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Article *in* Journal of Aircraft · July 2005

DOI: 10.2514/1.12255

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JOURNAL OF AIRCRAFT
Vol. 42, No. 4, July–August 2005

Engineering Notes

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Aerodynamic Drag of Parafoils

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Introduction

THE parafoil is an aerodynamic decelerator that uses the concept of parachute and airfoil aerodynamics. The device has been used as a parachute for high-precision delivering of payload (military and civilian), to recover sounding rockets, for various tethered applications (to carry instrumentation for weather survey, air pollution measurements, radar tracking systems), and as recreational parachuting since the 1970s, as discussed by Nicolaides et al.[1] and Knapp and Barton.[2] All of these systems take advantage of the low landing speed and maneuverability of the parafoil. The invention is rather old, and it was used as far back as World War II for stabilization of supersonic vehicles by H.G. Heinrich, as reported by Meyer.[3] The essential concept was that in addition to suitable aerodynamic resistance the parafoil had to provide lift, stability, and control, so that it could be used for high-precision landing.

The technical literature in the field has addressed aerodynamics, performances, and longitudinal stability, from flight testing, wind-tunnel measurements, and theoretical models. Relevant publications in the field include the work of Lingard,[4] who showed equations for the lift and drag coefficients from low-speed aerodynamic theory and discussed the effects of wind speed, geometry, and size of the parafoil. Other studies address glide ratio and rate of descent under various wind conditions, in addition to deployment/inflation mechanisms, warping, turn control, effects of rigging lines, and more. These analyses are not directly applicable. A summary of this literature is given by Matos et al.[5]

This paper discusses the low-speed wind-tunnel drag characteristics of parafoils. The devices tested are flexible (but not inflatable) strips of cloth that adjust to the conditions of the incoming wind and produce relatively large drag forces and little or no lift. Therefore, they are essentially aerodynamic decelerators with spanwise camber increasing with their length because their edges were tied at a constant distance. Ram pressure builds up on the side of the parafoil facing the freestream and creates considerable drag.

Experimental Setup

The parafoils were mounted on a U-shaped support rod, as shown in Fig. 1. This distance was maintained constant in the experiments described. No rigging lines of any length have been used.

Received 29 September 2004; revision received 26 January 2005; accepted for publication 26 January 2005.

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Measurements were taken in a low-speed wind tunnel having a working test section of 0.9 × 0.9 m, 3.14 m long. Twelve parafoils of cotton cloth were cut. Three planform areas were used: 0.025, 0.05, and 0.075 m^2. For each of the planforms, four aspect ratios have been considered: 3.3, 10, 20, and 30. The material properties of the fabric used are as follows: weight $W = 177$ g/m^2, bending rigidity 0.0642 g cm^2/cm; bending hysteresis 0.0446 g cm/cm.

A string was used to connect these to the eyelets of the parafoils, so that the fixed edges were pulled taut and tight against the downwind side of the mounting rod. This was manufactured such that the parafoil ends would be held 0.42 m apart. This was fixed length equal to less than half the wind-tunnel's width, to avoid complicated wall effects. In any case, the relevant geometric parameter of the arrangement is the ratio L/b that is a geometric similarity. A greater or longer arm would increase or decrease the Reynolds number, but the effects of this parameter on the results have been found small compared to the aspect ratio and the planform area. Those parafoils not long enough to span this distance had a string pulling the parafoil tight between the vertical struts of the mounting rod.

The velocity range in the wind-tunnel test section was between 6 and 18 m/s, corresponding to Reynolds numbers in the range 1.7×10^5 to 5.2×10^5. The Reynolds number was calculated by using as a reference length the horizontal arm b of the U-support rod (Fig. 1). The wind speed was measured using a pitot static probe. The probe connected to a high-accuracy digital manometer that took readings within 0.01 mm H_2O (0.0981 Pa).

Force measurements were taken using a force balance through which the mounting rod was secured. A voltage-time series was taken for each data point, 2048 samples over 5 s , and averaged to give a mean drag measurement. The voltage output was converted to a force measurement through a calibration curve obtained by applying loads at the center of the force balance. A vibration unit was connected through the balance and used immediately before readings were taken, to reduce sticking of the mounting rod through the force balance collet.

