Table A1 Precision at t = 100s

Δt, s	ω_x, rad/s	ω_y, rad/s	ω_z, rad/s
0.01	0.00254935	0.00456295	0.01518767
0.001	426	46752	1564
0.0001	75	5811	840
Error @ Δt = 0.01s	0.00000460	0.00010484	0.00006927
Percentage	0.18%	2.35%	0.45%

to sideslip. An accurate determination of stability and dynamic response requires a more rigorous analysis, and ultimately a detailed simulation or live test. Equation (1) is merely a quick "ballpark" estimate.

Appendix A: Computational Error

The computer program AIRPLANE integrates the six degree-of-freedom rigid airframe equations by an advanced/retarded Euler integration scheme. All computations are carried out double precision (51 bit mantissa—15 digit accuracy). A time step of 0.01 s is used. The solution is constructed for a period of 100s (10,000 steps). With these parameters, the dominant source of error is the use of finite steps. The error builds up with time. It can be reduced by decreasing the integration step Δt.

Table A1 demonstrates that this is indeed so. The values of the three components of $\boldsymbol{\omega}$, computed for t = 100 s (the worst case), are presented. The values obtained with Δt = 0.01 s are compared to ones obtained with Δt = 0.001 s and Δt = 0.0001 s. It is seen that the values converge as Δt is reduced. (Only the digits that change are shown in subsequent lines.)

Accepting $\boldsymbol{\omega}$ at t = 100s computed with Δt = 0.0001 s as ground truth, the errors in the values obtained with Δt = 0.01 s can be found (Table A1). The error in ω_y amounts to 2.35%. The error in the other components is a fraction of a percent.

Appendix B: Evaluation of Definite Integral

The definite integral

$$I = \int_0^1 \sqrt{1 - \eta^2}\eta^2 \, d\eta \tag{B1}$$

is evaluated by use of Cauchy's theorem. Consider the integrand as a complex function of the complex variable η. This function is single valued in the complex η plane with a slit running between -1 and 1. The integrand is positive just below the slit and negative just above the slit. It is easy to see that

$$I = \frac{1}{4}\oint_C \sqrt{1 - \eta^2}\eta^2 \, d\eta \tag{B2}$$

where the contour C runs counterclockwise around the slit. This contour may be deformed into the large circle C' (Fig. B1) without changing the value of the integral.

Now expand the integrand in powers of $1/\eta$:

$$\sqrt{1 - \eta^2}\eta^2 = i\sqrt{1 - (1/\eta^2)}\eta^3 = i\eta^3 - (i\eta/2) - (i/8\eta) + \cdots \tag{B3}$$

The expansion converges for $|\eta| > 1$, therefore, converges on C'. The contour integral becomes equal to $2\pi i$ times the residue at the simple pole, therefore,

$$I = \tfrac{1}{4}2\pi i[-(i/8)] = \pi/16 \tag{B4}$$

The integral in the numerator of (24) is $(4/\pi)I = \frac{1}{4}$.

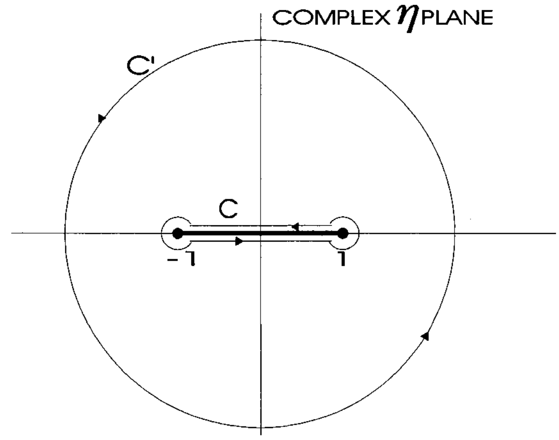

Fig. B1 Integration contours in the complex η plane.

References

[1]Seckel, E., *Stability and Control of Airplanes and Helicopters*, Academic, New York, 1964, p. 225.

[2]Katz, A., *Topics in Dynamics*, Lecture Notes, Univ. of Alabama Flight Dynamics Lab., 4th Printing, Pt. III, Tuscaloosa, AL, 1994.

[3]Evans, M., and Katz, A., "C++ Types for Three Dimensions," Univ. of Alabama Flight Dynamics Lab. (UA FDL), Rept. 93S01, Tuscaloosa, AL, 1993.

