surface, rigid flares and no suspension lines.[15]

¶¶¶ Jumps conducted by the U.S. Army Golden Knights in cooperation with the University of Notre Dame. The U.S. Army Golden Knight team is under the command of G. V. Plummer who, with R. F. McDermott and his teammates, have carried out numerous para-foil jumps.

* Ascending flight tests conducted by University of Notre Dame students.

† This program is under the direction of J. E. Forehand, Project Manager, U.S. Army Aviation Material Laboratories, Ft. Eustis, Va.

‡ Lift-to-drag ratios in excess of 5 were measured by Notre Dame from smoke trails on tests conducted at Ft. Bragg and South Bend.[14]

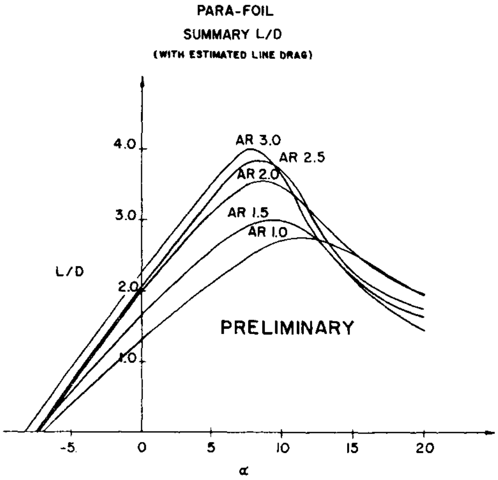

Fig. 12 Summary lift-to-drag (with estimated line drag effects included) as function of angle of attack.

The U.S. Air Force Flight Dynamics Laboratory has also sponsored Notre Dame in a full-scale wind-tunnel program with NASA-Langley. The 30-ft × 60-ft tunnel was used to test para-foils ND 1.0 (147), ND 1.5 (147), ND 2.0 (147), ND 2.5 (147), and 3.0 (147). Also an additional ND 3.0 (147) unit was progressively cutoff to yield additional smaller models of aspect ratios 2.5, 2.0, 1.5, and 1.0. These para-foils were tested in the freely tethered and the strut supported modes.[15]

Figures 8 and 9 present lift-to-drag§ data and coefficient of lift data as functions of angle of attack for the AR = 2.0 units.[15] Figures 10 and 11 present summary curves for the lift-to-drag§ data and coefficient of lift¶ data as functions of angle of attack for the various aspect ratios.[15] Figure 12 provides summary data which include line drag, based on 0.94-in.-diam (about 400-lb) suspension lines and a cascade rigging technique.[15] Wind-tunnel data acquired at NASA-Langley on the 300-ft² AR 1.5 para-foil beings used by the AFFDL is shown in Fig. 13. The data presented herein are for particular para-foil designs and do not necessarily represent an optimum airfoil section, planform, flare, and aspect ratio design.

Free-Flight Tests

Numerous free-flight tests of various para-foil designs have been carried out. Two testing techniques discussed under

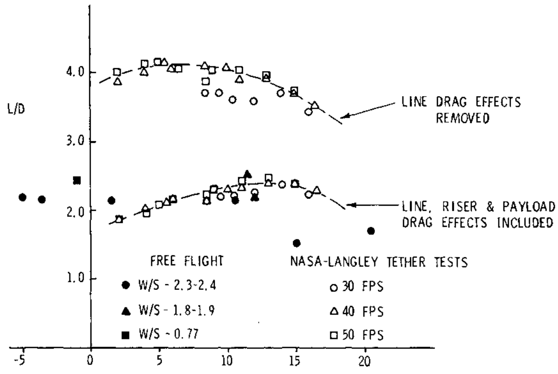

Fig. 13 Lift-to-drag as function of angle of attack for AR 1.5 cargo delivery para-foil.

§ NASA-Langley test data plotted after removing line drag effects.

¶ A common zero lift point was used.

