Status of Research on Parawing Lifting Decelerators

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The development of flexible-wing technology has been underway for several years and a considerable amount of aerodynamic research has been obtained. Results from these research investigations have shown that maximum lift-drag ratios from about 2.0 to 17.0 can be obtained with different types of flexible wing configurations. Recent emphasis has been given to all-flexible parawings that provide lift-drag ratios from 2.0 to 3.0 because of their reliable opening characteristics, good inherent stability, and their kinship to parachutes in simplicity of construction, packaging, and deployment. This paper summarizes the status of technology development of all-flexible parawings in regard to general research, the application to recovery of manned spacecraft, and for personnel use such as escape from a disabled aircraft.

Introduction

THE development of flexible-wing technology by the NASA Langley Research Center has been underway for the past ten years and grew from earlier work of F. M. Rogallo on flexible kites. Wind-tunnel investigations of parawings have covered a wide scope of wing configurations and accompanying aerodynamic characteristics. The spectrum of performance obtained for different types of parawings is shown in Fig. 1 for parawings that differ primarily in the type of structure that supports the flexible canopy. The data of Fig. 1 are presented as a function of the resultant-force coefficient because the resultant-force coefficient is a fundamental parameter for gliding flight; the flight velocity at a given altitude can be defined by the parameter W/SC_R.

The results of Fig. 1 show that maximum lift-drag ratios from about 2.0 to 17.0 can be obtained with different types of parawing configurations. The performance capabilities of parawings are shown to be a function of the degree of flexibility, which can range from a small, very rigid frame to a larger inflated tube frame to a completely flexible, parachute-like lifting surface.

The type of parawing that one would select for a particular use would, as with conventional aircraft wings, depend upon the performance and operational requirements of the particular application. For an application requiring relatively high performance, such as powered or towed vehicles, wing lift-drag ratios above 10.0 can be obtained with a parawing having a carefully shaped canopy and rigid frame. On the other hand, for some applications, complete flexibility is required, and lift-drag ratios as low as 2.0 can be accepted. Interest in advanced landing systems for manned spacecraft has, in the past three years, focused attention on all-flexible parawings because of their reliable opening characteristics, good inherent stability, and their kinship to parachutes in simplicity of construction, packaging, and deployment. Because of the research emphasis on completely flexible surfaces, this paper will be concerned with only the all-flexible parawings. Some of the latest work on parawings having rigid frames is reported in Refs. 1–4, and data for all-flexible parawings are presented in Refs. 5–7.

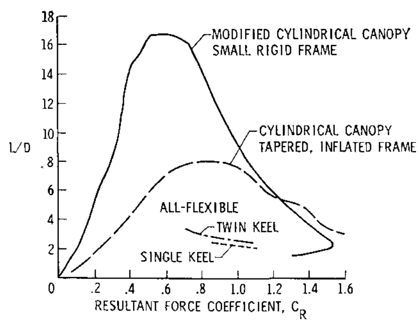

Fig. 1 Spectrum of lift-drag ratio for different types of parawings.

Scope of Parawing Configurations

The scope of parawing planform and configuration variations that have been studied in wind-tunnel investigations are shown in Figs. 2–5. Ten basic planforms that included variations in leading-edge sweep and nose cut are shown in the upper part of Fig. 2, and various detailed configuration changes are shown in the lower part of Fig. 2. Slotted wings and wings having ram-air inflated keels, shown in Fig. 3, complete the series of single-keel parawings investigated.

A systematic planform variation for twin-keel parawings is shown in Fig. 4 for 45°-swept outer panels. Several twin-keel parawings designed for use as variable-geometry wings are also shown in Fig. 4, with the planform designated by the included angle of each of the three panels. Three triple-keel

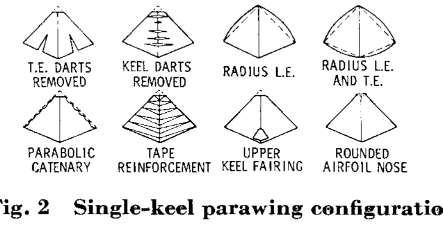

Fig. 2 Single-keel parawing configurations.

