NASA RESEARCH ON FLEXIBLE WINGS

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SUMMARY

Flexible wings are wings made of very loose or slack cloth whose configuration in flight is maintained by the combination of the aerodynamic forces and the reactions from the load suspension system. Such wings can be completely flexible, or they may be stiffened in several ways to meet the requirements of particular applications. Wing planforms and the geometry of the load suspension system are also subject to wide variations.

The overall spectrum of flexible wings investigated at the Langley Research Center is presented and the state of the art with regard to maximum lift-drag ratios obtained is defined for a wide range of wing configurations. Maximum lift-drag ratios above 3.0 were obtained on completely flexible wings; and for cylindrical-type flexible wings, values of lift-drag ratios up to 17.0 were obtained when the wing had small, tapered rigid leading edges.

The flexible wings of most immediate interest are those with no structural stiffening because they have weight, volume, packing, and deployment characteristics potentially as good as those of conventional parachutes, but provide a stable and controllable glide with performance adequate for aerial delivery of cargo and personnel, for landing space capsules, boosters, or hypersonic aircraft, and as emergency wings for aircraft or aircraft escape systems.

The high-performance flexible wings at the other end of the spectrum, although not presently of general interest, show promise of becoming lightweight, rugged, stowable wings for applications such as roadable aircraft, flying

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boats, flying submersibles, cargo tow gliders, a variety of sport gliders, and perhaps advanced recovery systems for boosters and hypersonic aircraft.

INTRODUCTION

Observers of nature have long noted that the wings of living creatures are rather flexible and generally are folded neatly out of the way when not in use. Through the ages men have dreamed of flying with flexible wings like those in nature and many tried, but with little success. Other types of flexible aerial devices were developed - hot air balloons and parachutes, which are still being used - but apparently no one had devised a successful fully flexible wing that would give more aerodynamic lift than drag. Very recently, however, men, and at least one woman, have succeeded in flying with truly flexible wings, pure tension structures like parachutes, as shown in figure 1 and discussed in references 1 and 2.

Although completely flexible wings are feasible and practical for some applications, for others performance and other characteristics may need to be improved by the judicious addition of local stiffening. Consequently a complete spectrum of wing shapes and degrees of stiffening is being developed to fill the gap between the conventional parachute and the rigid wing. To include this complete spectrum in one definition, we can define flexible wings as wings made with very loose or slack membranes whose configurations in flight are determined primarily by the aerodynamic forces on the membranes and the reactions from the load suspension system.

After the usual dreaming about flexible wings since childhood, the author in 1945 at the close of World War II decided to undertake a serious study of the subject. Because pressure of work along more conventional lines did not permit such a study to be made on government time, it was decided to undertake it at home, jointly with Mrs. Rogallo and later including other members of the family and friends. This private endeavor covered the 13 years from 1945 until late in 1958, when America's entry into the exploration of space brought about government consideration of this and other unconventional ideas, and the subsequent formation of what is now officially the Flexible-Wing Section of Langley Research Center, a truly dedicated group.

In the pre-NASA years the wing was called a kite because of the three experimental methods used: testing in a homemade wind tunnel, free flying as hand-launched gliders, and tethered outdoor flying as kites. The kites appeared to be the nearest to a useful marketable application. Thus U.S. Patent No. 2,546,078 (ref. 3) filed in November 1948 and issued in March 1951 to Gertrude and Francis Rogallo is entitled "Flexible Kite" even though it proposes applicability of the concept to all heavier than air flying machines. The first national publicity about our early work was an article written in December 1949 entitled "First Flexible Kite," published in Ford Times in March 1951 (ref. 4). A brief history of the concept was given in a luncheon talk in September 1963 before the American Astronautical Society at Edwards Air Force Base. (See ref. 5.)

FLEXIBLE-WING SPECTRUM

Figure 2 presents the spectrum of flexible-wing configuration and the maximum lift-drag ratios obtained by the Flexible-Wing Section in NASA wind-tunnel tests of each type of wing shown. The abscissa of figure 2 has been selected to illustrate a progression of configurations having increasing structural rigidity. The left end of the spectrum, indicated as having no stiffening, represents the original concept of a flexible lifting surface as described in reference 3. The shaded area, labeled "all-flexible," indicates that this type of lifting surface can provide maximum lift-drag ratios up to at least 3.0.

The use of some structural stiffness such as would be obtained with a single-curvature lifting surface made of flexible thin sheet metal or plastic provided maximum lift-drag ratios of around 7.0. Test results obtained on this type of wing are presented in reference 6. The remainder of the spectrum presented in figure 2, which is divided into two canopy shapes, has received most of the research attention since the publication of reference 6. Most of the data and unpublished information on flexible wings are therefore on configurations having rigid leading edges and keel, and the sweep angle fixed by a spreader bar, or by a very rigid apex.