[4]Katz, A., and Evans, M., "C++ Types for Three Dimensions," *ACM Transactions on Software Engineering and Methodology* (submitted for publication).

Stable Cross-Type Parachute with Inflation Aid

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Introduction

THE reduction of the minimum altitude needed for a safe release of personnel and payloads from low-flying aircraft is a real challenge to the parachute designer. The problem posed is to design a very reliable parachute system with short filling time, high drag coefficient, and little or no tendency to oscillate. In the following, a new parachute design is discussed that seems to have the potential to be used safely from low-flying aircraft and from helicopters as well.

Design of the LAP-LEONARDO Canopy

Several years ago Hoenen[1] invented a stable version of the cross parachute (German Patent DP 27 06 006 A1). The stabilizing effect was achieved by arms of trapezoidal shape plus horizontal slots between the roof and the four arms of the canopy (Figs. 1 and 2). This parachute (called STABKREUZ)

Presented as Paper 93-1201 at the RAeS/AIAA 12th Aerodynamic Decelerator Systems Technology Conference, London, England, UK, May 10–13, 1993; received June 26, 1994; revision received Dec. 28, 1994; accepted for publication Jan. 6, 1995.

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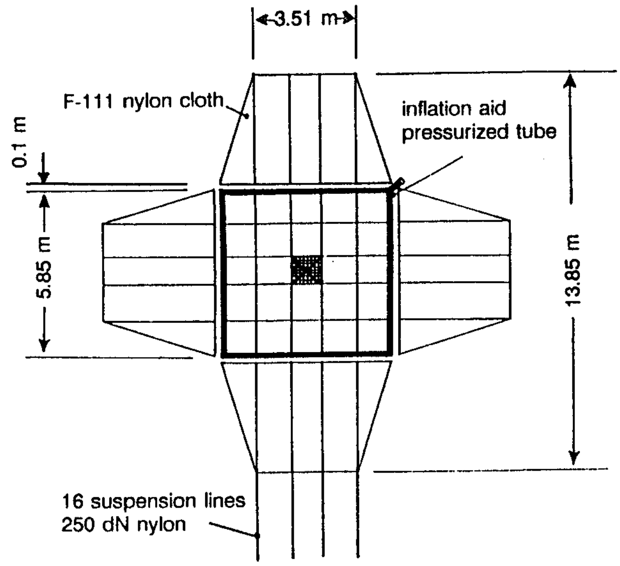

Fig. 1 LAP-LEONARDO canopy layout.

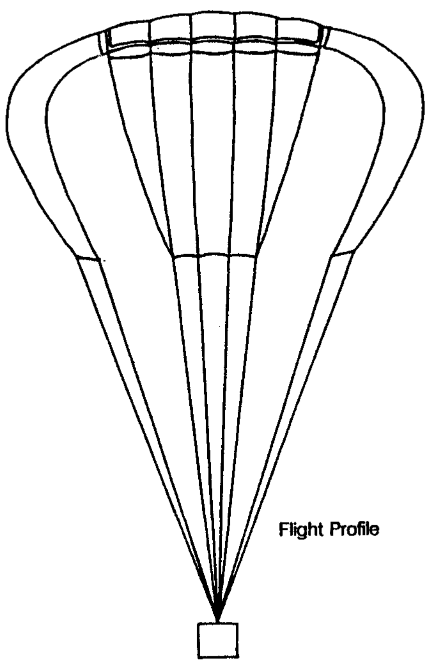

Fig. 2 LAP-LEONARDO flight profile.

has been used, e.g., in the three-canopy cluster recovery system of the tailless glider SB13 of the Akaflieg student group at the Technical University of Braunschweig.

In 1987 Krebber[2] introduced a pressurized plastic tube attached to the skirt of a parachute to improve its inflation characteristics and reduce the filling time. Since then this inflation aid has been tested on different parachute types and sizes, including personnel parachutes like the standard T-10.

Jumps with the T-10 canopy showed undesirable large oscillations. Therefore, a modified version of the Krebber tube was applied to Hoenen's stable cross chute (Figs. 1 and 2). The resulting parachute is called LAP-LEONARDO. Here, the tube is not placed at the skirt of the canopy, but at the hem of the square roof. The tube helps to spread the roof of the canopy at the beginning of the inflation, which should make the inflation sequence more reproducible and, as a consequence, reduce the scatter in the filling time.