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Table 1 Full-scale tunnel and flight-test results obtained on all-flexible parawings

Wing configuration	LRC 30 × 60 tunnel $(L/D)_{max}$	LRC 30 × 60 tunnel $C_{R max}$	Ames 40 × 80 tunnel $(L/D)_{max}$	Ames 40 × 80 tunnel $C_{R max}$	Flight L/D
Single keel	2.5	1.10	2.6	1.05	2.3
Twin keel	2.9 to 3.4	1.09	2.9 to 3.2	1.10	2.7 to 2.9
Slotted single keel	...	...	2.2	1.06	...

parawings that have been tested only at small scale in the wind tunnel and in free flight are shown in Fig. 5.

A total of at least 100 wing configurations and modifications have been investigated in static wind-tunnel tests, and in general, the single-keel parawings provided lift-drag ratios slightly above 2.0 and twin-keel parawings provided values near 3.0. Therefore, development work on all-flexible parawings has focused on a single-keel, a twin-keel, and a slotted wing, which are shown in Fig. 6. The remainder of this paper will describe work that is being done on these parawing configurations.

Full-Scale Tunnel Test Results

Aerodynamic performance parameters obtained in the Langley and Ames full-scale tunnels are summarized in Table

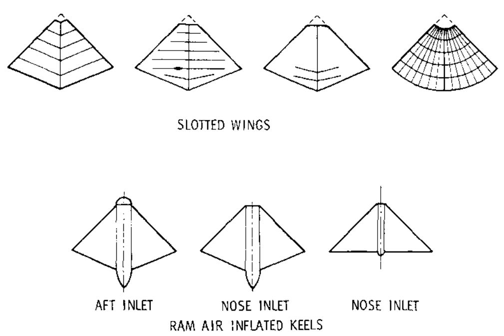


Fig. 3 Slotted and ram inflated parawing configurations.

1. Also shown in Table 1 are some flight values of L/D that were obtained from Northrop-Ventura tests of a radio-controlled parawing test vehicle as part of a Langley Research Center sponsored parawing contract effort. The results for the single-keel wing show a maximum lift-drag ratio of about 2.5 in both wind tunnels. Different construction methods and number of lines were investigated for the twin-keel wings. The range of maximum lift-drag ratios obtained for the different configurations is indicated, and a nominal value of 3.0 could be considered representative. All of the wings had maximum resultant force coefficients near 1.1. Lift-drag ratios measured in flight were slightly lower than the values obtained in the wind-tunnel tests. A decrease in lift-drag ratio of 0.3 to 0.4 could be expected for flight tests of the wing-payload combination when comparing flight results with wind-tunnel data for the wing alone.

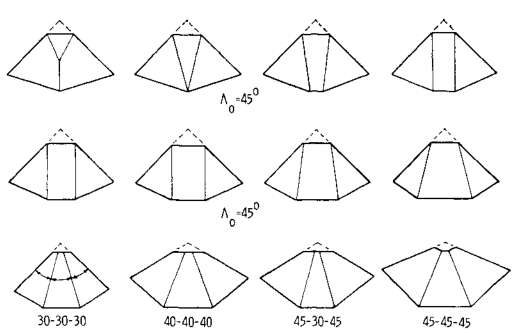


Fig. 4 Twin-keel parawing configurations.

The slotted wing showed a slightly lower value of maximum lift-drag ratio than the basic single-keel wing. However, selection of the slotted wing for development was based on its lower opening shock rather than on the basis of maximum performance. Because of its lower opening shock, the slotted wing is receiving considerable attention for application to personnel use, as will be discussed later.

Parawing Research Areas

Parawing research areas that are presently receiving attention can be outlined as follows: 1) general research, 2) development of technology at large scale for recovery of manned space vehicles, 3) personnel wings, and 4) precision aerial delivery of cargo (U.S. Army AVLABS).

