JOURNAL OF AIRCRAFT
Vol. 43, No. 5, September–October 2006

Engineering Notes

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Experimental Investigation of Three Rotating Parachutes

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DOI: 10.2514/1.21576

I. Introduction

SINCE they were first invented, parachutes have been widely used to lower men and goods to the ground safely, and to decelerate aircraft, race cars, etc. Although new types of parachutes were designed, this mission remained the same for years. During the last decades, new tasks began to be given to parachutes. These tasks are related to controlling the trajectories of their payloads and following complex flight patterns to carry out defined flight requirements. Today, rotating parachutes are a means of introducing dynamic maneuvers to their payloads to follow a predefined flight path and/or traces on the ground.

In the design of a rotating parachute-payload system, the appropriate parachute system can be found by studying the aerodynamic properties of rotating parachutes in wind tunnels. While different types of parachutes are designed and studied in a wind tunnel [1], the same parachute can also be tested by changing its geometrical parameters such as suspension line length and staggering distance [2–6].

In this experimental study, three rotating parachutes were tested in a wind tunnel. Each canopy had the same surface area but had a different shape. The affects of the canopy geometry and the physical parameters (suspension line length and staggering distance) on the tangential force coefficient and the spin rate were studied [7]. Because the same size cross canopies and the same canopy fabric material were used, the spin rate and the force coefficient results were compared with the corresponding results of the experimental studies found in the literature. During the tests, the oscillations of the configurations constructed from their symmetry axes were also observed, and different dynamic behaviors were classified.

II. Experimental Setup

A. Wind Tunnel

The experiments were conducted in a subsonic wind tunnel having a 3.05×2.44 m^2 cross section. The tunnel is a close type wind tunnel and has a top speed of 100 m/s. Experiments were conducted at a constant air velocity of 19 m/s ($Re = 1.25 \times 10^6$/m).

B. Setup

Test setup is a single support system. It carries one load cell (the dynamometer) and the rotating body mechanism. The dynamometer measures the force in one direction. The rotating body mechanism is to simulate the payload which is used with a rotating parachute. The spin rate measurement mechanism is a tachometer which is adopted onto the setup. A photograph of the setup is shown in Fig. 1.

C. Parachute Models

In the experiments, three different parachutes were tested. Two of them were "cross parachutes" having the arm ratios (L/W) of 3.0 and 3.8, respectively. The third rotating parachute was named a "round parachute". The round parachute has a dome-shaped canopy. There are eight jet openings on the sides of the canopy. It is designed in such a way that it should have a similar descent rate and spin rate to those of cross parachutes. All parachutes are made of the same fabric material, and they have approximately the same canopy surface area, S_{ref}. Schematic views and the geometric dimensions of the parachutes are presented in Fig. 2.

III. Tested Parameters and Experimental Results

A. Tested Parameters

Sixteen configurations were constructed by using the parachutes. Cross configurations were constructed by changing the suspension line length l_s and the staggering distance Δl (Fig. 2). Round configurations were constructed by changing only the suspension line length l_s of the parachute. The configurations created are presented in Table 1.

Four of the cross configurations are nonrotating configurations. Each has zero staggering distance. The round parachute always rotates. It does not have a nonrotating configuration. The suspension lines of this parachute always have the same length.

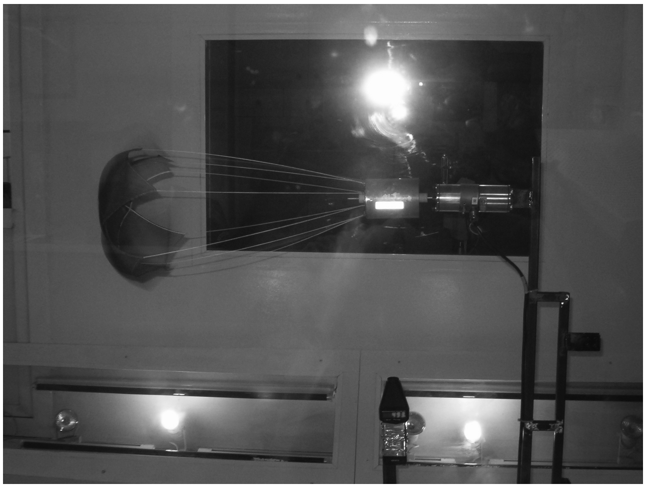

Fig. 1 Setup.