Each parafoil was tested six times over two days. The results were averaged to give drag coefficient × area results.

Results and Discussion

The drag data for the parafoils are presented in terms of the product $C_D A$ (drag × reference surface): $C_D\, A$ is the ratio between the

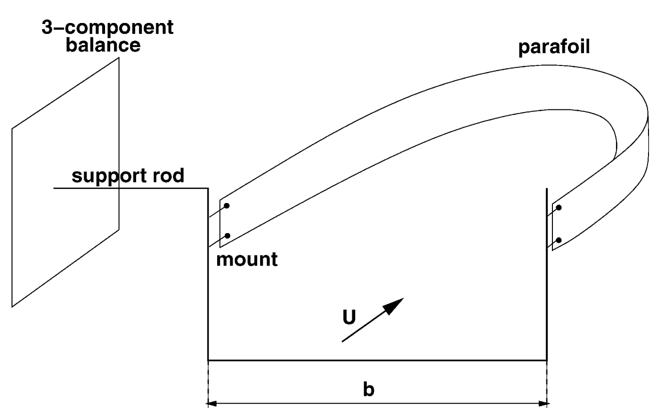

Fig. 1 Mounting method of parafoils in wind-tunnel test section.

drag force and the dynamic pressure $q = \rho U^2/2$, a quantity readily measurable. Our choice was dictated by the fact that a reference area is arbitrary: it can be the wetted area, the planform area, the area offered to the incoming flow. Although the first two are variable with the parafoil's geometry, the latter one is more arbitrary because of forced oscillations that sometimes led to a wrapping and twisting of the parafoils.

The effects of aspect ratio on the drag coefficient × area $C_D A$ are shown in Figs. 2–4, in the whole range of speeds tested, for each given wetted area. The effects of aspect-ratio are stronger than the effects of increasing wind speed. The average data over the speed range are fitted with a logarithmic function like $C_D A = a\,\ell\text{n}(\mathit{AR}) + b$ with the coefficients a and b as shown in the figures. From this we conclude that low-aspect-ratio parafoils are more efficient drag devices with increasing velocity.

The effects of wind speed can be seen when considering one aspect-ratio point only. The lower velocities occupy the higher $C_D A$ range, and the higher velocities the lower $C_D A$ range. There is little difference between the higher and lower velocities in comparison to the influence of aspect ratio. However it is clear that there is a decrease of $C_D A$ with increasing velocity, except for the case of an aspect ratio $\mathit{AR} = 30$, where twisting of the parafoil (as discussed later) causes an opposite effect to occur.

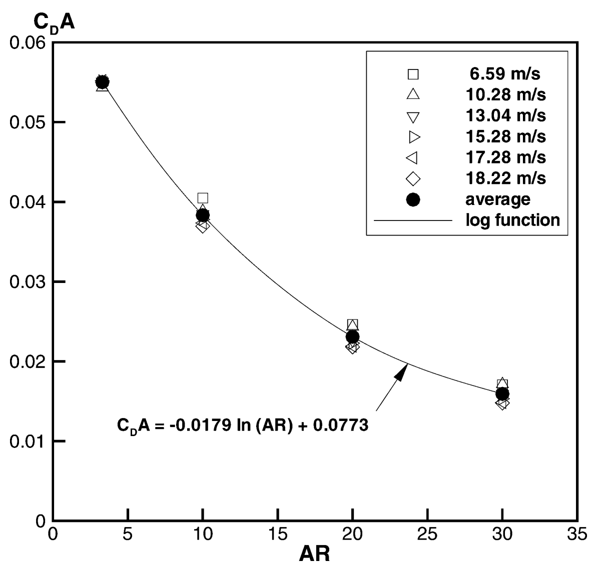

Fig. 2 $C_D A$ of parafoils vs aspect ratio, at wind speeds indicated, area $A = 0.025$ m^2: ——, logarithmic fit of the average data.

