JOURNAL OF AIRCRAFT
Vol. 44, No. 2, March–April 2007

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Momentum-Impulse Balance and Parachute Inflation: Clusters

J. Potvin*
Saint Louis University, St. Louis, Missouri 63103

DOI: 10.2514/1.26285

I. Introduction

In a previous publication [1] the momentum-impulse theorem (or MI theorem) was used for estimating the maximum parachute drag force $F_{\max}$ generated during inflation. This paper showed how to calculate $F_{\max}$ for *any* type of parachute, reefing, and drop conditions. The author [2] continued the discussion, this time by applying the theorem to a more specific application, namely to that of hemispherical parachutes dropped from fixed points such as cranes, buildings, or from very slow-moving aircraft. This engineering note continues using the impulse and momentum concepts, this time for the analysis of clusters of hemispherical parachutes dropped from slow or fast aircraft (parachute clusters are built by connecting at least two parachutes side-by-side [3]). As with [1,2], the goal here is to sharpen our understanding of the inflation process in general and of cluster inflation in particular, using new analytical approximations derived from the MI theorem. In some cases, these approximations confirm key knowledge that so far has been acquired only empirically. In other cases, the results suggest altogether new or extended conclusions.

The estimator used herein is based on the following formula, which expresses the maximum drag $F_{\max}$ in terms of the a priori knowledge of the opening-shock factor C_k [1,3–5]:

$$F_{\max} \equiv (SC_D)_{\rm sd}\left(\frac{1}{2}\rho V_i^2\right)C_k \tag{1}$$

This expression is written in terms of the dynamic pressure sustained by the parachute–payload system at the beginning of the inflation process, most typically at the moment of the full stretching of the suspension lines, and also in terms of the parachute's drag area $(SC_D)_{\rm sd}$, generated when the parachute is fully opened and descending in a steady manner. The empirical data compiled in [3–5] on the value of C_k can be used, along with a procedure motivated by the MI theorem [1], to predict the value of $F_{\max}$ for any parachute and reefing systems. Here the discussion will proceed from an analytical and exact result that also follows from the theorem, but a result that applies only to parachute systems inflating along a vertical trajectory, including many current cluster applications involving very large parachutes (i.e., 100 ft diam or larger):

$$C_k = \left[\frac{2\Gamma}{R_m n_{\rm fill}^{\rm gen}}\right] \tag{2a}$$

with

$$\Gamma = \left(1 - \frac{V_f}{V_i} + \frac{gD_0}{V_i^2}n_{\rm fill}\right) \tag{2b}$$

As derived in [2], this result involves knowing the speeds V_i and V_f characterizing the parachute-payload fall speeds at the beginning and end of the inflation process, respectively. The factor Γ represents the sum of the momentum change experienced by the parachute-payload (per unit initial speed and mass) and of the impulse supplied by gravity (namely the term proportional to the gravitational acceleration constant g). Usually a small contribution for human-sized parachutes, the gravitational impulse becomes a major contributor to inflation dynamics for very large parachutes as will be seen here. Another important input is the so-called inverse mass ratio R_m [3,5], a nondimensional constant defined as

$$R_m = \frac{\rho(SC_D)_{\rm sd}^{3/2}}{m} \tag{3}$$

The mass ratio is an estimate of the air mass that decelerates (or accelerates) along with the parachute system during inflation. As such, R_m reveals how important drag is relative to total weight and hints at which types of deceleration or acceleration profiles (and parachute wakes) are to be anticipated during the inflation process. Note that (2) is valid for any value of the mass ratio, although the applications considered here are more typical of large-R_m systems.