The area of general research will be discussed briefly, and some details and test results of the work on technology development and personnel wings are given. Research on the use of parawings for precision aerial delivery of cargo is being sponsored by the U.S. Army; this work has been covered in other papers.

General Research

General research is an area that is often overlooked or proceeds without significant emphasis when an intensive development effort is undertaken. A continuing general research effort is needed, however, in order to gain a fundamental understanding of the results that flow from the development effort and to provide advanced designs that can more fully utilize the potential of the technology developments. The present general research effort can be summarized in the following areas.

Systematic wind-tunnel and free-flight tests are being conducted on relatively small models for the purpose of developing new configurations and improving present wing designs. These tests are directed toward obtaining improved performance, stability, control, and deployment characteristics.

Free-flight tests of wings designed for payload weights from 200 to 500 lb are being conducted on several types of test vehicles. Deployment loads and reefing studies are being conducted on instrumented bomb-type vehicles, and reefing techniques and turn rate studies are being made on inert lead weight payloads. Radio-controlled flights of an instrumented lifting-body test vehicle are being made to obtain data on landing and flight dynamics.

Theoretical studies have been undertaken in two contract efforts. The Nielsen Engineering and Research Corporation is conducting an exploratory theoretical investigation of all-flexible parawings with the long-term goal of establishing rational procedures and theory for predicting the longitudinal aerodynamic characteristics. A contract effort with the Massachusetts Institute of Technology has been initiated to obtain a theoretical and experimental study of thin, highly

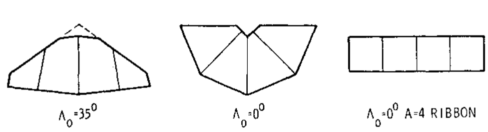


Fig. 5 Triple-keel parawing configurations.

Table 2 Objectives and test approach for the parawing technology development being conducted at Northrop-Ventura under contract to Langley Research Center

Project objectives:
Development to large-scale, 15,000 lb weight in the areas of:
- Deployment and reefing
- Aerodynamic performance, stability, and control
- Scaling relationships
- Materials and construction

Flight-test approach:

Small size (500 lb) deployment	Intermediate size (5,000 lb) deployment and flight dynamics	Large size (15,000 lb) deployment and flight dynamics
Single keel →	Single keel	→ Selected design
Twin keel →	Twin keel	

cambered airfoil sections. In addition to the contract work, special wind-tunnel tests are being conducted to provide fundamental research information on canopy shape and aerodynamic characteristics. Other work is being conducted to develop sensors for measuring canopy fabric stress and the pressure difference across the canopy.

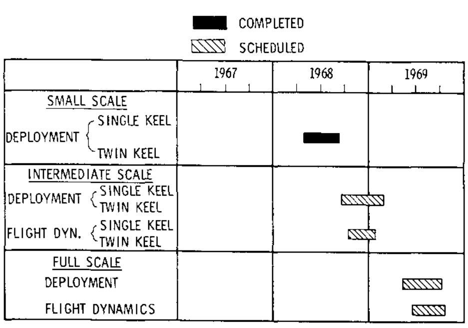
The general research discussed so far has been conducted or sponsored by the Langley Research Center; however, significant parawing work is presently underway by industry and other government organizations. An investigation of all-flexible parawings for recovery of lifting-body spacecraft is being conducted on radio-controlled test vehicles at the NASA Flight Research Center with the end objective of conducting manned flight tests for obtaining pilot evaluations of flight handling qualities. The Manned Spacecraft Center has, for several years, been conducting radio-controlled parawing flight tests with their Landing Operations Test Vehicle for the purpose of defining operational requirements for gliding descent systems for manned spacecraft. With regard to work being conducted by private industry, Irvin, Bell Aerosystems, All American Aviation, and Goodyear have active flight-test programs.