Table 1 LAP-LEONARDO design data

	Type no. 1	Type no. 2
Canopy	Main	Reserve
Constructive diameter	13.85 m	9.0 m
Nominal diameter	11.81 m	8.13 m
Vent dimensions	0.60 × 0.60 m	——
Panels	4	4
Canopy material	F-111	F-111
Suspension lines	16	12
Line material	250-dN nylon	2 mm Kevlar®
Line length	8.3 m	4.9 m
Parachute weight	<4 kg	<2 kg
Drag coefficient C_{D_c}	0.70	0.70

Table 1 shows the design data of a complete parachute system consisting of a D_c = 13.85-m main canopy and a D_c = 9-m reserve canopy.

To avoid high filling shocks, a panel of low-porosity material is placed in the center of the roof of the larger canopy. This will eliminate to a certain extent the envisaged decrease of the filling time from the pressurized tube.

Drop Test Results

A 100-kg payload was dropped from a helicopter at 130 km/h and from a transport aircraft at 150–300 km/h in horizontal flight at altitudes between 50–80 m. On landing, in all cases the system had essentially achieved its steady-state velocity of descent. No severe oscillations were observed.

The flight tests were recorded by a video camera. In the evaluation of the inflation time from the video films, the usual difficulty arose. A standard definition of the inflation time is to take the time from suspension line stretch until the steady-state diameter is reached for the first time. From the video film it was not possible to decide when the second event happened. Koch[3,4] had similar problems when he analyzed cinetheodolite films. He therefore reported as inflation time the time t_V between the opening of the parachute pack until the system had achieved a vertical attitude for the first time. Johnson and Peterson[5] took the time from canopy stretch until the canopy reached its maximum diameter.

What really counts, when jumping from an aircraft at low altitude, is that before landing the parachute has achieved its maximum diameter and has become vertical for the first time without too much of an oscillation. The corresponding times, $t_{D\max}$ and t_V, respectively, plus the landing time t_L, are plotted vs the drop altitude h_0 in Fig. 3.

The parachute became vertical for the first time after 3.9–4.7 s and reached its maximum diameter after 5.1–5.9 s. By drawing a straight line through the $t_V(h)$ data points, an average of the steady-state velocity of descent of V_e = 3.9 m/s is estimated. This is comfortably low.

Dropped from 50 m at 300 km/h, the parachute reached its maximum diameter after 5.9 s and landed after 9.8 s. The parachute was fully open 3.9 s before landing or about 15 m above the ground. Thus, the altitude loss between leaving the aircraft until the parachute was fully open was about 35 m.

It must be pointed out that the inflation time $t_{D\max}$ did vary only slightly with the drop speed V_0. This means that the expected relationship

$$t_{D\max} V_0 / D_c = \text{const}$$

was not observed during these tests. The reason for this can be that the high porosity in the vent area keeps the parachute from inflating fully at high speed. Experimental data is lacking to prove this assumption.

From the steady-state velocity of descent the drag coeffi-

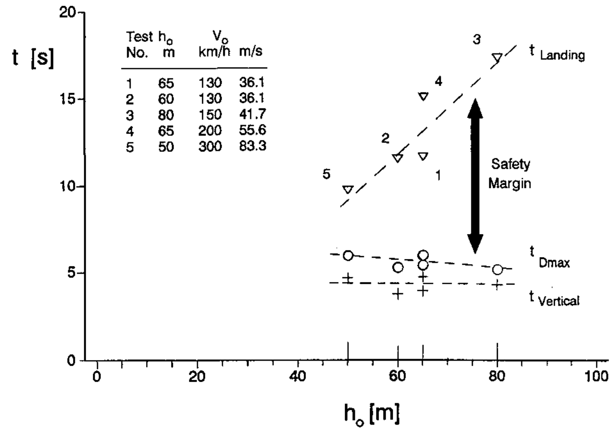

Fig. 3 Time sequences of the five drop tests.

cient can be calculated. Based on the constructive diameter $D_c = 13.85$ m:

$$C_{D_c} = \frac{mg}{(\rho/2)V_e^2(\pi/4)D_c^2} = 0.70$$

and, based on the nominal diameter $D_0 = 11.81$ m:

$$C_{D_0} = \frac{mg}{(\rho/2)V_e^2(\pi/4)D_0^2} = 0.96$$

With $C_{D_c} = 0.70$ the rate of descent of the reserve canopy will be about 6.0 m/s for a 100-kg payload and about 6.8 m/s for a 130-kg payload. This 9-m version of the LAP-LEONARDO is presently being investigated for its potential as a rescue parachute for glider, aircraft, and helicopter pilots.