It should be noted that the spectrum shown in figure 2 encompasses a wide range of possible configurations and no particular wing should be considered as the optimum. For example, the unstiffened wing is expected to be the most useful where factors such as deployment simplicity and minimizing wing loading, packing volume, wing weight, and complexity are considered more important than obtaining high lift-drag ratios. On the other hand, a cylinderical wing with small leading edges and a rigid frame may be desirable where performance and cruise speed (towed or powered vehicles) are of more importance than structural simplicity, and deployment capability is not needed. Selection of a wing for a particular use should include a study of design trade-offs, including consideration of performance, stability, control, loads, and structural requirements.

In the remaining discussion of the spectrum a brief summary of the state of the art with regard to maximum lift-drag ratios of conical and cylindrical wings is given and reference is made to published data, where available, for each type of wing.

Conical Wings

Early flight tests at the Langley Research Center on inflated-tube configurations indicated a possible design approach for the recovery of spacecraft and for aerial delivery of cargo. The need for research information on conical wings for support of the Gemini Project and the Army cargo-drop glider prompted extensive wind-tunnel research on simplified rigid models which simulated inflated-tube type of wing configurations (see refs. 7, 8, and 9). Other work on wings having small leading edges and a rigid frame led to the construction of manned flight vehicles such as the flexible-wing glider (ref. 10), flexible-powered aircraft (refs. 11 and 12), and unmanned Army tow glider (ref. 13), and led to studies of flexible-wing recovery of the Saturn booster (ref. 14). As indicated in figure 2, the highest lift-drag ratio obtained with conical wings was about 7.0. Analysis of the test results and theoretical studies on conical wings (ref. 15) indicated that the relatively high drag of these wings was associated with the large variation of aerodynamic twist across the wing span. For some wings this washout at the tips was as high as 60°.

Cylindrical Wings

In order to determine the extent that lift-drag ratios could be improved by eliminating the wing twist, a general research investigation was undertaken on a series of zero-twist cylindrical wings having small rigid leading edges (refs. 15 and 16). The shaded area in the upper-right-hand side of figure 2 shows that maximum lift-drag ratios as high as 17.0 were obtained with the small tapered leading edge cylindrical type of wing.

Interest in deployable wings that would provide lift-drag ratios greater than those obtained with the conical wings led to work on the advanced-concept cylindrical wing which had tapered inflated-tube leading edges. The wind-tunnel studies of simplified rigid models indicated that maximum lift-drag ratios from about 6 to 8 could be obtained with this type of wing.

EFFECT OF ASPECT RATIO

The vertical spread in the shaded areas of figure 2 can be attributed to variations in aspect ratio and canopy fullness. Effects of aspect ratio on maximum lift-drag ratios for rigid frame 50° swept wings having conical and cylindrical canopies are summarized in figure 3.

Conical Wings

Data for the conical wings on the left side of figure 3 show the critical nature of the leading-edge configuration on the maximum lift-drag ratios. Use of the very small tapered leading edge allowed an increase in $(L/D)_{max}$ with increasing aspect ratio, whereas the use of a slightly larger untapered leading edge caused $(L/D)_{max}$ to decrease with increasing aspect ratio. A decrease in washout, which was obtained by reducing the canopy fullness, provided an increase in $(L/D)_{max}$ for the high-aspect-ratio wing having tapered leading edges. The test point shown for the rigid model which simulated an inflated-tube untapered leading-edge configuration (ref. 8) again indicates the level of L/D to be expected for this type of wing.

Cylindrical Wings

Considering now the cylindrical wings, shown on the right side of figure 3, it is evident that increasing the aspect ratio was much more effective in increasing $(L/D)_{max}$ than for the conical wings. A value of maximum lift-drag ratio of about 12 was obtained at high aspect ratio for the zero-twist wing with small tapered leading edges. By careful tailoring of the canopy to provide a small amount of washout, the maximum lift-drag ratio of this wing was increased to about 17.0 (ref. 16). A comparison of the data for the rigid frame conical and cylindrical wings having large leading edges (simulating inflated-tube designs) indicates that significant gains in $(L/D)_{max}$ can be realized for this type of wing by the use of a cylindrical canopy and tapered leading edges.