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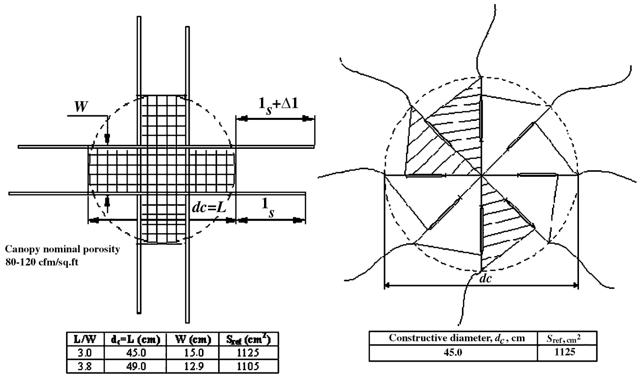

Fig. 2 Parachute models.

In the tests, tangential force and spin rate (for rotating configurations) measurements were done at zero angle of attack for all configurations. Dynamic stability of them was also observed.

B. Experimental Results and Discussion

All test results are submitted in Table 1. The table includes the spin rate and the tangential force coefficient results of the configurations. The dimensionless spin rate results, which are based on the constructive diameter d_c, are also presented in the table. Tangential force T is the force which is measured along the symmetry axis of the parachute system. The dimensionless tangential force is the tangential force coefficient $C_T = (T)/(q \cdot S_{\mathrm{ref}})$. This equation is based on the canopy surface area S_{ref}, and "q" is the dynamic pressure $\mathrm{N/m^2}$. The last column in the table is the dynamic stability observation results. Different dynamic behaviors of the configurations with respect to each other were classified according to their oscillations from their symmetry axes as small, medium, and large oscillations.

In Tables 2 and 3, the results of the cross canopies were compared to the results obtained by Z. Shpund and D. Levin [3–6]. These authors have made extensive experimental studies on cross parachutes. In their studies, they measured the spin rates and the tangential force coefficients of different cross parachutes. They studied also the concepts for cross parachutes such as static stability and the center of pressure position. Furthermore, they considered other dynamic parameters for rotating cross parachutes such as transferable moment coefficients, angular motion, etc., in their works.

The results presented in [3–6] are the most suitable results to be compared with the current study. Although the setup and the test conditions in the current study are different from those in these

Table 1 Configurations constructed and experimental results

Config.	Suspen. line length, ℓ_s	Staggering distance, $\Delta\ell$	Spin rate, f at $\alpha = 0^0$, rpm	Nondimensional spin rate, $pd_c/2V$	Tangential force coefficient C_T	Dynamic stability observation results
			Cross parachute $L/W = 3.0$			
1	$0.7 \times L$	0	0	0	0.65	large
2	$0.7 \times L$	$0.05 \times L$	495	0.61	0.69	medium
3	$0.7 \times L$	$0.1 \times L$	630	0.78	0.72	small
4	$1.0 \times L$	0	0	0	0.72	large
5	$1.0 \times L$	$0.05 \times L$	520	0.64	0.81	small
6	$1.0 \times L$	$0.1 \times L$	661	0.82	0.84	small
			Cross Parachute $L/W = 3.8$			
7	$0.7 \times L$	0	0	0	0.59	medium
8	$0.7 \times L$	$0.05 \times L$	554	0.75	0.73	small
9	$0.7 \times L$	$0.07 \times L$	595	0.80	0.74	small
10	$0.7 \times L$	$0.1 \times L$	485	0.66	0.55	small
11	$1.0 \times L$	0	0	0	0.66	medium
12	$1.0 \times L$	$0.05 \times L$	612	0.83	0.76	small
13	$1.0 \times L$	$0.07 \times L$	620	0.84	0.79	small
14	$1.0 \times L$	$0.1 \times L$	578	0.78	0.53	medium
			Round parachute			
15	$0.7 \times L$	——	603	0.75	0.83	medium
16	$1.0 \times L$	——	618	0.77	0.89	medium

Table 2 Comparison of force coefficient results of the cross canopies at $\alpha = 0$ deg