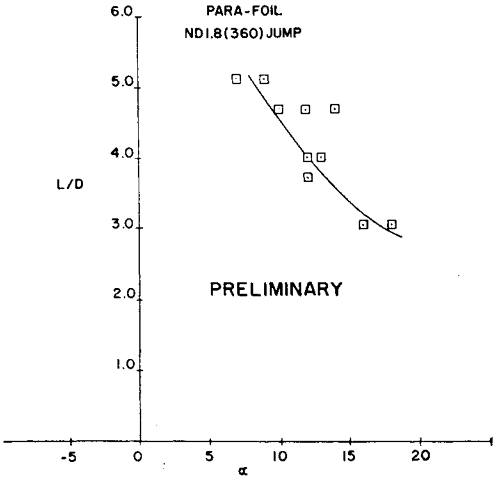

Fig. 14 Lift-to-drag as function of angle of attack for ND 1.8 (360) para-foil.

previous sections which have been employed are deploying the para-foil from an aircraft and the towed ascending flight technique where the inflated para-foil is towed aloft and then released.

Free-flight lift-to-drag ratio data obtained by the AFFDL on the 300 ft² AR 1.5 para-foil being used in the cargo delivery application are shown in Fig. 13. These data that were arrived at as discussed in the cargo delivery section of this report are felt to be fairly accurate as far as lift-to-drag valves are concerned, however, the corresponding angles of attack are questionable and may be off by as much as 5°.

Free-flight lift-to-drag ratios obtained on para-foil ND 1.8 (360) are shown in Fig. 14. These data were obtained by Notre Dame, using the trailing smoke technique, from unmanned ascending flights, manned ascending flights, cart flights, and manned jumps.

Free-flight lift-to-drag ratio obtained by Notre Dame, using the trailing smoke technique, on para-foil ND 2.0 (360) are given in Fig. 15. These data were obtained from manned and unmanned University ascending flights, and from drops carried out by the U.S. Navy at El Centro.

Free-flight lift-to-drag ratio data obtained by Notre Dame, using the trailing smoke technique, on para-foil ND 2.0 (242) are given in Fig. 16. These data were obtained from University ascending flight tests, and from live jumps carried out by the U.S. Army Golden Knights at Ft. Bragg.

In general, the lift-to-drag data from free-flight tests exhibit two basic characteristics. First, it is usually higher

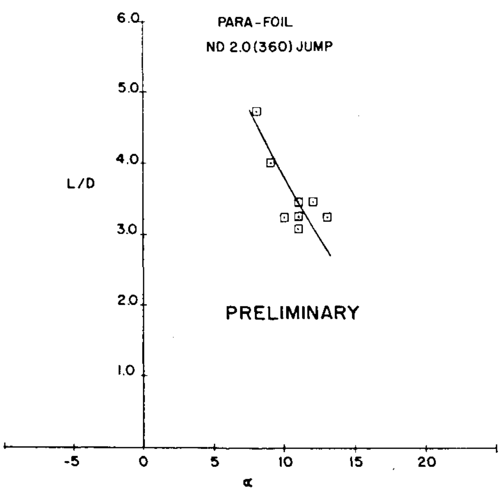

Fig. 15 Lift-to-drag as function of angle of attack for ND 2.0 (360) para-foil.

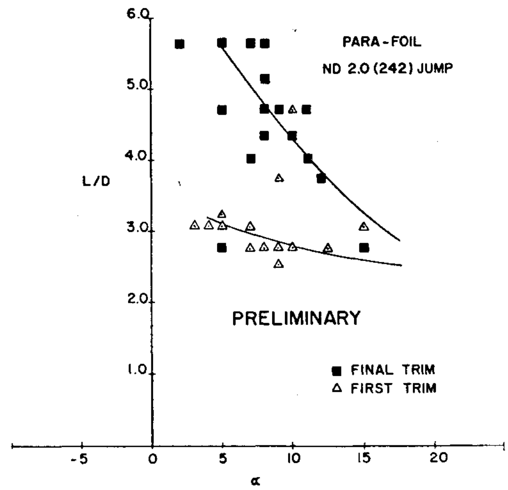

Fig. 16 Lift-to-drag as function of angle of attack for ND 2.0 (242) para-foil.

than wind-tunnel measurements and, second, there is considerable despersion in the data. The higher values are perhaps due to the larger Reynolds number providing an earlier turbulent boundary layer on the upper surface thereby delaying separation of the flow. The higher dispersion in the data is believed to be due to inaccuracies in the measuring techniques.