ALL-FLEXIBLE WINGS

Many configurations of all-flexible wings, which are now of primary interest, have been investigated by the Flexible-Wing Section in the wind tunnels of the Langley Research Center and in free flight after being dropped from aircraft. Some typical wind-tunnel results are shown in figure 4 from tests of single- and twin-keel wings. The maximum lift-drag ratio of the single-keel wing shown is about 2.5 while that of the twin-keel wing is about 3. The single-keel wing has a higher maximum resultant-force coefficient C_R and range of C_R, a simpler geometry with fewer bridle lines, and a much more complete background of experience than the twin-keel wing. By the spring of 1966 confidence in the single-keel wing was sufficient to permit scheduled live demonstration by the U.S. Army parachute team of wings built by NASA, Pioneer Parachute Company, and Irving Airchute Company within 2 weeks after the NASA design was given to the parachute companies (see ref. 1). The NASA wings used by the team had, of course, been under test with dummy loads for several months. During the past year hundreds of live jumps have been made with this wing configuration and it is now being marketed for sports flying (see ref. 2). In wind-tunnel tests the twin-keel wing has shown a slightly higher maximum lift-drag ratio than the single-keel wing and offers the possibility for reefing of the center panel to reduce wing area for deployment and initial glide whenever the higher speed accompanying the reduced area is advantageous. The disreef could be made at any time during the flight or just before landing to reduce landing speed in much the same way as conventional aircraft landing flaps are used. Single- and twin-keel configurations are still under development and both will probably have many applications. The resultant-force coefficient of a conventional parachute is shown for comparison and is seen to be significantly lower than the maximum C_R of the flexible wings.

To give a clearer picture of the performance potential of all-flexible wings, the horizontal and vertical velocities corresponding to the data of figure 4 are given in figure 5 for wing loadings, W/S, of 1/2, 1, and 2 pounds per square foot of wing surface. The lowest wing loading shown is approximately that used in the more than 400 manned flights, whereas cargo delivery and spacecraft landing systems will probably use W/S between 1 and 2.

The horizontal velocity component permits reaching a suitable landing site, even against some wind, and the low sink rates available permit a long flight and a soft landing. Even without the reefing previously mentioned, some modulation of horizontal and vertical velocity is apparent in the steady-state characteristics of figure 5, and even more may be possible during a flare maneuver. For the same canopy loading, steady-state sink rates possible with all-flexible wings are less than one-third of those with conventional parachutes, or conversely, for the same gross weight and steady sink speed a conventional parachute will require about ten times as much area. Remember that force varies with the square of the velocity.

Because the wind-tunnel tests that provided the data of figure 4 were made upright in horizontal flow, the resultant force and gravity were not in the same direction as they would be in steady gliding flight (see fig. 6). Such horizontal-flow test data are therefore considered to be slightly conservative, whereas inverted or vertical-flow test data may sometimes give erroneously optimistic results because the weight of the lines and forward parts of the wings tends to prevent nose collapse. It is also difficult to obtain and interpret lateral stability and control information in wind-tunnel tests of all-flexible wings.

CONCLUDING REMARKS

This paper has reviewed some of the history of flexible wings, has shown that the flexible wing concept covers a very broad spectrum of wing shapes, wing structures, and applications, and has presented performance characteristics of some typical all-flexible wings. All-flexible wings are rapidly gaining general and often enthusiastic acceptance for applications that can be satisfied by a lift-drag ratio of 3 or less. Research and development of such wings is expanding rapidly. The stiffened high-performance flexible wings at the other end of the spectrum, however, are not getting the attention they deserve. Such wings show promise of becoming economical, light-weight, rugged, stowable wings for applications including roadable aircraft, flying boats, flying submersibles, cargo tow gliders and a variety of sports gliders, and for recovery of boosters and hypersonic aircraft. Enthusiasm for stiffened flexible wings may have been dulled by previous attempts to use rigid or inflated frame wings of conical shape (low performance) in some applications that need greater performance to be practical. It is hoped that research can be accelerated on the entire spectrum, especially on high-performance flexible wings, and that the results will generate a variety of useful applications, private, commercial, and military.