Equation (2) also involves the very important concepts of generalized filling time $n_{\rm fill}^{\rm gen}$ and standard filling time $n_{\rm fill}$, two nondimensional numbers that are built out of the dimensional inflation time $t_{\rm fill}$. The correspondence between all three temporal concepts is as follows:

$$n_{\rm fill}^{\rm gen} \equiv \frac{V_i t_{\rm fill}}{(SC_D)_{\rm sd}^{1/2}} I_F^{\rm if} = n_{\rm fill}\frac{D_0}{(SC_D)_{\rm sd}^{1/2}} I_F^{\rm if} \tag{4}$$

Here $n_{\rm fill} \equiv (t_f - t_i)V_i/D_0$ with D_0 being the so-called nominal canopy diameter, defined from the total canopy surface area S_0 as $D_0 = (4S_0/\pi)^{1/2}$ for hemispherical-type canopies [3]. Finally, the constant $I_F^{\rm if}$ is the normalized integral of the drag force over time (i.e., over the interval $t_{\rm fill}$), thereby being given by $I_F^{\rm if} = \int[F_D(t)\,{\rm d}t]/F_{\max}t_{\rm fill}$ [1]. The appearance of the drag integral in (4) makes the point that $n_{\rm fill}^{\rm gen} \sim n_{\rm fill}$ when $I_F^{\rm if} \sim 1$, i.e., when the opening force is pretty much sustained at its maximum level throughout the inflation process. On the other hand, $n_{\rm fill}^{\rm gen} \ll n_{\rm fill}$ when $I_F^{\rm if} \ll 1$, i.e., when the inflation dynamics generates low-level drag during most of the process and a high but brief drag peak at the end. In other words, $n_{\rm fill}^{\rm gen}$ represents the filling time associated with the dominant peak of the F_D vs t curve [1].

Note that Eq. (2) can be used to study any type of parachute and reefing designs. Applying it to the case of hemispherical parachute clusters is also straightforward, although a key assumption shall be used to enhance its simplicity while maintaining its usefulness.

Received 30 June 2006; revision received 24 August 2006; accepted for publication 1 October 2006.

*Professor, Parks College Parachute Research Group, Department of Physics. Senior Member AIAA.

II. Parachute Clusters Basics

A. Design Advantages

The parachute cluster is the standard solution to the airdropping and recovery of high-weight payloads that are required to land at low velocity. Parachute systems used for the air delivery of military cargo or for the atmospheric reentry of Apollo-type spacecraft are two examples of clusters handling payloads in excess of 5000 lbs. The advantages of using clusters reside primarily in the ease of rigging, as well as of the ease of building and packing smaller parachutes, compared with using one single, but also very large parachute [3,4]. Moreover, and this is important for drops required to be carried out at low altitudes above ground, clusters inflate at much faster rates, and therefore require less altitude for full deployment and inflation.

B. Lead/Lag Problem

Because the member chutes of a cluster are in close proximity to each other, there will be interference which will affect the overall drag-producing capacity of the system, as well as its inflation. With respect to the latter, the major technical challenge in cluster design has been to make each member inflate at roughly the same time and at the same rate, i.e., to obtain the perfectly synchronized opening of all the parachutes of the cluster so to avoid the extreme loading that a fewer number of cluster members would experience if opened prematurely [3,6,7]. Typically, unsynchronized inflation, or "lead/lag" inflation, involve the early opening of at least one cluster member, an event that would then impede the inflation of all other members. Lead/lag comes about by the expanding skirts (mouths) of the fast-inflating canopies getting in the way of the skirts of the slower opening canopies. Moreover, with canopies opening prematurely, a larger than expected deceleration of the parachute-payload would occur, which in turn would further reduce the pressure inside the laggers and further slow down their opening rates. Mastering of the lead/lag problem has been achieved by line-reefing the skirt of each cluster member, a strategy that keeps the skirt/mouth to a smaller diameter during the early part of inflation, thereby keeping the skirt of each cluster member out of each other's way [3]. The reefing line is severed by time-activated cutters during the later stages of the inflation process. Another approach, pioneered by Lee and Sadeck [7], consists in physically tying together the contiguous skirt sections of the members with reefing lines, thus eliminating the gaps between the neighboring parachutes. The result is a configuration that inflates like a single canopy. Again, timed line cutters sever the reefing lines during the later stages of the inflation process. Actual opening force data collected on clusters can be found in [4], as well as in the work of Lee et al. [6,7], and in the parachute studies of the F-111 ejection capsule by Behr [8] and Johnson [9].

III. Inflation and Descent Properties: Cluster vs Single Parachute

The use of Eq. (2) becomes very informative once several of the cluster-specific inputs, such as $(SC_D)_{\text{sd}}$ and $n_{\text{fill}}^{\text{gen}}$, are expressed in terms of those characterizing each cluster member.