Powered Para-Foil Flight

The concept of a flying jeep or "Flying Flivver" has been fundamental with the para-foil since its origin at Notre Dame.[16] Hundreds of cart flights such as shown in Fig. 5 have been carried out at Notre Dame, both manned and unmanned.

Various designs of a propeller powered cart have been studied and continue to be analyzed.** The first experimental demonstration used a modified Bensen Gyrocopter (Fig. 17). The rotor was removed and a 6-ft spar substituted. The shrouded propeller was powered by a 70 hp McCullogh engine. The total weight was 500 lb with pilot and the ND 2.4 (360) para-foil. For the feasibility demonstration, the propeller powered cart was towed to altitudes of approximately 100 ft and released. Six powered sustained level flights were carried out, each terminating with a fully flared near zero velocity landing.[17]

Conclusions

Numerous free-flight tests and wind-tunnel tests have shown that the para-foil is able to achieve, dependent on the

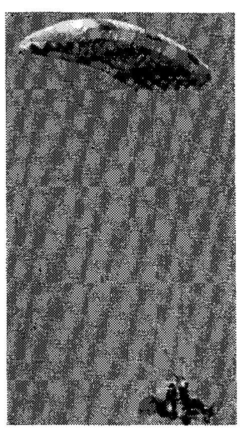

Fig. 17 Propeller powered manned flight.

** These studies have also considered the Bell Jet-Belt.

specific design (aspect ratio, etc.) and on the specific angle of trim, lift-to-drag ratios exceeding 4.

Full-scale unmanned drops and live jumps have demonstrated fast and reliable deployment (with and without reefing), excellent flight stability in free glide and under manned or automatic control. Fully flared landings with near zero landing velocity have been demonstrated through use of the para-foil's wide range of controlled trim angles ($-5° \leq \alpha \leq 90°$).

In applying the para-foil to various applications, it has been shown that 1) Controlled cargo delivery at drop speeds up to 130 KIAS can be accomplished with weights of up to 2000 lb. 2) Payload recoveries at dynamic pressures of 120 psf and at drop speeds of 350 fps have been demonstrated with 150 lb. 3) Tethered flights have been conducted to altitudes of over a mile for tracking, targetry and meteorological applications. 4) Numerous manned jumps and controlled landings have been accomplished. 5) Sustained manned-power flight and flare landings have been carried out.

Pare-foil designs for operation within the performance parameters discussed herein can be provided to satisfy current military and NASA requirements. Sufficient data are available for investigation of the para-foils capability to satisfy future military and NASA requirements.

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SEPT.-OCT. 1970 J. AIRCRAFT VOL. 7, NO. 5

A Two-Dimensional, Mixed-Compression Inlet System Designed to Self-Restart at a Mach Number of 3.5

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The methodology leading to the design of a Mach number 3.5 high-performance, two-dimensional, mixed-compression, inlet system with self-restart capability is reviewed. The principal feature of the design is a variable ramp system employing a flexible isentropic surface to provide efficient external compression ondesign and engine airflow matching with low spillage drag offdesign. An engine-face variable bypass system was also provided. Pertinent experimental results are presented for a range of Mach numbers from 1.55 to 3.5. Results show high over-all performance with moderate penalties associated with self-restart at Mach numbers of about 3.0 and above. Further bleed system optimization promises a means to eliminate these penalties and extend the self-restart capability to inlet systems of higher contraction ratios and thus potentially higher performance.

Nomenclature

A	= duct cross-sectional area
A_c	= inlet capture area, 196 in.^{2}
A_{LIP}/A_{THROAT}	= inlet contraction ratio
$(A_{LIP}/A_{THROAT})_{RESTART}$	= inlet restart contraction ratio (reference)
h	= height above surface, in.
M	= Mach number
M_1	= initial ramp Mach number
m_∞	= capture mass flow, $P_\infty V_\infty A_c$
m_{bl}/m_∞	= boundary-layer bleed mass-flow ratio
m_{by}/m_∞	= bypass mass-flow ratio
p_t	= total pressure
$\bar{p}_{t_2}$	= area-weighted average total pressure at engine-face station

Presented as Paper 69-447 at the AIAA 5th Propulsion Joint Specialist Conference, U.S. Air Force Academy, Colo., June 9–13, 1969; submitted September 25, 1969; revision received January 19, 1970.

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