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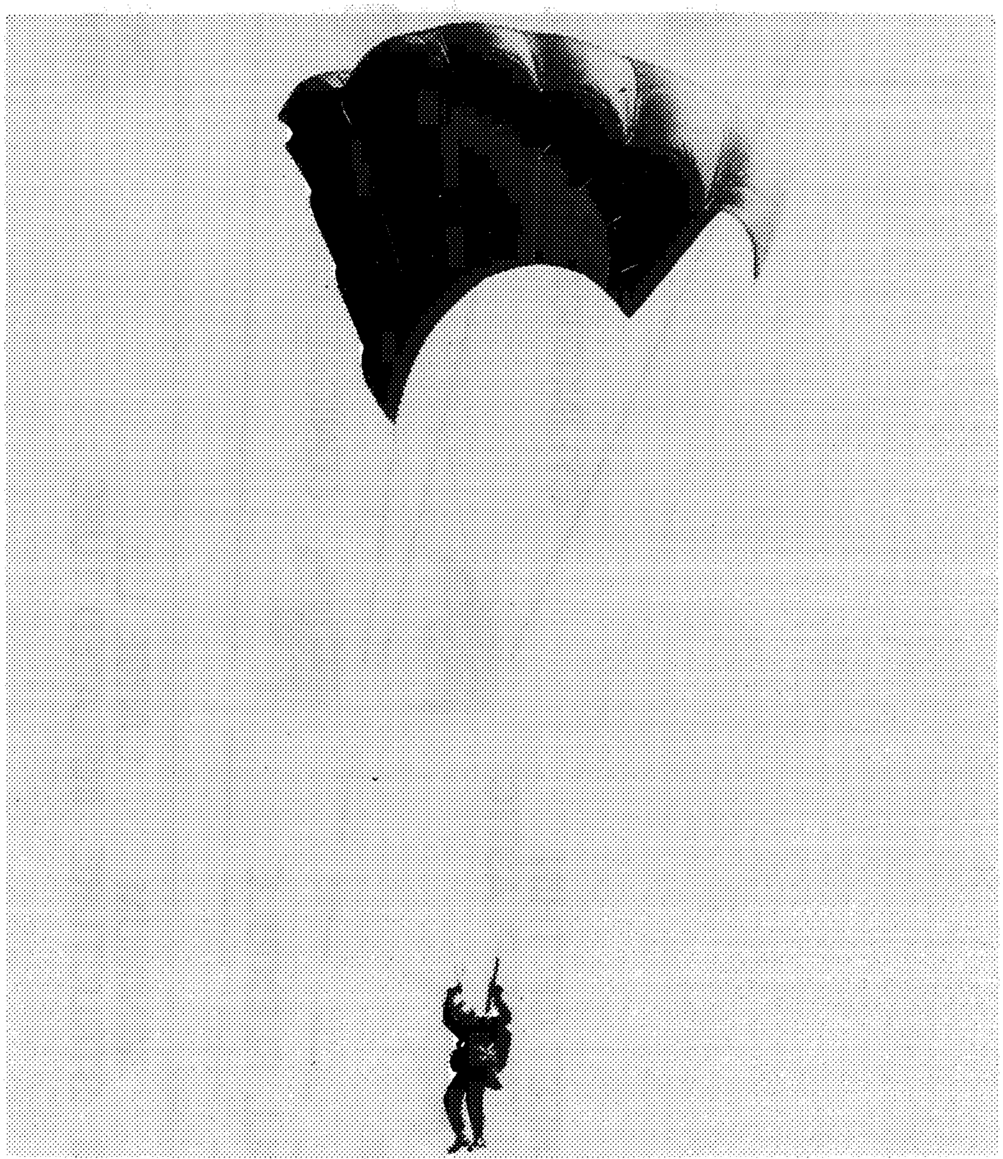

Figure 1.- Flexible-wing (parawing) flight by member of U.S. Army parachute team.