Parawing Technology Development Contract

A large amount of research information on deployment, reefing, wind-tunnel data, and flight behavior have been obtained on relatively small parawing vehicles at low speeds. The hard-core technology advances required to deploy 12,000 ft^2 of wing fabric at a dynamic pressure of 100 psf for a payload weight of 15,000 lb are expected to come from the contract work currently being conducted by Northrop-Ventura for the Langley Research Center. The project objectives and flight-test approach being taken in this contract effort are shown in Table 2 and the test schedule is given in Table 3.

Both the test approach and schedule recognize the importance of the development of deployment technology and compatible wing structural design. When these most difficult problems begin to yield to solutions, then attention will be given to measurement of flight dynamics and performance by means of radio-controlled tests of instrumented test vehicles. The flight dynamics work will be supported by the Manned Spacecraft Center, using their 5000-lb and 15,000-lb instrumented vehicles.

Table 3 Test schedule for the parawing technology development contract



Reefing for Single-Keel Parawing

A multistage reefing technique developed for the single-keel parawing is illustrated in Fig. 7. The parawing is extracted from the packing bag and deployed to the first reefed stage with all of the suspension lines of equal length. Skirt and trailing-edge reefing, and foreshortening of the keel by a keel reefing line provide approximately the canopy shape shown for stage 1. In the second stage of reefing, the wing leading edges are disreefed. In the third stage, the keel reefing is released and in the fourth stage, the trailing edges are released. The final disreefing step is the suspension line extension from equal length to glide rigging. Deployment lines attached to the trailing edges are allowed to go slack for the glide portion of the flight.

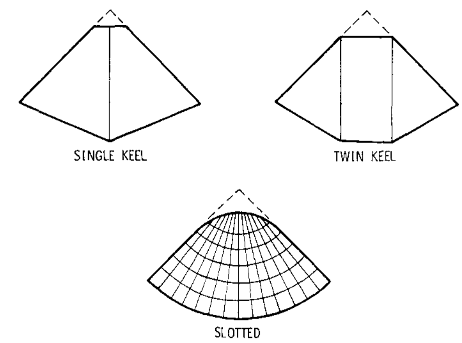


Fig. 6 45°-swept parawing configurations selected for development.

A sample time history of opening loads for the staged opening of a single-keel parawing is presented in Fig. 8. The data were obtained from early exploratory drop tests of a 24-ft

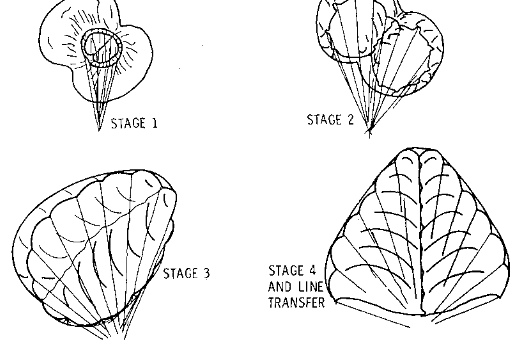


Fig. 7 Multistage reefing for a single-keel parawing.

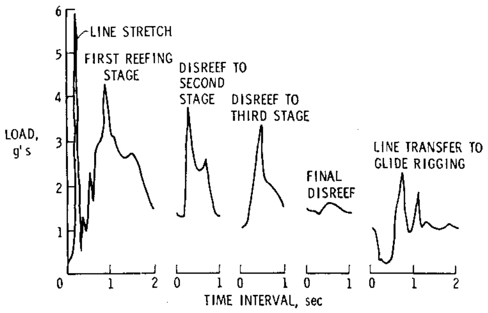


Fig. 8 Load data obtained during opening of a single-keel parawing having multistage reefing.

parawing with a reefing sequence similar to that just described. The main points illustrated by the results shown in Fig. 8 are that conventional reefing methods for parachutes can be successfully adapted to all-flexible parawings, and that the opening and disreef loads can be fairly well balanced throughout the stages of opening. Although some differences in peak loads are evident in these data, experience has shown that the load peaks can be varied by minor modifications to the reefing parameters in the same manner as for reefed parachutes.

