A General Theory of Parachute Opening

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Theme

PREVIOUS theories of parachute opening,[1-3] useful as they are, may be criticized for two reasons. First, they are complicated and involve many assumptions of uncertain validity. It is often hard to tell which assumptions are fundamental and what is the effect of changes in the assumptions. Second, each theory is only tested for one parachute design, leaving the reader in doubt about the accuracy of the theory for other parachutes.

The purpose of the present paper is to develop a theory of parachute opening with the following properties: a) It should be simple enough so that the basic properties of the process, which are common to all parachutes, can be distinguished from the details, which may vary between parachutes; b) It should be general enough so it can be verified and applied with some confidence for a range of parachute designs.

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The governing equations of parachute opening are taken to be

$$d(mu)/dt = m_0 g \sin\theta - D \tag{1}$$

$$dV/dt = uA_pH_I \tag{2}$$

$$D = (\rho/2)U^2C_DA_pH_D \tag{3}$$

where t is time, u is canopy speed, D is drag, m is the total effective mass of the system, m_0 is the mass of canopy plus cargo, g is gravity acceleration, θ is the angle between the velocity vector and horizontal, V is the canopy volume, ρ is the mass density of air, A_p is the projected area of the canopy, and C_D is the drag coefficient of the fully open canopy. H_D is a function which corrects C_D for the partial-openness at any time, and H_I is a function which corrects uA_p at any time. The effects of angular momentum and centrifugal force are neglected in the above equations, and it is assumed that the canopy axis of symmetry is in the same direction as the system velocity vector.

The solutions to these equations are found in terms of V as independent variable

$$u = \{2[S_i + Q(V)]/F(V)\}^{1/2} \tag{4}$$

$$D = \rho C_D H_D(V)A_p(V)[S_i + Q(V)]/F(V) \tag{5}$$

$$t = t_i + \int_{V_i}^{V} [U(V')H_I(V')A_p(V')]^{-1}dV' \tag{6}$$

$$F(V) = \left[\frac{m(V)}{m(V_i)}\right]^2 \exp\left\{\rho C_D \int_{V_i}^{V} H_D(V')[m(V')H_I(V')]^{-1}dV'\right\} \tag{7}$$

$$Q(V) = gm_0\int_{V_i}^{V} \frac{F(V')\sin\theta(V')dV'}{m(V')H_I(V')A_p(V')} \tag{8}$$

$$S_i = U_i^2/2 \tag{9}$$

and U_i, t_i, and V_i are the speed, time, and volume at the start of opening. Formulas (4–9) provide the general form of the solution and hence embody the basic properties of the entire process. The only general requirement on the functions is that all integrals must exist. The only important difficulty arises near the end of inflation, i.e. at $V = V_f$, the fully inflated volume, because $H_I(V_f) = 0$. This merely tells us that it is not advantageous to use V as the independent variable near the end of inflation, where V is almost constant.

The details of the opening process are governed by the functional forms ascribed to $m(V)$, $\theta(V)$, $H_D(V)$, $A_p(V)$, $H_I(V)$, and the value assumed for C_D. All of these but $H_I(V)$ are estimated as follows:

$$\left.\begin{aligned} m &= m_0 + \rho V[1 + C_{m1}(V/V_f)^{Cm2}] \\ \theta &= C_{g1}(V/V_f)^{Cg2} \\ H_D(V) &= \Delta_1 + \Delta_2(V/V_f)^{\Delta_3} \\ A_p(V)/R_0^2 &= 1.867 - 2.399[0.6057 - (V/R_0^3)]^{1/2} \end{aligned}\right\} \tag{10}$$

where R_0 is the flat canopy radius, and it is assumed that the vent is not pulled down. The values of the constants appropriate for a horizontally launched, solid, flat canopy are

$$C_D = 1.5, \quad \Delta_1 = \Delta_2 = 0.5, \Delta_3 = 1, \quad C_{m1} = 0.375 \tag{11}$$
$$C_{m2} = 0.333, \quad C_{g1} = \pi/2, C_{g2} = 1$$

These estimates are similar to, and in some cases based on, those of previous investigators, apart from our use of V (rather than t) as independent variable.

The remaining function $H_I(V)$ is both important, because it strongly affects the rate of canopy inflation (see Eq. 2), and difficult to estimate because it represents the effect of many uncertain factors (e.g. porosity of cloth, the flapping of slack cloth, and the flowfield ahead of the canopy). Previous writers have tried to estimate and combine these factors, but the results are complicated and not convincing, usually because the effect of the changing flowfield is ignored. Our procedure consists of assuming the general form

$$H_I(V) = [1 - (V/V_f)][h_0 + h_1(V/V_f) + h_2(V/V_f)^2]$$

then trying various combinations of values of h_0, h_1, h_2, calculating numerically the solutions (4–8), and comparing the calculated values of maximum drag and opening time with experimental results. The test results consist of measurements made on three different solid, flat parachutes, having 28, 64, and 100 ft diam.

After many trials, the function

$$H_I(V) = 0.35[1 - (V/V_f)^2] \tag{12}$$

was found to give fairly good agreement between theoretical and experimental results, Table 1:

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Table 1 Comparison of theory and experiments

Diam ft	Load lb	U_i, fps	D max th.	lbs exp.	t_f th.	secs exp.
28	225	170	1,400	1,200	1.15	1
64	2,250	220	9,050	9,000	2.60	unknown
100	3,860	220	8,460	8,500	6.59	7

The theory is not wholly satisfactory because the maximum drag is found to occur somewhat earlier than is usually observed in tests, especially for the 28-ft parachute. This may be due to the theory's excessively simple treatment of the end of inflation.

A number of computations were made to test the behavior of the theory with respect to changes in the parameters. In particular, the effect of changes in $H_I(V)$ on the maximum drag and opening time are not excessive unless $H_I(V) \approx 0$ for $V = V_p$, say, in which case the results are sensitive to the behavior of H_I near V_p. The effects of load, initial velocity, apparent mass etc. were also studied. In all cases, the theory gives reasonable-looking results although experimental data was not available for a definitive check.

When the theory is applied to model parachutes three ft in diameter, it gives poor agreement with some early tests[3] and better (but still unsatisfactory) agreement with more recent tests[4] on very flexible models. Even these models, however, were relatively stiff compared with a full-sized canopy. Thus it is possible that the theory, which is fairly satisfactory for full-sized canopies, may also be satisfactory for small models, provided the model flexibility duplicates that of full-sized canopies.

Further progress in understanding and predicting parachute-inflation probably requires that it be viewed as a stochastic process. The general solution (4–9) may be a convenient starting point for studies of this type. In any case the theory obtained by combining Eqs. (10–12) with the general theory gives fairly satisfactory results for several different flat circular canopies when horizontally launched. The theory differs from existing ones in that canopy volume rather than time, is used as the independent variable, and the estimate of $A_p(V)$ is based on a simple approximation to the area-volume relation for an ellipsoid of revolution.

References

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