A. Drag Area

The cluster empirical data compiled in [3,4] include the parameterization of the drag loss that occurs during steady descent, a loss mainly caused by each member flying in a tilted attitude. Whereas the tilt can be reduced by increasing the distance between each canopy and payload via the use of longer bridles [4], cluster drag losses are inevitable. This effect is usually represented as an average with the following equation, i.e., one that relates the steady-state drag coefficient of a cluster composed of j parachutes to that of single parachute (of the same type):

$$(C_{D0})_{\text{sd}}^{(j)} = \psi(j)(C_{D0})_{\text{sd}}^{(1)} \tag{5}$$

The factor $\psi(j)$ is the so-called drag-loss coefficient, a number that depends strongly on the value of j. The data of [4] shows that $\psi(j)$ depends also on the tilt angle being flown by each member. Typically, $\psi(4) \sim 0.80$ for cluster members flying with high tilts and $\psi(4) \sim 0.93$ for cluster members flying with low tilts (either low- or high-porosity). Note that the drag coefficients C_{D0} used in (5) are calculated with respect to the total canopy surface area S_0 (including the area of the vents, and of any other openings [4]). By definition of S_0, this means that

$$S_0^{(j)} = jS_0^{(1)} \tag{6}$$

B. Inflation Time

Two crucial assumptions involving inflation duration will be used here: 1) assuming the cluster members inflating in perfect synchronicity (i.e., no lead/lag), and 2) that the filling time of each cluster member being similar in magnitude to that of each cluster member descending alone, albeit with a smaller payload, but at descent rates that are similar to that of the cluster. These two approximations mean that

$$V_i t_{\text{fill}}|_{j\text{-cluster}} \sim V_i t_{\text{fill}}|_{\text{cluster-member}} \sim V_i t_{\text{fill}}|_{1\text{-cluster}}$$

According to the definition of n_{fill}, this in turns means that

$$V_i t_{\text{fill}}|_{j\text{-cluster}} = D_0^{(j)} n_{\text{fill}}^{(j)} = D_0^{(1)} n_{\text{fill}}^{(1)} \tag{7}$$

an expression that involves again the nominal diameter $D_0 = (4S_0/\pi)^{1/2}$. Combining (6) and (7) yields this important new result:

$$n_{\text{fill}}^{(j)} = \sqrt{\frac{1}{j}}\, n_{\text{fill}}^{(1)} \tag{8}$$

Equation (8) implies the well-known empirical fact that, in nondimensional terms, parachute cluster inflation is characterized by smaller filling times. Again, the one important physical assumption behind (7) and (8) is that of minimized mutual interference. This means that (8) should not be expected to be very accurate for systems that have substantial lead/lag problems.

IV. Maximum Inflation Force for Clusters

A. Main Result

Putting (2), (4), (5), and (8) into (1) yields this final result:

$$F_{\max}^{(j)} \equiv \left(\frac{1}{2}\rho V_i^2\right)(SC_D)_{\text{sd}}^{(1)}\left[\frac{[j\cdot\psi(j)]^{3/2}\sqrt{\pi C_{D0}^{(1)}}}{R_m^{(j)} n_{\text{fill}}^{(1)} I_F^{\text{if}}|_{j\text{-cluster}}}\right]\left(1 - \frac{V_f^{(j)}}{V_i} + \frac{gD_0^{(1)}}{V_i^2} n_{\text{fill}}^{(1)}\right) \tag{9}$$

Here the mass ratio $R_m^{(j)}$ is still that of the entire cluster parachute system; in the same vein, the drag integral $I_F^{\text{if}}|_{j\text{-cluster}}$ is the value obtained after integrating the total drag force measured on the cluster. On the other hand, the ratio V_f/V_i has been rewritten as $V_f^{(j)}/V_i$, to point out the sensitivity of V_f and insensitivity of V_i on the number of cluster members. The reason for V_i being mostly insensitive to j is that its value is determined mainly by the drop-aircraft's speed, payload weight, parachute unfolding dynamics during deployment, and deployment duration. Note also that the gravitational impulse is independent of the number of cluster members, a result of Eq. (7) and of V_i being insensitive to j. Finally, the product $[j\psi(j)]^{3/2}$ may or may not change appreciably with j, depending on whether the canopies are flying at low or high tilt. For example, the data of [3,4] for ribbon chutes at $j = 3$ and $j = 5$ suggests $[j\psi(j)]^{3/2}$ varying from 4.81 to 9.54 for small-tilt flight, and from 4.07 to 6.55 for high-tilt flight.

