JOURNAL OF AIRCRAFT
Vol. 31, No. 5, Sept.-Oct. 1994

Comparison of Electrostatic and Aerodynamic Forces During Parachute Opening

M. Horenstein*
Boston University, Boston, Massachusetts 02215
and
N. Roberts†
United States Army Natick Research, Development, and Engineering Center, Natick, Massachusetts 01760

The work reported here seeks to determine the conditions, if any, under which electrostatic effects become comparable to aerodynamic forces during parachute opening. A simple Bernoulli model is used to estimate the principal aerodynamic forces during the early stages of inflation. The electrostatic forces during this period are found by computing the Coulomb attraction between two folds of parachute cloth charged to opposite polarity. These attractive Coulomb forces produce an inward "electrostatic tension" that acts to oppose the outwardly directed tension caused by the Bernoulli pressure. The investigation involves theoretical analysis, small-scale wind-tunnel tests, and extrapolations to full-size parachutes. Our present estimates suggest that aerodynamic forces are two to three orders of magnitude larger than electrostatic forces for typical levels of air velocity and charge density. Typical levels of charge density are defined as those easily obtained in the laboratory via the process of triboelectrification (creation of static charge by friction).

Introduction

THE standard circular canopy parachute, essentially unchanged since the 1940s, still forms the cornerstone of many military airdrops involving personnel or equipment. Parachutes are made of nylon, a material known for its ability to acquire and retain electrostatic charge. Parachute designers have long suspected that electrostatic attraction—"static cling"—may impede the opening of parachutes or lead to catastrophic failure under certain circumstances. Despite this widely held suspicion, few references to electrostatic effects can be found in the literature. In his classic book, Brown[1] briefly cites the nuisance effect of electrostatics on parachute packing. One study[2] investigated antistatic agents for use on parachute fabrics, indicating some previous interest in the problem. A handful of reports in Ref. 3 allude to the possible role of electrostatics in parachute failure without reaching any definitive conclusions. A study[4] performed for the U.S. Army Natick Laboratory concluded that charge on parachute cloth generated by the process of triboelectrification (charge generation by friction) is capable of exerting reasonable force. Aerodynamic and electrostatic forces were not compared in this study, however, therefore no conclusion could be reached concerning the role of electrostatics in retarding or preventing full parachute opening.

At present, no known parachute failures can be unequivocally attributed to electrostatic effects. Nevertheless, the notion has persisted that electrostatic attraction of oppositely charged cloth surfaces might act to impede parachute opening under extremes of low humidity and low temperature, or during atmospheric electrical disturbances. The goal of our research, which is still in progress, has been to determine the conditions, if any, under which electrostatic forces become comparable to or exceed aerodynamic forces. Many possible scenarios exist by which charge of opposite polarity might be deposited on adjacent folds of a parachute. Our objective has been not to identify such deposition mechanisms, but simply to determine whether charge, deposited by any means, might have a significant effect on the opening process. This article summarizes the predictions of our theoretical models, their approximate verification via small-scale wind-tunnel experiments, and their extrapolation to full-size parachutes.

Model for Aerodynamic Forces Just After Snatch

Although each of the various stages of the opening process is of interest in studies of inflation dynamics, the status of the parachute immediately after the snatch impulse is of principal interest from the point of view of electrostatics. At this stage of the opening process, aerodynamic forces are at a minimum, electrostatic forces are at a maximum, and the parachute is most sensitive to any factors that may impede its ability to open rapidly. A simplified model for the post-snatch parachute is shown in Fig. 1. The central portion, termed the "mouth," initially represents an area that is open, regardless of airflow, due to the physical presence of the suspension lines. The folded gores are initially closed and are presumably peeled apart as pressure builds inside the mouth, causing its radius to expand. If adjacent sides of a folded gore are charged to opposite polarities, the attraction will tend to prevent the gore from being pulled apart, thereby impeding the overall opening of the parachute. For a given mouth radius, the air velocity U_M into the mouth will be determined by the fill rate of the canopy. The air velocity U_F outside the mouth just after snatch is assumed to be equal to the free-fall velocity of the payload, since the parachute provides little deceleration until inflation begins in earnest.