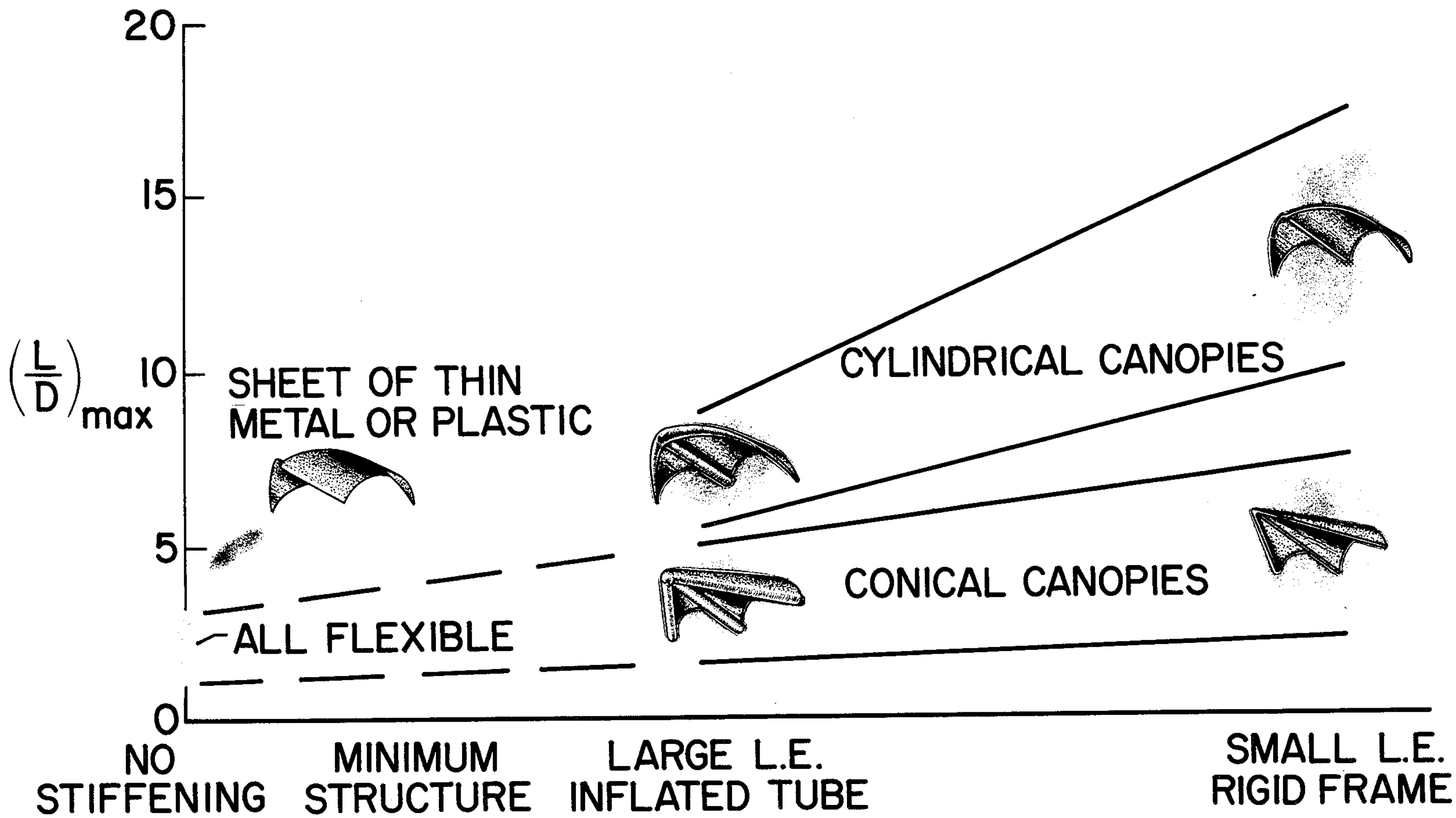

Figure 2.- Spectrum of flexible wings investigated and maximum lift-drag ratios obtained in wind-tunnel tests.

