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Momentum-Impulse Balance and Parachute Inflation: Disreefing

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

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I. Introduction

PARACHUTE inflation control often involves a reefing line that constrains to smaller diameters the opening of the parachute's mouth (hemispherical parachutes) or wing inlets (parafoils). Disreefing occurs when the constraint is mechanically removed at a given preset time or altitude, or when a critical pressure is attained inside the canopy. It is only after the removal of the reefing constraint that the canopy is allowed to expand to its full size for steady descent [1,2]. Currently, there are two broad families of disreefing devices being used on both hemispherical canopies (low- and high-porosity) and parafoils: namely, those based on line reefing and cutters [1–3] and those based on sliders [4,5]. This Note discusses simple, yet instructive calculations of the opening shock sustained by the severing of skirt reefing lines on hemispherical parachutes. The computations are based on a general result obtained in [6] from the momentum-impulse (MI) theorem. Like its predecessors [7,8], this paper continues exploring the many consequences of this important theorem on a vast array of parachute systems. New formulas shall be derived here, for the calculation of the maximum drag generated during each one of the two inflation phases that occur before and during disreefing. The discussion shall also include a new derivation of the duration of this inflation process.

Potvin [6] shows that the MI theorem applied to inflating parachutes allows a general and exact calculation of the maximum parachute drag $F_{\max}$ as follows:

$$F_{\max} \equiv \left(\frac{1}{2}\rho V_i^2\right)(SC_D)_{\mathrm{sd}}\left[\frac{2\Gamma}{R_m n_{\mathrm{fill}} I_F^{\mathrm{if}}}\right]\frac{\sqrt{(SC_D)_{\mathrm{sd}}}}{D_0} \tag{1}$$

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 $(SC_D)_{\mathrm{sd}}$, generated when the parachute is fully opened and descending in a steady manner. The constant I_F^{if} is the normalized integral of the drag force $F_D(t)$ over the duration of inflation t_{fill}, i.e., $I_F^{\mathrm{if}} = \int[F_D(t)\,\mathrm{d}t]/F_{\max} t_{\mathrm{fill}}$. The factor Γ is the sum of the momentum change sustained by the parachute-payload during inflation and of the impulse supplied by gravity (per unit initial speed and mass). This sum is greatly simplified in the case of inflation sequences occurring along purely horizontal or vertical trajectories:

Horizontal inflation

$$\Gamma = \left(1 - \frac{V_f}{V_i}\right) \tag{2}$$

Vertical inflation

$$\Gamma = \left(1 - \frac{V_f}{V_i} + \frac{gD_0}{V_i^2} n_{\mathrm{fill}}\right) \tag{3}$$

These two results can be used for any parachute and reefing designs. The gravitational impulse term appears in (3) as the term proportional to the constant of gravitational acceleration (g). This term is usually small for human-sized parachutes carrying human-size weights, but becomes important to inflation dynamics when the parachutes become very large and/or take a long time to inflate [7,8]. Note that Eqs. (1–3) involve knowing also the speeds V_i and V_f characterizing the parachute-payload fall speeds at the beginning and end of the inflation process, respectively. Another important input is the so-called inverse mass ratio R_m [1], a nondimensional constant defined as

$$R_m = \frac{\rho (SC_D)_{\mathrm{sd}}^{3/2}}{m} \tag{4}$$

The mass ratio is an estimate of the air mass that decelerates (or accelerates) along with the parachute system during inflation [1,2,6]. 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 (1–3) are valid for any values of the mass ratio, although the applications considered here are more typical of large-R_m systems. Finally, Eq. (1) involves the very important concept of "standard" filling time n_{fill}, here defined as

$$n_{\mathrm{fill}} \equiv \frac{V_i t_{\mathrm{fill}}}{D_0} \tag{5}$$

with D_0 being the so-called nominal canopy diameter, itself defined from the total canopy surface area S_0 as $D_0 = (4S_0/\pi)^{1/2}$ for hemispherical-type canopies [1] (S_0 includes the areas of the vents and all other openings in the canopy). Note that knowing the value of the filling time is crucial for the usefulness of Eq. (1). Fortunately, it is a well-documented empirical input [1,2,6].

II. Hemispherical Parachute Skirt Disreefing

Skirt reefing on hemispherical parachutes systems is implemented by routing a line through rings sewn around the skirt (or "mouth") of the parachute [1]. This arrangement is used together with altitude- or time-activated cutters that will sever that line, typically after the reefed parachute has inflated or is in the process of inflating. Although skirt reefing is used to reduce opening shock (compared to unreefed inflation), there are other reasons for using skirt reefing on hemispherical parachutes, including the improvement of inflation consistency in cluster systems [8,9], or the need for stabilized freefall

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

before full canopy extension (i.e., have a drogue stage while using only one parachute) [10]. Regardless of whether reefing is used primarily for opening shock control or not, it is obviously important to be able to estimate maximum drag $F_{\max}$ sustained during the entire inflation sequence.