B. Numerical Example

Consider the case of a 4-cluster of low-porosity, flat circular parachutes of the G-11 type [4], but line-reefed along skirt sections according to the method of Lee and Sadeck [7] (an approach that guarantees synchronicity). Here the parachute system is carrying a 14,000 lb payload and each parachute opens completely in about six seconds. Each member has a nominal diameter of $D_0 = 100$ ft, which yields, as a cluster, a near sea-level descent rate of ~25–30 ft/s for this payload weight (with severed reefing lines). Typical for this system is $V_i \sim 150$ ft/s, attained a few seconds after being dropped from an aircraft flying at 130 kn, indicated, and at 2000 ft mean sea level; such drop conditions yield $\frac{1}{2}\rho V_i^2 \sim 24.7$ lbs/ft^2. Given a typical filling time of $n_{\text{fill}}^{(1)} \sim 10$ for this parachute type (reefed; large reefing ratio [3]), Eq. (8) gives $n_{\text{fill}}^{(4)} \sim 5$. On the other hand, the steady-state drag area of the cluster configuration is given as follows, using a short-bridle configuration (i.e., canopies flying at a high tilt) [4]:

$$(SC_D)_{\text{sd}}^{\text{4-cluster}} \sim \psi(j)j(C_DS)_{\text{sd}}^{\text{1-clute}} \sim 4 \times 0.8 \times [0.8 \times \pi(100/2 \text{ ft})^2] \sim 20,096 \text{ ft}^2$$

with the corresponding drag coefficient of a solo parachute set at $C_{D0}^{1\text{-cluster}} \sim 0.8$ [4]. According to (3), the values of the corresponding inverse mass ratio stands at $R_m^{(4)} = 14.4$. Finally, the value of the Γ-factor becomes $\Gamma \sim 2.43$, with the gravitational impulse being estimated at $gD_0^{(1)}n_{\text{fill}}^{(1)}/V_i^2 \sim 1.43$ and the momentum change at $1 - V_f/V_i \sim 1$ (here $V_f/V_i \sim 10^{-1}$). With $I_F^{\text{if}}|_{j\text{-cluster}} \sim 0.5$ [1], the resulting value of the maximum drag generated by the cluster stands at $F_{\max} \sim 44,917$ lbs or $F_{\max}/W \sim 3.2$; an estimate in good agreement with the measured value $F_{\max} \sim 48,000$ lbs [8].

V. Comparative Study: Cluster Member-Number Effect

The value of Eq. (9) becomes most obvious when comparing the maximum drag generated by a cluster of k members to that of a cluster of j members, with both clusters using the same type of member parachutes (in other words, only the number of member parachutes is different). The comparison is performed at the same deployment altitude and initial fall speed V_i and involves three cases.

Case 1: Big parachutes: same total mass

This case involves the following input parameters: $D_0^{(1)} \sim 100$ ft or greater, $n_{\text{fill}} \sim 10$ and $V_i \sim 100$–150 ft/s. Here again, the momentum impulse term $gD_0^{(1)}n_{\text{fill}}^{(1)}/V_i^2$ in (9) is significantly greater than the V_f/V_i term if $V_f < V_i$. This means that in the ratio $F_{\max}^{(k)}/F_{\max}^{(j)}$, the Γ-factors in both the numerator and denominator are identical and cancel out; likewise, the factors $(\frac{1}{2}\rho V_i^2)$ and $(C_DS)_{\text{sd}}^{\text{1-clute}}$ also cancel out, thus leaving:

$$\frac{F_{\max}^{(k)}}{F_{\max}^{(j)}} \sim \left[\frac{k\psi(k)}{j\psi(j)}\right]^{3/2}\left[\frac{R_m^{(j)}}{R_m^{(k)}}\right]\left[\frac{I_F^{\text{if}}|_{j\text{-cluster}}}{I_F^{\text{if}}|_{k\text{-cluster}}}\right] = \left[\frac{I_F^{\text{if}}|_{j\text{-cluster}}}{I_F^{\text{if}}|_{k\text{-cluster}}}\right] \tag{10}$$