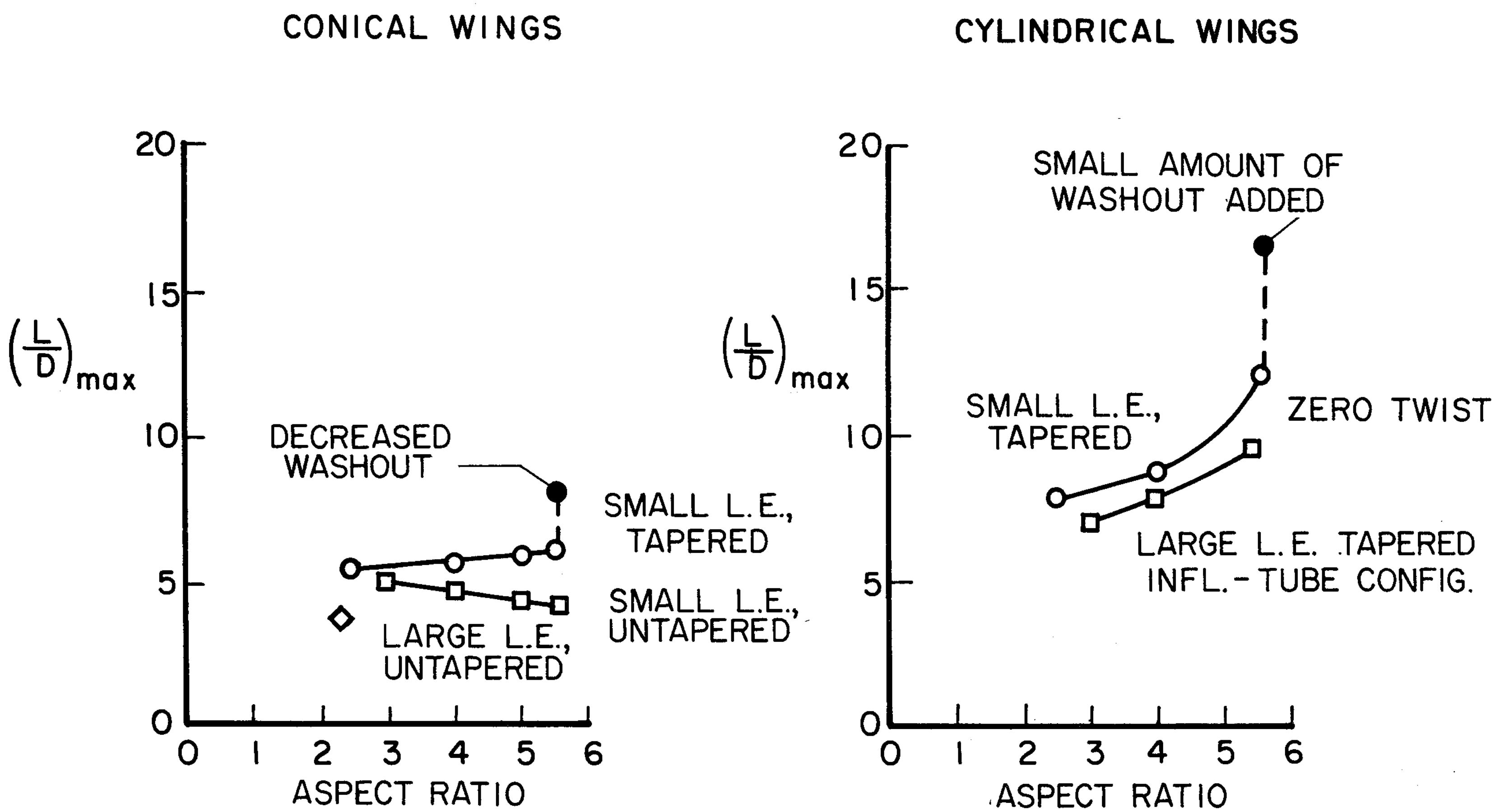

Figure 3.- Effect of aspect ratio on maximum lift-drag ratios of 50° swept flexible wings having rigid frames.