Config.	Suspen. line length, ℓ_s	Staggering distance, $\Delta\ell$	Current study C_T	C_T [3]	C_T [5][a]	C_T [6]
			Cross parachute $L/W = 3.0$			
1	$0.7 \times L$	0	0.65	0.67	0.56	0.67
2	$0.7 \times L$	$0.05 \times L$	0.69	0.82	0.68	0.88
3	$0.7 \times L$	$0.1 \times L$	0.72	0.95	0.77	1.1
4	$1.0 \times L$	0	0.72	0.77	0.68	0.75
5	$1.0 \times L$	$0.05 \times L$	0.81	0.84	0.80	0.93
6	$1.0 \times L$	$0.1 \times L$	0.84	0.96	0.88	0.98
			Cross parachute $L/W = 3.8$			
7	$0.7 \times L$	0	0.59	0.58	——	——
8	$0.7 \times L$	$0.05 \times L$	0.73	0.84	——	——
9	$0.7 \times L$	$0.07 \times L$	0.74	——	——	——
10	$0.7 \times L$	$0.1 \times L$	0.55	0.92	——	——
11	$1.0 \times L$	0	0.66	0.71	——	——
12	$1.0 \times L$	$0.05 \times L$	0.76	0.76	——	——
13	$1.0 \times L$	$0.07 \times L$	0.79	——	——	——
14	$1.0 \times L$	$0.1 \times L$	0.53	0.93	——	——

[a]for G3[5]

studies, there are also some differences among them. In Shpund and Levin [3,5,6], the lengths L of the cross canopies having the arm ratios ℓ_s/L of 3.0 and 3.8 were 45.0 and 48.6 cm, respectively. The sizes of the canopies used in [4] were not designated. However, when the other studies and the test conditions used are considered, the same size canopies are thought to have also been used in [4]. The arm ratio of 3.8 was only used in [3,4]. In three of the studies [3,5,6], the same setup was used with a single and/or double support system. The setup used in [4] has a different design. During the tests, the constant wind tunnel speed was 20 m/s in [3,5], but it was 25 m/s in [6]. Although the staggering ratios $\Delta\ell/L$ used in other studies were 0.05 and 0.1, they were 0.044 and 0.09 ($\Delta\ell = 20$ and 40 mm) in [5]. Therefore, due to these differences, the measurement results in these papers are different from each other.

1. Nonrotating Configurations

The configurations with zero staggering distance $\Delta\ell = 0$ in Table 1 (configurations 1, 4, 7, and 11) represent the nonrotating configurations. They are cross configurations. Because of its design, the round parachute does not have a nonrotating configuration.

When the tangential force coefficient results presented in Table 1 are considered, it is noticed that as the suspension line length increases, the tangential force increases for each cross parachute. This might be due to the increased projected area of the canopy with longer suspension lines.

When the corresponding short or long suspension line configurations of two cross parachutes are brought together, it is observed that the configurations having the arm ratios of 3.0 have larger force coefficients than their corresponding configurations having the arm ratios of 3.8. This might be due to the geometric porosity of the canopy. The geometric porosity of cross parachutes increases as the arm ratio increases. Thus, the configurations with $L/W = 3.0$ have larger force coefficients than their corresponding configurations with $L/W = 3.8$.

According to the dynamic stability observations, medium oscillations were designated for the configurations having the arm ratios of 3.8. The configurations with $L/W = 3.0$ had large oscillations from their symmetry axes with respect to the other nonrotating configurations.

Tangential force coefficient results of nonrotating cross parachutes tested by Z. Shpund and D. Levin [3,5,6] are presented in Table 2. Although there are differences in the test setups and test conditions, the corresponding results of the current study are close to those obtained by the authors [3,5,6]. As in the current study, tangential force coefficients in other studies increase with an increase in suspension line length. Furthermore, there is a decrease in the force coefficients with an increase in the arm ratio.

2. Rotating Configurations

There are six rotating configurations for the cross parachute having the arm ratio of 3.8 (Table 1), due to the problems which occurred with configurations 10 and 14. During those tests, the parachutes failed to open successfully, which may have been because of the stretching of the parachute with this staggering distance. Therefore, configurations 9 and 13 were also constructed.

In the fifth column of Table 1, the spin rate measurement results are presented. As the staggering distance increases, the spin rate increases for cross parachutes, except with configurations 10 and 14. On the other hand, as the suspension line length increases, the spin rate increases for each parachute. The results of the round parachute are also comparable with cross canopies.