The last step comes about because of $R_m^{(l)}$ being given by $[l\psi(l)]^{3/2}\rho[(C_DS)_{\text{sd}}^{\text{1-clute}}]^{3/2}/m$, with the same value of m being used for both clusters. It is interesting to note that the explicit dependence on member number and drag efficiency has completely been cancelled out, although implicit dependence may remain, notably through the drag integral. To the extent that $R_m^{(k)}$ and $R_m^{(j)}$ have the same order of magnitude, it is expected that the drag integrals I_F^{if} be the same if k and j are nearly the same, for example when $k = 6$ and $j = 5$. This would leave the force ratio at $F_{\max}^{(k)}/F_{\max}^{(j)} \sim 1$. On the other hand, if k and j are very different, for example $k = 6$ and $j = 2$, one has $R_m^{(k)} \gg R_m^{(j)}$ and $I_F^{\text{if}}|_{j\text{-cluster}} < I_F^{\text{if}}|_{k\text{-cluster}}$ [1] thereby giving $F_{\max}^{(k)}/F_{\max}^{(j)} < 1$. This follows from the fact that during the early portions of the inflation process, the k-system decelerates at higher rates than the j-system because of the extra drag area being present, thereby yielding less fall rate and less drag force.

Case 2: Small parachutes: same total mass

This case is brought up to again illustrate the influence of the gravitational impulse term, or rather its lack of thereof. In this example, $n_{\text{fill}} \sim 10$ and $V_i \sim 100$–150 ft/s once more. What changes is the nominal diameter, which is reduced to $D_0^{(1)} \sim 10$ ft while both clusters are used with the same m, V_i, and ρ. The $gD_0^{(1)}n_{\text{fill}}^{(1)}/V_i^2$ term in (9) becomes similar in magnitude to the V_f/V_i term which has an opposite sign, and thus nearly cancel out. And so, here $\Gamma \sim 1$ for both clusters and the $F_{\max}^{(k)}/F_{\max}^{(j)}$-ratio is once more given by (10). This points out that (10) may be a valid approximation over a wide range of $D_0^{(1)}$.

Case 3: Big parachutes: differing total mass and initial fall rate

This example illustrates another use of cluster systems, where the number of cluster members is dictated by the payload weight: for example, when adding an extra canopy to the cluster whenever payload weight exceeds a given value. Here the discussion shall be simplified by rewriting the total mass in terms of cluster number l and a unit mass m_u as $m = m(l) = lm_u$, which translates into

$$R_m^{(l)} = [l\psi(l)]^{3/2}\rho(C_DS)_{\text{sd}}^{\text{1-clute}}/m(l) = (l)^{1/2}[\psi(l)]^{3/2}\rho(C_DS)_{\text{sd}}^{\text{1-clute}}/m_u$$

But changing payload weight is also bound to change V_i in a nontrivial way. For example, in cases where the value of m_u is large but where the airspeed of the drop aircraft remains the same, one could assume $V_i^2 = V_i^2(l) \propto m \sim lm_u$ as long, that is, as adding cluster members does not appreciably increase the system's drag area before inflation. But the exact form of $V_i^2(l)$ does not really matter when the gravitational impulse becomes dominant in the calculation of Γ, as the ratio $F_{\max}^{(k)}/F_{\max}^{(j)}$ becomes

$$\frac{F_{\max}^{(k)}}{F_{\max}^{(j)}} \sim \frac{V_i^2(k)}{V_i^2(j)}\left[\frac{k\psi(k)}{j\psi(j)}\right]^{3/2}\left[\frac{R_m^{(j)}}{R_m^{(k)}}\right]\left[\frac{I_F^{\text{if}}|_{j\text{-cluster}}}{I_F^{\text{if}}|_{k\text{-cluster}}}\right]\frac{V_i^2(j)}{V_i^2(k)} \sim \left[\frac{k}{j}\right] \cdot \left[\frac{I_F^{\text{if}}|_{j\text{-cluster}}}{I_F^{\text{if}}|_{k\text{-cluster}}}\right] \tag{11}$$