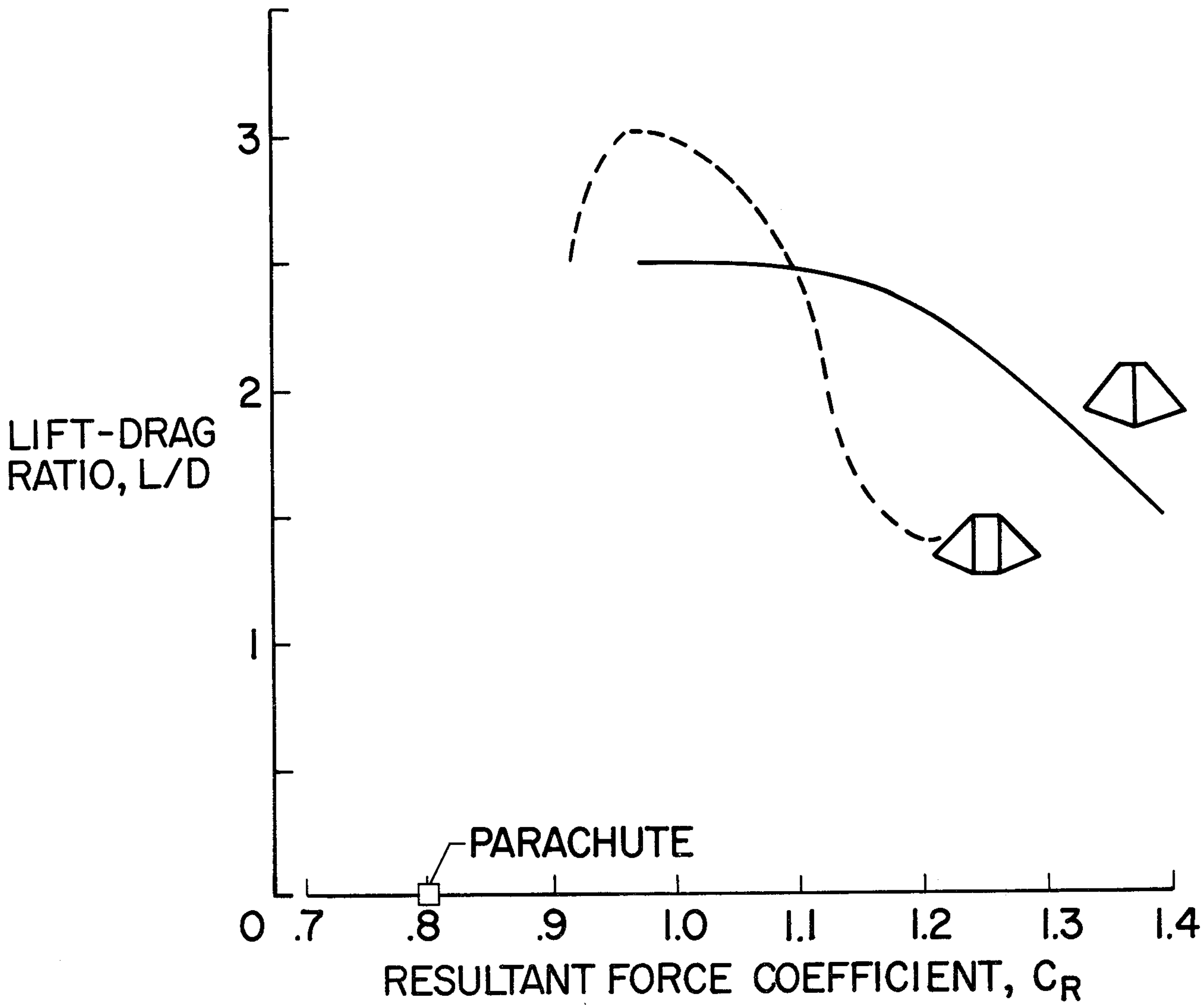

Figure 4.- Variation of lift-drag ratio with resultant-force coefficient of all-flexible wings.

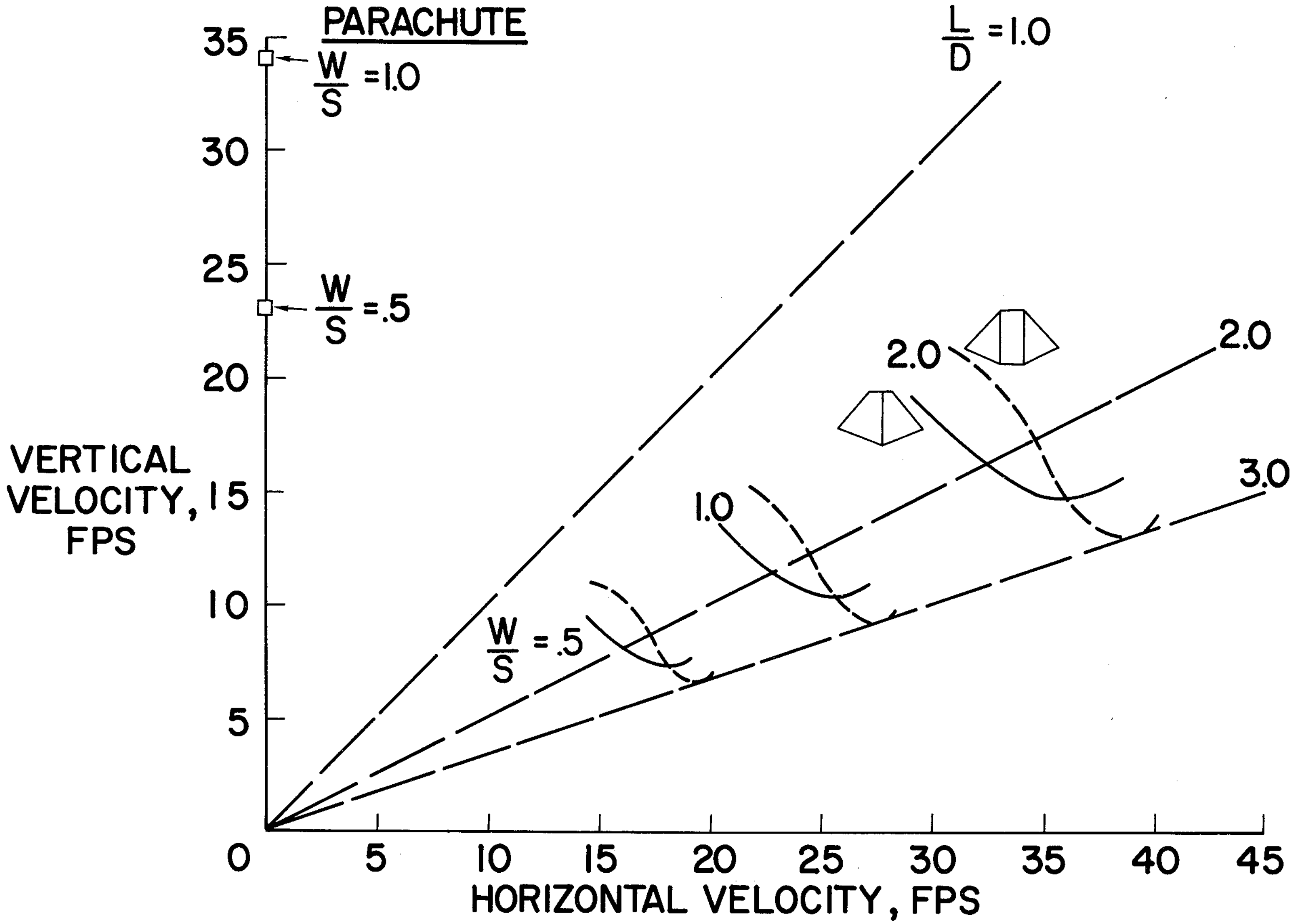

Figure 5.- Horizontal and vertical velocities of flexible wings in steady glide.