Reefing techniques have also been developed for the twin-keel wing, based on the same approach as used for the single-keel wing. The reefing method for the twin-keel wing constrains the two keels in the first stage and releases the keels in the second stage. Opening shock loads comparable to those of the single-keel wing have been obtained with staged reefing on the twin-keel wing.

Prediction of Parawing Opening Loads

Some encouraging results on the estimation of parawing opening loads have been obtained in the past year, and the next two figures present some of these results. The work started with wind-tunnel deployment load measurements conducted by T. G. Gainer, and his subsequent modifications to existing procedures for parachute opening load estimation. Wind-tunnel results in the form of time histories of resultant force coefficient and its inclination were obtained for various constant values of dynamic pressure for each deployment, and a sample of these data are presented in Fig. 9. Inasmuch as the canopy filling time was found to vary inversely with the tunnel velocity, the time scale was nondimensionalized with respect to an empirically derived filling time. A curve was faired through the test points to obtain the time history of C_R and θ for the infinite mass case and the results were used in the equations of motion for a point mass to obtain estimated flight opening loads.

A comparison of calculated and measured opening loads for 400-ft^2, single- and twin-keel parawings is presented in Fig. 10. The results of Fig. 10 show very good agreement between calculated and measured load-time histories, except that the load peak was underestimated. Some minor revisions are being

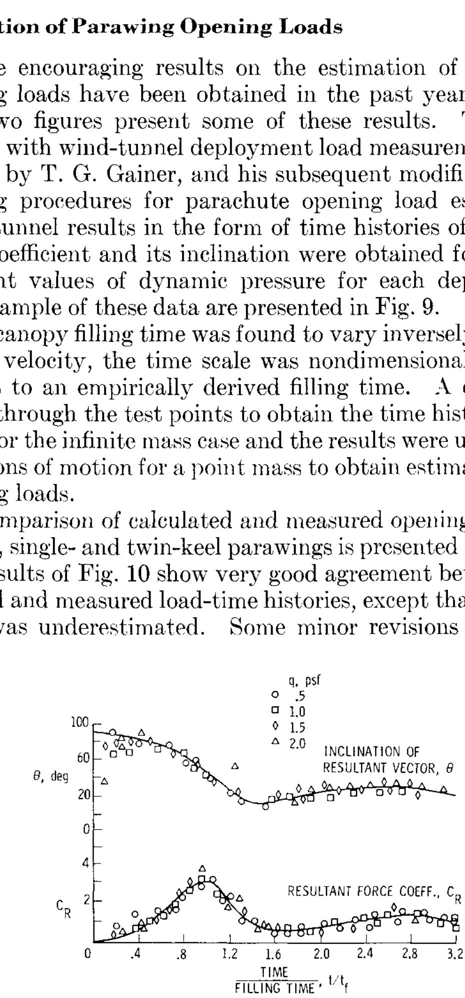


Fig. 9 Wind-tunnel results from deployment of a 5-ft, single-keel parawing.

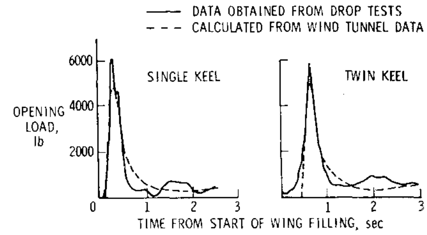


Fig. 10 Comparison of calculated and measured opening loads for 400-ft^2 parawings.

studied in order to improve the prediction of peak load. Calculations made to show effects of primary variables such as dynamic pressure and wing loading have been found to provide very good results, when compared with the measured effects. Experimental data on wings up to only 400-ft^2 area have been obtained and results from the Northrop-Ventura technology development effort will provide the experimental basis for assessing the applicability of the estimation procedures for large parawings.