Summary

A stable cross-type parachute of 13.85-m constructive diameter with an inflation aid for quick and reliable inflation has been developed as main canopy for low-altitude jumping from an aircraft or helicopter. A 9-m version of the so-called LAP-LEONARDO parachute has been designed as a reserve canopy and is also considered as a rescue parachute for pilots.

Acknowledgments

A number of dedicated parachute people like Peter Hoenen, Horst Buchsein, Norbert Frohwein, and Rüdiger Brumme, just to name some, designed, manufactured, and tested the parachute and financed the work.

References

[1]Hoenen, P., "Glider Recovery System," CCG-UofM-Course F12.01 on Parachute Systems Technology: Fundamentals, Concepts and Applications, Oberpfaffenhofen, Germany, June 1987.

[2]Krebber, B., "Rapidly Opening Parachute," CCG-UofM-Course F12.01 on Parachute Systems Technology: Fundamentals, Concepts and Applications, Oberpfaffenhofen, Germany, June 1987.

[3]Koch, R., "Technische Studie über Sprungfallschirmsysteme hoher Zuverlässigkeit für niedrige Absetzhöhen," DFVLR IB 154-73/4, Braunschweig, Germany, Nov. 1973.

[4]Fu, K.-H., and Koch, R., "Theoretical and Experimental Determination of Altitude Loss for Load-Systems Using Cluster Parachutes," AIAA Paper 75-1356, Nov. 1975.

[5]Johnson, D. W., and Peterson, C. W., "High-Speed, Low-Altitude Payload Delivery Using a Single Large Ribbon Parachute," AIAA Paper 84-0803, April 1984.

Forebody Vortex Control Using Nose-Boom Strakes

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I. Introduction

THE typical flowfield around a fighter-type aircraft at moderate-to-high angles of attack is dominated by vortices. The erratic behavior of these complex vortex flows at high angle of attack contribute to degraded control capability. The vortex-induced yawing moments are of sufficient magnitude that they often could not be overcome by the yawing moment generated by a deflected rudder. Many methods of controlling the forebody vortices have been developed recently, with some examples being Refs. 1–10.

One method of control is using small strakes located at or near the nosetip. The study by Ng and Malcolm[8] on a truncated F/A-18 forebody model showed that a rotatable strake on the nosetip is highly effective in controlling the forebody flow over a wide range of angles of attack and sideslip. The water tunnel study by Ng et al.[9] on an F-16 forebody model showed that miniature, rotatable strakes located on the nose boom are also effective in controlling the forebody vortices. In both cases, the positions of the forebody vortices can be controlled by rotating a strake to different roll angles relative to the nosetip. Significant control power can be obtained at angles of attack between 40–60 deg.

The objectives of the present experimental study are to determine the fluid mechanism of forebody vortex control using miniature, rotatable strakes at or near the nosetip, and to study aspects of the fluid mechanism that may be common to different forebody vortex control methods.

II. Experimental Setup

Two 1/10th-scale, F-16-like models were used. One is a full model tested at the NASA Langley Research Center 14- × 22-ft tunnel, and the other a forebody-only model tested at the University of Toledo 3- × 3-ft wind tunnel. The same forebodies were used in both tests. Force, moment, and surface pressure measurements were conducted at a tunnel dynamic pressure of 957.6 Pa (20 psf) for both tests. This corresponds to a Reynolds number of about 2.69×10^6/m (tunnel speed = 41.4 m/s). Additionally, smoke and surface flow visualizations were performed in the forebody-only test. The smoke flow visualization was conducted at a tunnel dynamic pressure of 47.9 Pa (1 psf), whereas the surface flow visualization was conducted at a tunnel dynamic pressure of 957.6 Pa (20 psf).

The forebody-only model was supported by a five-component (no axial force) force balance. A PSI electronic pressure scanner was set in the nose to measure the surface pressure distributions at fuselage stations 50 and 70. The full model tested was equipped with a six-component balance for measuring forces and moments, and three PSI electronic pressure

Received May 15, 1994; revision received Dec. 19, 1994; accepted for publication Dec. 27, 1994.

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