Unlike (10), the force ratio has become explicitly dependent on the number of cluster members. In cases where $k > j$ (but are similar in magnitude), the ratio goes as $F_{\max}^{(k)}/F_{\max}^{(j)} > 1$ if $I_F^{\text{if}}|_{k\text{-cluster}} \sim I_F^{\text{if}}|_{j\text{-cluster}}$. The increase in force arises from the increase in initial fall rate, together with a decrease in mass ratio, i.e., two factors that conspire to rising $F_{\max}$.

VI. Cluster vs Single (and Very Large) Parachute

Consider using, at same total weight, a single but very large parachute instead of a j-cluster, with the size of the single chute being constrained to yield the same steady-state rate of descent. Here, the maximum force generated by each system shall be compared while using again the same V_i and ρ. The new constraint on the size and drag properties of the single chute translates into $(SC_D)_{\text{sd}}^{(j)} = (SC_D)_{\text{sd}}^{\text{(1-big)}}$, which means that $R_m^{(j)} = R_m^{\text{(1-big)}}$. The force ratio $F_{\max}^{(j)}/F_{\max}^{\text{(1-big)}}$ is obtained via the use of Eq. (9) for the cluster and Eq. (2) for the large single chute. The result is

$$\frac{F_{\max}^{(j)}}{F_{\max}^{\text{(1-big)}}} = \sqrt{j \cdot \psi(j)}\sqrt{\frac{C_{D0}^{(1)}}{C_{D0}^{\text{(1-big)}}}}\left[\frac{n_{\text{fill}}^{\text{(1-big)}}}{n_{\text{fill}}^{(1)}}\right]\left[\frac{I_F^{\text{if}}|_{\text{1-big}}}{I_F^{\text{if}}|_{j\text{-cluster}}}\right] \cdot \frac{1 - (V_f^{(j)}/V^i) + (gD_0^{(1)}/V_i^2)n_{\text{fill}}^{(1)}}{1 - (V_f^{\text{(1-big)}}/V_i) + (gD_0^{\text{(1-big)}}/V_i^2)n_{\text{fill}}^{\text{(1-big)}}} \tag{12}$$

Equation (12) can be simplified somewhat if both cluster members and the large single parachute are fabricated with the same shape and porosity, thus allowing $n_{\text{fill}}^{\text{(1-big)}} \sim n_{\text{fill}}^{(1)}$ and $C_{D0}^{\text{(1-big)}} \sim C_{D0}^{(1)}$. It is expected that in the case of the large chute, the term in $gD_0^{\text{(1-big)}}n_{\text{fill}}^{\text{(1-big)}}/V_i^2$ shall again dominate because $V_f < V_i$; Eq. (12) is simplified as

$$\frac{F_{\max}^{(j)}}{F_{\max}^{(1\text{-big})}} = \sqrt{j\psi(j)}\left[\frac{I_F^{\text{if}}|_{1\text{-big}}}{I_F^{\text{if}}|_{j\text{-cluster}}}\right]\frac{1-(V_f^{(j)}/V_i)+(gD_0^{(1)}/V_i^2)n_{\text{fill}}^{(1)}}{(gD_0^{(1-\text{big})}/V_i^2)n_{\text{fill}}^{(1\text{-big})}}$$
$$\sim \sqrt{j\psi(j)}\left[\frac{I_F^{\text{if}}|_{1\text{-big}}}{I_F^{\text{if}}|_{j\text{-cluster}}}\right]\frac{D_0^{(1)}}{D_0^{(1\text{-big})}} \sim \left[\frac{I_F^{\text{if}}|_{1\text{-big}}}{I_F^{\text{if}}|_{j\text{-cluster}}}\right] \tag{13}$$

The last two steps apply when $D_0^{(1)}$ is also large enough to make gravitational impulse the dominant factor with the cluster system. This result shows that using a single chute could yield lower, or higher, opening loads relative to using a cluster. In the case of dominating gD_0/V_i^2 terms for both parachute systems, the single large chute generates opening loads that are similar to the cluster's because, although involving a longer (dimensional) inflation time, the system picks up more speed as a result of the momentum gained through gravity.