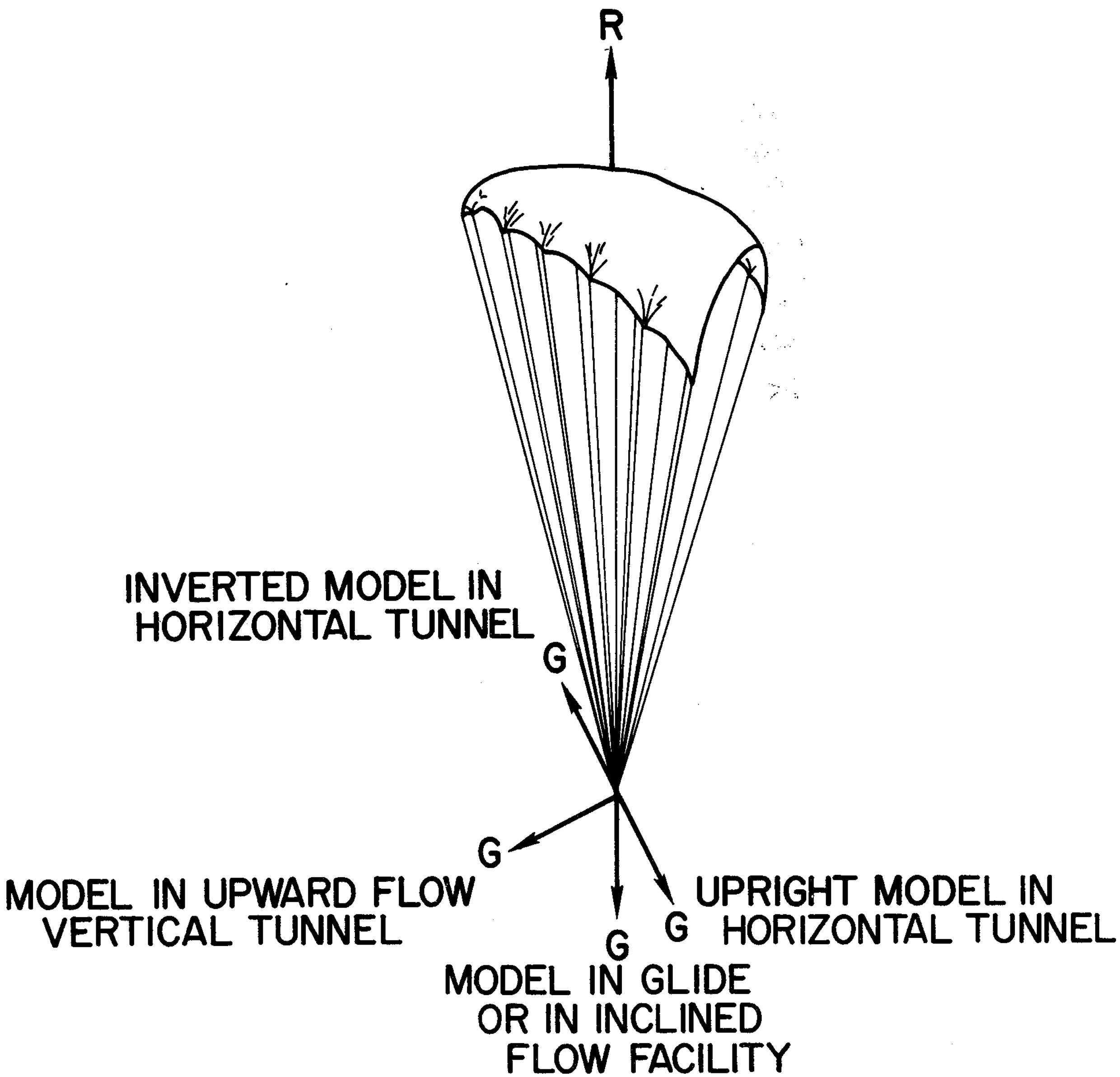

Figure 6.- Misrepresentation of gravity forces in wind-tunnel tests of flexible wings.