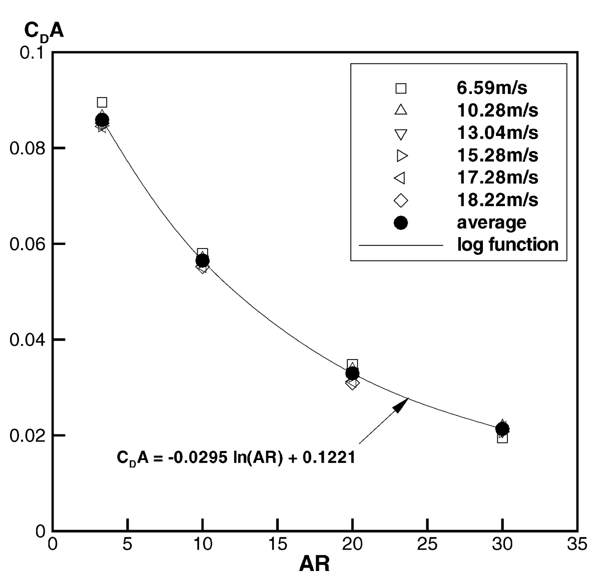

Fig. 3 $C_D A$ of parafoils vs aspect ratio, at wind speeds indicated, area $A = 0.050$ m^2: ——, logarithmic fit of the average data.

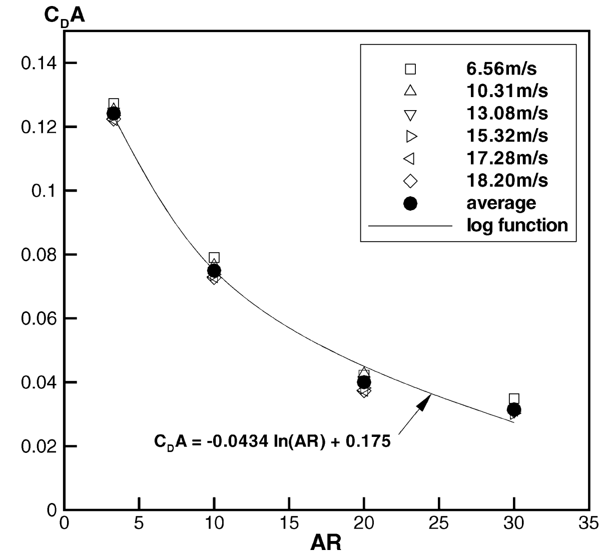

Fig. 4 $C_D A$ of parafoils vs aspect ratio, at wind speeds indicated, area $A = 0.075$ m^2: ——, logarithmic fit of the average data.

This opposite effect, caused by wrap-up, always appears at the lowest speeds with the most slender parafoils ($\mathit{AR} = 30$, $A = 0.050$ m^2, and 0.075 m^2). It causes the parafoil not to offer its actual area to the wind; hence, the drag is highly dependent on the parafoil's orientation. The other exception was $\mathit{AR} = 3.3$, $A = 0.025$ m^2. This geometry suffered significant vibrations at the upper end of the velocity range. The vibration limit was sensitive to minor differences in mounting, that is, the tightness of the string. Once a severe vibration began, to avoid damage to the balance we then operated changes in the wind-tunnel speed or stopped the tunnel and loosened the mount.

The results show that the quantity $C_D A$ on the parafoil scales roughly with the planform area. Therefore, by taking as a reference area the planform, the drag coefficient is not dependent on the length of the parafoil, provided the aspect ratio is maintained constant. Also seen from Figs. 2–4 is that the $C_D A$ scale, and therefore $C_D A$ itself, increases with increasing area. Again it can be seen that the effects of wind speed are negligible compared to aspect ratio.

The efficiency of the parafoil as an aerodynamic decelerator can be calculated as the ratio between the aerodynamic drag force and the parafoil's own weight at a given wind speed D/W. Consider the parafoil having the mean planform, $A = 0.050$ m^2 and aspect ratio $\mathit{AR} = 3.3$. Figure 3 indicates that an average value of the drag force $D \sim 7.5$ N at the average wind speed in the range tested, 12 m/s. Therefore the ratio sought is $D/W \simeq 850$—a fairly large number that can be verified for the other cases.

Modes of Oscillation

The modes of oscillation of the parafoils are dependent on the aspect ratio. At the low aspect ratio, $\mathit{AR} = 3.3$, the parafoils are relatively wide and do not twist at any velocity. These parafoils tend to catch in the flow being pulled taut and suffer slight flapping motions with increasing velocity. This flapping becomes stronger at the higher wind speeds, but not excessively so, except in the case $A = 0.025$ m^2.