Our simple aerodynamic model is based on the Bernoulli effect, whereby the velocity difference across the walls of the mouth results in an outward aerodynamic pressure P_A given by

$$P_A = \tfrac{1}{2}\rho(U_F^2 - U_M^2) \tag{1}$$

where $\rho \approx 1.2$ kg/m³ is the density of air at standard temperature and pressure. For a given U_F, the upper bound of P_A occurs when $U_M = 0$. Conversely, the faster the fill rate

Received July 7, 1993; revision received Sept. 29, 1993; accepted for publication Jan. 9, 1994.

*Associate Professor, Department of Electrical, Computer, and Systems Engineering, 44 Cummington St.

†Physicist, Engineering Technology Division, Aero-Mechanical Engineering Directorate, Kansas St., Attn: SATNC-UE.

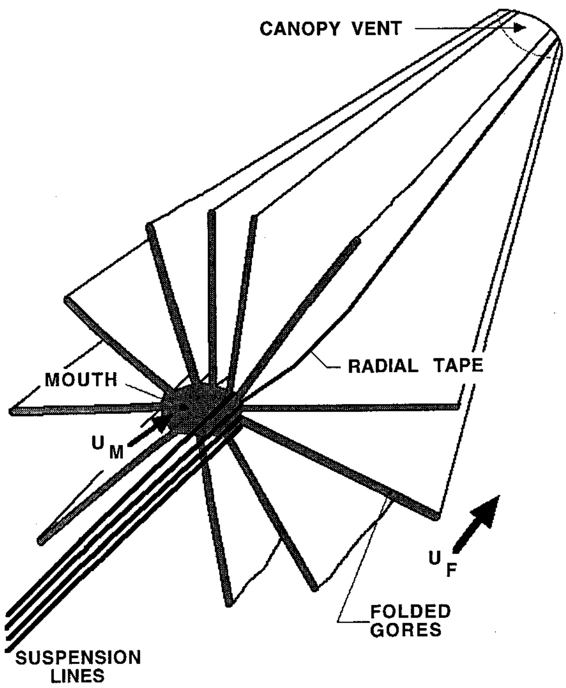

Fig. 1 Simplified model for a parachute just after snatch.

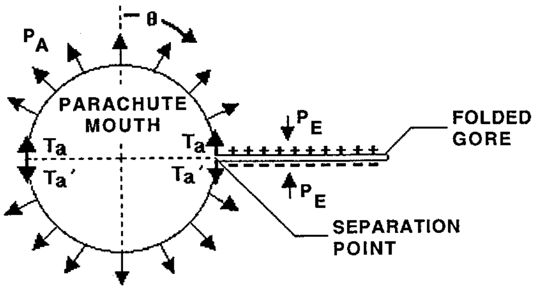

Fig. 2 Model for the gore separation point where aerodynamic and electrostatic forces interact.

of the parachute, the faster the mouth velocity U_M and the smaller the outward pressure P_A at the mouth.

In order to study the interaction between aerodynamic and electrostatic forces, it is helpful to focus on the separation point at the inner edge of a single charged, folded gore where it intersects the circumference of the mouth. This separation point marks the boundary between the mouth region, where the aerodynamic forces dominate, and the folded gore region, where electrostatic forces are likely to dominate. As depicted in Fig. 2, the aerodynamic pressure acting to open the mouth translates into a circumferential tension per unit length

$$T_a = P_A r = \tfrac{1}{2}\rho(U_F^2 - U_M^2)r \tag{2}$$

exerted at the separation point, where r is the mouth radius. This stress, which acts to pull apart the edges of the gore, is analogous to "hoop stress" in a wooden barrel[5] and acts tangentially to the mouth circumference at the separation point. Note that T_a has dimensions of force per unit gore-edge length L, where L is perpendicular into the page in Fig. 2.