Personnel Parawings

The very positive and rapid opening characteristics of the all-flexible parawing make it attractive for low-altitude, low-speed escape from disabled aircraft, even at altitudes too low to allow a significant controlled glide range. For escape from aircraft at higher altitudes or for paratroop type of operations, the all-flexible parawing can provide glide and steering capability that could enable a pilot to avoid undesirable landing zones and to avoid local obstacles at landing. The rapid opening characteristics, however, causes undesirably high opening shock loads at moderate and high speeds, and has prompted an intensive effort to find means for reducing the opening shock. An outline of the research effort on personnel parawings can be identified as follows: 1) U.S. Army exploratory evaluation at Ft. Bragg; 2) Langley Research Center tests of instrumented torso dummy to obtain a) opening shock loads, b) development of reefing techniques, and c) wing structural modifications for high-speed opening; 3) Langley Research Center sponsored whirl tower and air drop tests at El Centro; 4) DOD program at El Centro to evaluate different wing designs.

Most of the research on personnel parawings is concerned with development of very simple and reliable reefing techniques to reduce the opening shock load. Inasmuch as the tolerable opening loads for a personnel parawing can be higher than the more stringent requirement for spacecraft as dictated by minimal weight and packed volume of the descent system, only single-stage reefing is presently being investigated for personnel parawings. Several different reefing methods are currently being investigated, such as skirt reefing, line choke with a wrap-around device, and keel deformation by sortening one of the keel lines.

Many manned flights of all-flexible parawings have been made by members of the Army Parachute Team at Ft. Bragg, North Carolina, and exploratory evaluations of various methods of reducing opening shock are underway. In addition to studies of opening shock, evaluations are being made of different control arrangements and of flight characteristics.

Work currently underway at the Langley Research Center is indicated as tests of an instrumented torso dummy. Measurements of opening loads with and without reefing provide evaluations of the effectiveness of different types of reefing. In the process of developing wing systems for high-speed opening, delayed opening drops were made with an inert lead weight payload. Minor structural modifications were made to a commercially available slotted parawing that allowed a natural opening at a dynamic pressure of 104 psf without structural damage. An attempt to achieve a successful natural opening (no reefing) at q = 175 psf was made, but

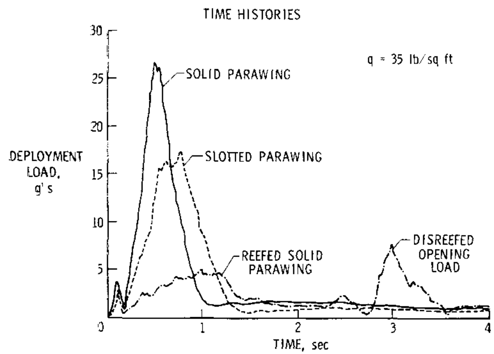


Fig. 11 Deployment load time histories for personnel parawings.

major structural damage to the wing occurred. An assessment of the damage is being made in order to define structural modifications that will insure integrity of the design.

An investigation of the opening loads of both slotted and solid (unslotted) personnel parawings was initiated about a year ago in whirl tower and air drop tests at El Centro. This work, which is almost completed, will be followed by a Department of Defense evaluation of three different flexible-wing configurations designed for personnel descent systems use. The configurations to be investigated are the sailwing, parafoil, and all-flexible parawing.

Some typical deployment load time histories are shown in Fig. 11 for both solid and slotted personnel parawings. These test results show that the high opening shock for the solid parawing can be significantly reduced by the use of a slotted wing configuration or by the use of skirt reefing on the solid wing. Although the opening shock for the slotted wing may be tolerable at $q = 35$ psf, some form of reefing will be required for the slotted wing in order to prevent injury from high-speed openings. Work is currently underway to develop satisfactory reefing methods for slotted personnel wings.

Concluding Remarks

The brief presentation of current parawing research activity has dealt with research highlights in several areas, and has been primarily concerned with progress since June of 1967. Additional developments in parawing research, not covered in this presentation, have also been made in such areas as measurement of parawing inertias and computation of apparent mass, measurement of parawing dynamic derivatives, development of simulator for pilot training and definition of pilot displays, and development all-flexible parawings for steady-state flight at speeds up to 200 mph. Much of the earlier work has been documented in Technical Notes and in Langley Working Papers, but most of the recent work is still in progress and documented details of this work are not yet available.

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