According to the tangential force coefficient results in Table 1, as the staggering distance increases, the force coefficient increases for each cross parachute, except with configurations 10 and 14. When the three parachutes are considered, it is noticed that long suspension line configurations have larger force coefficients than their corresponding short suspension line configurations, except configurations 10 and 14. Although having the same canopy surface area, the round parachute had the highest tangential force coefficient. The differences in the canopy design of the parachutes resulted in the differences in the force coefficients.

When the dynamic stabilities are considered, it is realized that rotating cross configurations have smaller oscillations than their nonrotating configurations. Their oscillations are also smaller than those of the round configurations. The oscillations classified in Table 1 are to designate the differences in the configurations and the parachutes. It is expected that they would not oscillate in the air as they did in the wind tunnel.

In Table 3, the spin rate results were compared with the results of the previous studies. Because of the differences already mentioned, the corresponding nondimensional spin rates in the current study are different from those obtained by Z. Shpund and D. Levin [3–6]. In all studies, the spin rate increases with an increase in the staggering distance, except configurations 10 and 14 in the current study. On the other hand, the other trend observed in the current study is only seen in the results of [5]. According to this trend, the spin rate increases with an increase in the suspension line length.

Tangential force coefficient results of the experimental studies were compared in Table 2. The differences in the works resulted in the differences in the values. However, they are close to each other for some configurations. According to the results, the trends found in the current study are usually observed in other studies [3,5,6]. As the staggering distance and/or the suspension line length increases, the tangential force coefficients of the corresponding configurations increase, except configurations 10 and 14.

IV. Conclusions

From the experimental results obtained and the observations made, these conclusions are reached:

Table 3 Comparison of force coefficient results of the cross canopies at $\alpha = 0^0$ deg

Config.	ℓ_s	$\Delta\ell$	Current study, $pd_c/2V$	$pd_c/2V$ [3]	$pd_c/2V$ [4]	$pd_c/2V$ [5][a]	$pd_c/2V$ [6]
			Cross parachute $L/W = 3.0$				
1	$0.7 \times L$	0	0	0	——	0	0
2	$0.7 \times L$	$0.05 \times L$	0.61	0.77	0.62	0.45	0.60
3	$0.7 \times L$	$0.1 \times L$	0.78	0.97	0.86	0.67	0.80
4	$1.0 \times L$	0	0	0	——	0	0
5	$1.0 \times L$	$0.05 \times L$	0.64	0.70	0.57	0.55	0.59
6	$1.0 \times L$	$0.1 \times L$	0.82	0.77	0.76	0.79	0.75
			Cross parachute $L/W = 3.8$				
7	$0.7 \times L$	0	0	0	——	——	——
8	$0.7 \times L$	$0.05 \times L$	0.75	0.74	0.76	——	——
9	$0.7 \times L$	$0.07 \times L$	0.80	——	——	——	——
10	$0.7 \times L$	$0.1 \times L$	0.66	0.78	0.79	——	——
11	$1.0 \times L$	0	0	0	——	——	——
12	$1.0 \times L$	$0.05 \times L$	0.83	0.72	0.73	——	——
13	$1.0 \times L$	$0.07 \times L$	0.84	——	——	——	——
14	$1.0 \times L$	$0.1 \times L$	0.78	0.73	——	——	——

[a]for G3[5]

1) Although having the same canopy surface area S_{ref}, all configurations possess different aerodynamic properties due to their different canopy shapes.

2) Although their spin rate results are not very different from cross configurations, the tangential force coefficient results of the round configurations are usually larger than those of the cross configurations. During the tests, only the suspension line length of the round parachute was changed. There are also other parameters which can be studied with this parachute, such as the jet opening area and the gore geometry.

3) From the dynamic stability observation results, it is realized that the oscillations of the rotating cross configurations from their symmetry axes are less than the oscillations of their nonrotating configurations. Furthermore, the oscillation of the round parachute is usually higher than that of each rotating cross parachute.

4) The cross parachutes tested are very similar to those considered by Z. Shpund and D. Levin [3–6]. Although there are differences in the setups and the test conditions, some values are close to each other. Furthermore, the trends found are usually observed in the previous studies.

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