Model for Electrostatic Forces on a Charged Parachute

The parachute depicted in Fig. 2 will open if T_a exceeds any electrostatic force acting to hold the folded gore together. A simple model for the electrostatic force at the separation point can be obtained from the "two slab" model of Fig. 3, in which any partially separated regions of the gore edges are represented by two oppositely charged, vertical slabs of cloth of height $\pm h$. These slabs exert an attractive force on each

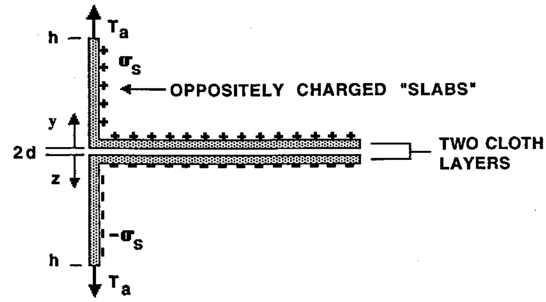

Fig. 3 Two-slab model for estimating electrostatic forces at the gore separation point.

other that directly opposes the hoop stress T_a. The electrostatic force contributed by the bulk of the cloth layers remaining in contact acts normal to their surfaces. Since this force does little to counteract tension along the length of the cloth, it may be ignored. Similarly, the repulsion force exerted by a given vertical slab on itself has no net component and may also be ignored.

The attractive electrostatic force resulting from the oppositely charged slabs in Fig. 3, expressed as a tension that counteracts the aerodynamic "hoop" tension, can be computed by treating each slab as a collection of strip charges of incremental width and infinitesimal thickness. The net tension can then be computed by direct integration. Specifically, an incremental positive charge element of width dy and length L (into the page) will experience a downward (attractive) force of

$$dF_y = -\int_{z=d}^{h} \frac{(\sigma_s L\, dy)(\sigma_s\, dz)}{2\pi\varepsilon_0(y+z)} \tag{3}$$

where σ_s is the strip charge density in Coulomb/m² (assumed to be of uniform magnitude for all strips). The integral (3) is equivalent to a summation of the forces felt by a positive strip charge of magnitude $\sigma_s L\, dy$ on the upper slab due to the field of a series of negative strip charges of magnitude $-\sigma_s\, dz$ that constitute the lower slab. Performing the indicated integration for the case $d \ll h$ (negligible cloth thickness compared to slab height), then integrating over the entire upper slab, results in an electrostatically produced "Coulomb" tension equal to

$$T_e = -\sigma_s^2[(\ln 2)/\pi\varepsilon_0]h \tag{4}$$

per unit gore length L. To the extent that actual separation at the gore edges can be modeled by two perpendicular, oppositely charged slabs, the threshold for parachute opening can be determined by finding the conditions under which the aerodynamic and electrostatic forces balance. Using Eqs. (2) and (4), this condition can be expressed as $T_a = -T_e$, or

$$\sigma_s^2[(\ln 2)/\pi\varepsilon_0]h = \tfrac{1}{2}\rho(U_F^2 - U_M^2)r \tag{5}$$

This equation can be solved for the minimum ambient airspeed velocity $U_F = U_{\min}$ required to open a parachute under the assumptions of zero mouth velocity ($U_M = 0$), a condition resulting in the maximum Bernoulli pressure, and fixed charge densities $\pm\sigma_s$ on opposite faces of the folded gore. Rearranging Eq. (5) results in

$$U_{\min}|_{U_M=0} = \sigma_s\left[\frac{(2\ln 2)h}{\pi\varepsilon_0\rho r}\right]^{1/2} \tag{6}$$

Equation (5) may also be solved for the minimum Bernoulli pressure P_A needed to open the parachute for a given value of cloth charge $\pm\sigma_s$:

$$P_A = \sigma_s^2[(\ln 2)/\pi\varepsilon_0](h/r) \tag{7}$$

Note that at large ratios of h/r, the "slabs" used in the model form a significant portion of the mouth circumference and will no longer be perpendicular to the folded gore faces. Under these conditions, the simple two-slab model breaks down. For small slab heights, however, representative of a parachute in the early stages of opening (gores just beginning to be peeled apart), the result provides a useful measure of the threshold conditions for gore opening.

Small-Scale Wind-Tunnel Tests

The basic theory described above was tested via a series of wind-tunnel tests performed at 5–20 mph (2.2–8.9 m/s) using a 36-in.- (0.9-m-) diam, six-gore parachute made from 0.003-in.- (80-μm-) thick, low porosity nylon (U.S. military specification MIL-C-44378-T/I). No attempt was made to apply general aerodynamic scaling laws to the test system. Rather, our approach was to calculate the forces directly for the small model parachute at the modest wind velocities available in our wind tunnel, predict and verify the parachute's minimum opening speed, and then apply the theory at the higher wind velocities typical of full-size parachutes.