VII. Conclusions

It should be noted that, having been derived for purely vertical trajectories, the results of this paper should provide upper bounds on the value of $F_{\max}$ for systems inflating along any ballistic trajectories. They should also be useful to cases characterized by extreme lead/lag, i.e., clusters of j parachutes with j–i parachutes opening quickly and synchronously, with the remaining i parachutes not opening at all. In this case Eq. (9) could yield force estimates for scenarios that have the potential of generating larger than nominal opening forces.

The results of this paper provide several new insights on the physics of clusters of large parachutes, in particular with regard to the important role played by the extra momentum provided to the system by gravity, a role enhanced by the large diameter of these canopies (i.e., $D_0 \sim 100$ ft) and by their moderately long filling times (i.e., $n_{\text{fill}} \sim 5$–10). As seen previously in [2], gravitational impulse can also be a dominating effect when the initial speed V_i is small enough. But it can be also suppressed if the parachute is made to inflate quickly, as will be shown in the case of disreefing parachutes [10]. But gravity is only one of many possible external sources of energy made available to an inflating parachute. Payloads sustaining a thrust force via rocket power or via other means represent one obvious example. Although thrusted payloads appear equivalent to those subjected to gravity only, important conceptual differences exist, including the necessity of redefining the concept of mass ratio (i.e., R_m), an issue that shall be discussed further in [11].

Acknowledgments

This work was performed with funding from the Natick Soldier Center (Natick, Massachusetts) under U.S. Army contract number W9124R06P1068. The author wishes to thank the following individuals for the many fruitful discussions he has enjoyed: R. Charles, K. Desabrais, C. K. Lee, and J. A. Miletti from Natick; G. Peek from Industrologic, Inc., and my AIAA Aerodynamic Decelerator Systems Technical Committee colleagues K.-F. Doherr, R. Howard, and D. F. Wolf.

References

[1] Potvin, J., "Universality Considerations for Graphing Parachute Opening Shock Factor Versus Mass Ratio," *Journal of Aircraft*, Vol. 44, No. 2, 2007, pp. 528–538.

[2] Potvin, J., "Momentum-Impulse Balance and Parachute Inflation: Fixed-Point Drops," *Journal of Aircraft* (to be published).

[3] Knacke, T. W., *Parachute Recovery Systems Design Manual*, Para Publishing, Santa Barbara, CA, 1992.

[4] Ewing, E. G., Bixby, H. W., and Knacke, T. W., "Recovery Systems Design Guide," Rept. AFFL-TR-78-151. Air Force Flight Dynamics Lab., Wright Aeronautical Lab., Wright-Patterson AFB, Dec. 1978, pp. 254–257 (unpublished).

[5] Wolf, D., "Opening Shock," *15th CEAS/AIAA Aerodynamic Decelerator Systems Technology Conference*, AIAA Paper 99-1702, 1999.

[6] Lee, C. K., Lanza, J., and Buckley, J., "Experimental Investigation of Clustered Parachute Inflation," *14th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar*, AIAA Paper 97-1478, 1997.

[7] Lee, C. K., and Sadeck, J. E., "Controlled Opening Method for Clustered Parachutes," *Journal of Aircraft*, Vol. 29, No. 2, 1992, pp. 264–272.

[8] Behr, V. L., "Measurement of Individual Parachute Loads In a Clustered Parachute System," *10th AIAA Aerodynamic Decelerator Systems Technology Conference*, AIAA Paper 89-0923, 1989.

[9] Johnson, D., "Testing a New Recovery Parachute System for the F111 Aircraft Crew Escape Module: An Update," *10th AIAA Aerodynamic Decelerator Systems Technology Conference*, AIAA Paper 89-0891, 1989.

[10] Potvin, J., "Momentum-Impulse Balance and Parachute Inflation: Disreefing," *Journal of Aircraft*, Vol. 44, No. 2, 2007, pp. 691–694.

[11] Potvin, J., "Momentum-Impulse Balance and Parachute Inflation: Rocket-Propelled Payloads" (to be published).