The parafoils of aspect ratio $\mathit{AR} = 10$ catch immediately in the airflow, with slight oscillations beginning to appear by 9 m/s. As the airflow is increased to 17 m/s, the oscillations become stronger, a fact compounded by the increasing planform area. The parafoils with aspect ratio $\mathit{AR} = 20$ had similar oscillation mode, with a low-frequency oscillatory movement at wind speed. This was more notable for the larger planforms.

At higher velocities the oscillations become more pronounced, and the center of the parafoil has a crossover motion. This motion is caused by each half of the parafoil tending to move in a figure eight, as seen in the case of the streamers.[6] However, as the two sides are linked in the center, this figure-eight tendency is reduced, and the two sides move up and down, one moving up while the other moves down, and a motion similar to a cross is observed with the point at the center moving least.

The parafoils of aspect ratio $\text{Æ} = 30$ have a tendency to twist at the lowest velocities tested and were therefore tested from the highest velocity toward the lowest. At the highest velocity a high-amplitude, high-frequency oscillation is observed, which diminishes in amplitude and frequency as the wind speed is reduced. The parafoils with smallest planform area, $A = 0.025$ m^2, do not have problems with twisting. At a wind speed of about 12 m/s, there is a twist of the parafoils. This effect does not always occur, but it does in the majority of instances and can be sorted out by quick alterations in wind speed, then settling back to the required testing point. However, at around 8 m/s the twisting occurs again, but for this and lower velocities the parafoil once twisted will not unwrap.

We concluded that there must be a critical value of the ratio between the length of the parafoil and the distance between the ends that creates a twisting and warping behavior. The length L/b (ratio of the parafoil length to its arm) must be around two or below for avoiding oscillations. For values L/b up to 2.5, there can occur a warping and twisting, but this depends on how tight the attachment is. For higher values we cannot guarantee that the parafoil will be free of unwanted oscillations.

For cases where no wrapping or oscillations occur, the shape assumed by the parafoils is approximately a catenary because the problem is similar to a tension-resistant fiber under constant load (the ram pressure created by the wind).

Conclusions

Cotton parafoils of all combinations of four aspect ratios and three planform areas were tested over a range of wind speeds. The time averaged data show that the aspect ratio is the most important parameter affecting the drag. Higher $C_D A$ is obtained with comparatively low aspect ratios. The best fit of the $C_D A$ is a logarithmic function.

The parafoils' $C_D A$ scales roughly with the planform area. To a doubling of the area, it corresponds a doubling of the $C_D A$, all other parameters being constant.

Regarding the fluctuations under the wind, most parafoils caught the wind and did not suffer twisting. The exception to this was the largest aspect-ratio parafoil ($\text{Æ} = 30$) with planform areas 0.05 and 0.075 m^2. The ratio between the arm of the support and the length of the parafoil L/b reaches a critical limit of about 2.5; above this value wrapping is very likely. At values $L/b < 2$ the parafoil assumes the shape of a catenary and is stable under the wind loading.

The wind speed is the weakest parameter—all other parameters being the same.

References

[1]Nicolaides, J. D., Speelman, R. J., and Menard, G. L. C., "A Review of Para-Foil Applications," *Journal of Aircraft*, Vol. 7, No. 5, 1970, pp. 423–431.

[2]Knapp, C. P., and Barton, W. R., "Controlled Recovery of Payloas at Large Glide Distance, Using the Para-Foil," *Journal of Aircraft*, Vol. 5, No. 2, 1968, pp. 112–118.

[3]Meyer, J., "An Introduction to Deployable Recovery Systems," Sandia Nat. Labs., Rept. SAND85-1180, Albuquerque, NM, Aug. 1985.

[4]Lingard, J., "Ram-Air, Parachute Design," AIAA Paper 95-1561, May 1995.

[5]Matos, C., Mahalingam, R., Ottinger, G., Klapper, J., Funk, R., and Komerath, N., "Wind Tunnel Measurement of Parafoil Geometry and Aerodynamics," AIAA Paper 98-0606, Jan. 1998.

[6]Carruthers, A. C., and Filippone, A., "On the Aerodynamic Drag of Flags and Streamers," *Journal of Aircraft* (to be published).