Prior to each opening test, the parachute was installed in the test fixture of Fig. 4, where it's six gores were folded in half, three on each side of the parachute, with the suspension lines concentrated in the center. A 0.02-in.- (500-μm-) thick paperboard-foil-paperboard sandwich was inserted inside each folded gore to function as an isolating electrical spacer between upper and lower cloth faces. This insert provided a floating reference plane of constant potential against which each face could be charged using custom fabricated stainless-steel high-voltage brushes located on opposite sides of each folded gore. The folded gores were charged in parallel by passing the brushes, energized at 2–4 kV, in a slow, sweeping, contact motion over the outer surfaces of the folded gores for a duration between 10–20 s. This brushing was designed to charge all but the outermost edges of each gore surface (near the seams) with approximate uniform density, as depicted in Fig. 5. The outermost gore edges, left uncontacted by the high-voltage brushes, were assumed to remain uncharged. The magnitude of the deposited charge after brushing was monitored prior to release with a noncontacting electrostatic voltmeter using the foil layer of the paperboard separator, now grounded, as a reference plane. The average deposited charge for all tests was about 12 $\mu C/m^2$, a value typical of those encountered during the frictional rubbing of nylon cloth under laboratory conditions.

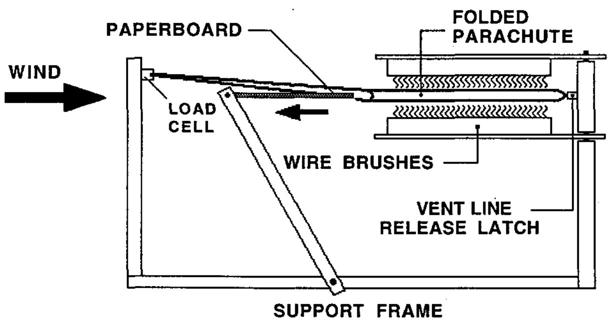

Fig. 4 Parachute test fixture (overall length approximately 2 m).

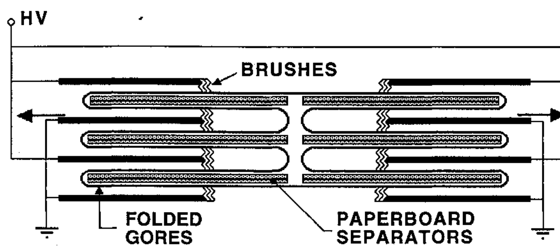

Fig. 5 Detail of parachute charging system.

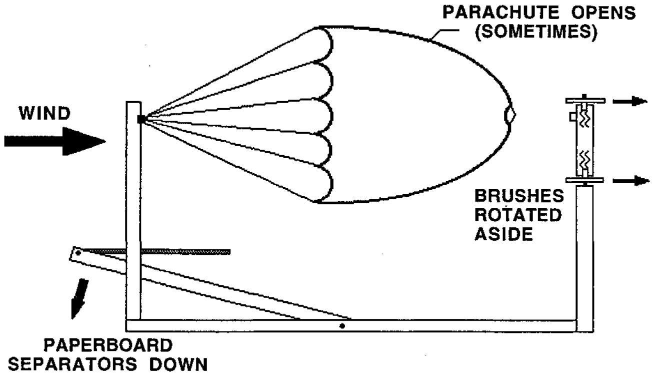

Fig. 6 Parachute in test fixture after release.

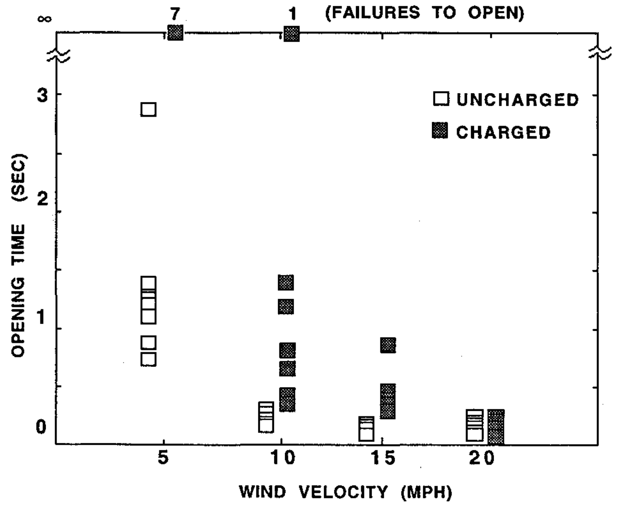

Fig. 7 Model parachute opening times at various wind velocities.

Prior to release in the airstream, the flat folded parachute was held shut by two skirt clamps. After longitudinal removal of the paperboard separators, as depicted in Fig. 4, the skirt clamps were quickly retracted and the vent line released, thus freeing the parachute to interact with the ambient airstream under infinite-mass conditions, as in Fig. 6. In order to determine the time between release (force minimum) and full opening (steady-state force), the net drag on the parachute was monitored using a load cell attached between the ends of the suspension lines and the stationary test fixture.

The results of these experiments, which involved over 40 trials, are summarized in Fig. 7. At 5 mph (2.2 m/s), the charged parachute failed to open every time. At 10 mph (4.5 m/s), the opening time of the charged parachute was always longer than the uncharged opening time, and one failure to open was observed. At 15 mph (6.7 m/s), no total failures to open were observed, but most of the charged tests exhibited some delay in opening. At 20 mph (8.9 m/s), charged and uncharged opening times follow essentially the same statistical distribution. From these tests, one can conclude that the minimum air velocity for charged parachute opening lies somewhere between 5–10 mph for our set of test conditions.

Comparison of Theory and Data

The theoretical model summarized by Eq. (6) was tested against the observed experimental results by assuming the parachute mouth consists of the portion of cloth left uncharged by the stainless-steel brushes immediately after release, and by further assuming the charged layers of cloth remain in contact until after release. Given the observation that most of the gore surfaces were held together by charge up to the moment of release, U_M was assumed to be approximately zero at the moment of release. Under these sets of assumptions, the minimum airspeed needed to open the parachute was determined by computing U_{min} for the initial mouth radius and for successively larger mouth radii representative of an opening parachute. For the initial mouth radius, the lengths of the "charge slabs" used to compute the electrostatic force was assumed to be zero. At each larger mouth radius, the length of each slab was assumed to be equal to the net increase in mouth circumference divided by twice the number of gores. (Each peeled gore contributes two increments of slab length to the increasing mouth circumference.) Note that the calculated U_{min} increases as the gores peel apart because the exposed "charge slabs" responsible for the electrostatic attraction become longer. The resultant electrostatic force increases more rapidly than does the aerodynamic Bernoulli force.

Plots of the calculated U_{min} vs increasing mouth radius for several values of initial radius are shown in Fig. 8. The parameters used in making these plots included an average σ_s of 12 μC/m^2 and an air density of 1.2 kg/m^3. As is evident in the figure, the curves are asymptotic to the value $U_{min} \approx 4.8$ mph, which we interpret to represent the minimum opening speed of the parachute for the assumed set of parameters. Our experimentally determined minimum opening speed, which lies between 5–10 mph, is within the range of this theoretically determined value. Given the simple nature of the theoretical model, our assumption that $U_M = 0$ even as the mouth opens, and the fact that the small parachute quickly departs from a two-dimensional structure as the parachute opens, the rough agreement between the model and the experimental data shows that the former can provide a reasonable estimate of the minimum opening speed of a charged parachute.

Application of the Model to Full-Scale Parachutes

The theory described above was extended to the case of full-size parachutes by substituting suitable parameters into Eq. (1). In this case the mouth velocity was not assumed zero in order to present a worst-case scenario from the point of view of the possible role of electrostatic effects. With nonzero U_M, a smaller outward Bernoulli pressure is calculated for the mouth region, resulting in a higher minimum opening air speed U_{min}. Because, hypothetically, the mouth velocity can approach the ambient airspeed, resulting in zero outward Bernoulli pressure, the actual value of U_M was estimated for two full-size parachutes using the high-speed photographs of Fig. 9 plus other photographs not shown. As is evident in these photographs, the inflating parachute fills from the mouth upward, forming a bubble that grows and propagates toward the canopy peak. Estimates of mouth velocity were made by measuring the bubble volume and mouth diameter on each photographic frame. The approximate mouth velocity between frames was then computed using the formula

$$U_M = \frac{\text{(increase in bubble volume)}}{\text{(time between frames) (mouth area)}} \tag{8}$$

The outward Bernoulli pressure associated with each frame was then computed using Eq. (1). The results are summarized in Table 1 for representative 64-ft- (19.2-m-) and 100-ft- (30.5-m-) diam parachutes. The aerodynamic pressure estimates from Table 1 were compared to the minimum opening pressure of an electrically charged full-sized parachute. Applying Eq. (7) with an assumed charge density of $\sigma_s = 27$ μC/m^2, a value equal to the theoretical limit set by the breakdown strength of air, a representative mouth radius of $r = 50$ cm, and a slab height of $h = 10$ cm, representing the maximum possible h/r ratio and maximum electrical force, the minimum opening pressure becomes $P_A = 3.6$ N/m^2. This value for P_A is significantly smaller than any of those given in Table 1, suggesting that, at the higher velocities of a full-size parachute drop, the aerodynamic forces significantly dominate over electrostatic forces.

The relationship between T_a and T_e can be manipulated into a form that can be used to determine the minimum charge needed to prevent gore opening at a deployment airspeed U_F. For a P_A of 2 kN/m^2, representing an average of the values given in Table 1, the minimum charge needed to prevent opening becomes

$$\sigma_s = \left(\frac{\pi\varepsilon_0 P_A}{2}\frac{r}{h}\right)^{1/2} \approx 630\ \mu\text{C/m}^2 \tag{9}$$

This value of charge exceeds the fundamental limit of 27 μC/m^2 set by the breakdown strength of air, which we assume to apply to the porous parachute cloth, and is also well above the value of tribo charge generally encountered on surfaces in air.[6–8] These results seem to suggest that, at least for the assumptions made in our calculations, the accumulation of charge by friction is insufficient to enable electrostatic forces to dominate over aerodynamic forces in a full-size parachute. It should be emphasized that this conclusion is preliminary. It is based on the adequacy of the Bernoulli model for calculating the aerodynamic forces and on the validity of the assumed maximum surface charge density supportable by nylon parachute fabric. The aerodynamic force model may not necessarily apply to a full-size parachute. Similarly, it may be possible for parachute fabric in the field to acquire more charge than we were able to deposit in our experiments. Investigations to resolve both of these issues are in progress.

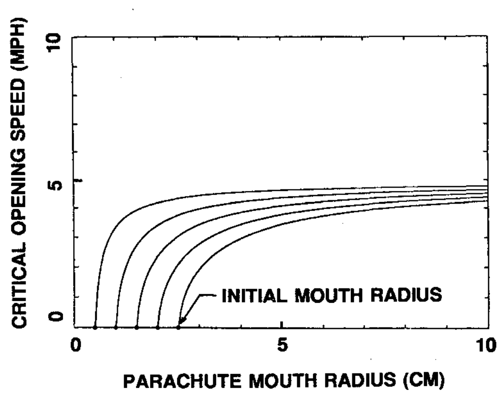

Fig. 8 Airspeed at which aerodynamic and electrostatic forces balance as a function of mouth radius.

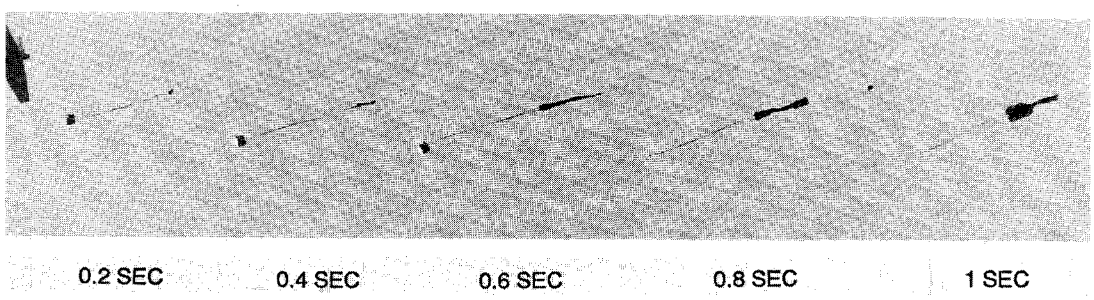

Fig. 9 Estimating the fill rate of an inflating parachute (U_F = 66 m/s and U_M = 54 m/s).

Table 1 Mouth velocity measurements and aerodynamic pressure estimates for two full-scale parachutes

	19.2-m-diam parachute				30.5-m-diam parachute			
Frame	Bubble volume, m^3	Mouth area, m^2	U_M, m/s	P_A, kN/m^2	Bubble volume, m^3	Mouth area, m^2	U_M, m/s	P_A, kN/m^2
1	0.043	0.09	—	—	0.11	0.14	—	—
2	0.22	0.14	7.8	2.50	1.12	0.54	14.8	2.40
3	0.600	0.27	9.3	2.48	17.05	2.16	58.9	0.45
4	7.200	2.16	27.1	2.09	34.50	3.38	31.5	1.94
5	50.800	7.65	44.4	1.35				

Airdrop velocity: U_F = 65 m/s. Time interval per frame: 0.2 s.

Summary and Conclusions

It has been shown experimentally that electrostatic forces on a strongly charged small-scale parachute are comparable to aerodynamic forces at airspeeds below about 10 mph. At these speeds, electrostatic forces are capable of completely preventing a parachute from opening.

A simple model, based on Bernoulli's equation, has been used to calculate the aerodynamic pressure inside a parachute during the early stages of opening. This model has been combined with a second simple model for calculating the electrostatic force to estimate the minimum airspeed at which a charged parachute should be expected to open. The minimum airspeed predicted by the combined models has been shown to agree approximately with experimentally measured values. This agreement indicates that the theory based on the aerodynamic and electrostatic force models may serve as a useful predictive tool.

The theory has also been applied to full-sized parachutes using realistic parameter values extracted from actual air drop data. The resulting aerodynamic pressures have been found to be several orders of magnitude larger than the pressures that can be produced by the strongest anticipated electrostatic forces. These results seem to suggest that, at least for the assumptions made in our calculations, the accumulation of charge by friction is insufficient to enable electrostatic forces to dominate over aerodynamic forces. The results thus lead to the preliminary conclusion that electrostatic forces may not be strong enough to prevent a full-sized parachute from opening in an actual jump. More work is required, however, to determine whether or not the present models can be applied to full-sized parachutes and to assess the conditions, if any, under which the actual charge density accumulated by parachute fabric might be larger than our assumed maximum value.

Acknowledgments

This article reports research sponsored by the U.S. Army Natick Research, Development, and Engineering Center, and has been assigned TP-2340 in the series of papers approved for publication. The authors would like to acknowledge the assistance of James Fairneny, Gary Vincens, Christina Udelson, and Daniel Litvack, who assisted with the experiments, and the helpful insights contributed by Thomas Godfrey, Louis Piscitelle, and Calvin Lee.

References

[1]Brown, W. D., *Parachutes*, Pitman and Sons, London, 1951, p. 251.

[2]Sweeney, J. W., *Evaluation of Antistatic Agents on Nylon Parachute Cloth*, Lowell Technological Inst. Research Foundation, WADC TR 54-513, Lowell, MA, Sept. 1955.

[3]Anon., "Airdrop Review and Malfunction/Safety Analysis," Vols. I & II, U.S. Army Quartermaster Center and School Rept. QAR&M/SA, 1991.

[4]Davey, C. T., Heffron, J. F., and Christopher, J. L., "The Effects of Static Electrification on Airdrop Systems," U.S. Army Natick Research and Development Center, NATICK/TR-85/015L, Natick, MA, Sept. 1983.

[5]Seely, F., and Ensign, N. E., *Analytical Mechanics for Engineers*, Wiley, New York, 1941, p. 186.

[6]Schaffert, R. M., *Electrophotography*, Wiley, New York, 1975, pp. 512–556.

[7]Davies, D. K., "Charge Generation on Dielectric Surfaces," *British Journal of Applied Physics (J. Phys. D)*, Ser. 2, Vol. 2, 1969, pp. 1533–1537.

[8]Horn, R. G., and Smith, D. T., "Contact Electrification and Adhesion Between Dissimilar Materials," *Science*, Vol. 256, No. 17, 1992, pp. 362–364.