As far as the disreefing process is concerned, there are two inflation phases to consider:

1) Phase 1, or "reefed inflation," a process consisting in the inflation of the parachute while remaining in a permanent reefed state. This phase precedes disreefing inflation.

2) Phase 2, or "disreefing," a process initiated after a predetermined time interval or at a predetermined altitude; this phase begins when the reefing line is mechanically severed by the line cutters, thereby allowing the parachute to open to a full, unreefed state. Note: if the reefing line is severed before phase 1, then one speaks of *unreefed* inflation.

In cases where disreefing occurs long after the completion of the first phase, great simplification can be achieved by regarding the two phases as two separate inflation events involving the use of (1–3) separately. To further simplify the problem, it shall be assumed that reefed inflation (i.e., phase 1) occurs nearly along a horizontal trajectory, soon after leaving a fast-flying aircraft (i.e., flying at a minimum of 120 KTSI). It shall be assumed also that disreefing (i.e., phase 2) happens long after the (reefed) parachute-payload system has reached a vertical steady descent mode. It turns out that such a sequence occurs frequently on several reefed parachute systems in use today. The usefulness of Eqs. (1–3) resides mostly in knowing the value of the nondimensional filling time n_{fill}, a number that can be estimated analytically for some reefed and disreefing systems.

III. Filling Time for Low-Porosity Reefed and Disreefing Parachutes

Conceptually, inflation time t_{fill} and filling time n_{fill} depend on two basic ingredients, namely, the *air flux* going through the canopy mouth, and the *total volume of air needed to fill the canopy*. The latter is rather straightforward to estimate with low-porosity canopies, i.e., with canopies that do not possess any venting, as the air that enters the canopy actually remains in the canopy. In this case such air volume can be calculated exclusively in terms of canopy dimensions, as it is similar to the "opened" volume outlined by the canopy. The air flux, on the other hand, depends on the actual fall rate of the parachute-payload as the mouth scoops in air, and on the actual opened surface area of the mouth. Fall rate is obviously the result of instant canopy size and shape (and therefore internal pressure), and payload weight. Opened mouth area is the result of design constraints, such as the presence of skirt reefing and parachute riser separation (at the payload). It is also the result of how the canopy mouth area unfolds and is initially exposed to the wind (in a limp state), after extraction from the parachute container. Thus inflation time and filling time depends on the details of the inflation evolution itself. Luckily, a great deal of empirical data on inflation time has been compiled already [1,2,6]. In the following, simple n_{fill} formulas are developed specifically for reefed and disreefing parachutes, written in terms of the filling time characteristic of unreefed parachutes.

Using the concepts discussed previously, one has

$$t_{\text{fill}} \sim \frac{\text{volume to fill}}{\text{flux}} \sim \frac{V_{\text{tofill}}}{V_i S_{\text{init}}^{\text{mouth}}} \tag{6}$$

with $S_{\text{init}}^{\text{net mouth}}$ and V_{tofill} being, respectively, the initial canopy mouth area and volume of air needed to fill the canopy. In contrast to (5), which is a definition, Eq. (6) is clearly an approximation, as the exact calculation of t_{fill} would involve the integral of the (time-changing) flux. With this limitation in mind, Eqs. (5) and (6) are used to express the nondimensional filling time as

$$n_{\text{fill}} \sim \frac{V_{\text{tofill}}}{S_{\text{init}}^{\text{netmouth}} D_0} \tag{7}$$

What Eqs. (6) and (7) imply is the fact that, as indeed $S_{\text{init}}^{\text{net mouth}}$ varies on a drop-to-drop basis depending on the precise ways a canopy unfolds into the airstream, then so will the nondimensional and dimensional filling times. But most important for the discussion at hand is the presence of the V_{tofill}-factor, which can be reliably estimated for low-porosity canopies reefed with a very short skirt reefing line. In such a case, the shape of the reefed parachute can be approximated by a sphere, and that of the unreefed parachute by a hemisphere. Here the sphere would be characterized by a radius of $\sim D_0/2\pi$ whereas the hemisphere would have a radius of $X_p D_0/2$, where X_p is the projected diameter ratio ($\sim$0.7 for low-porosity flat circular parachutes; see [1], Table 5-1). With these approximations in mind, calculating the filling times corresponding to the two inflation phases can now be performed.

During reefed inflation, the canopy is inflating in a permanent reefing configuration, a process that involves the canopy evolving from the shape of a narrow tube to that of a sphere. Using Eq. (7) while neglecting the volume of the tube yields

$$n_{\text{fill}}^{\text{phase-1}} \sim \frac{[(4\pi/3)(D_0/2\pi)^3]}{S_{\text{init}}^{\text{tube-mouth}} D_0} \tag{8}$$

In the disreefing phase, the canopy evolves from a sphere to a hemisphere. Moreover, the value of $S_{\text{init}}^{\text{net mouth}}$ at this point is actually different from that used in (8) (i.e., the mouth of the narrow tube), rather being given by the area of the mouth of the canopy inflated in its reefed state, namely, $S_{\text{init}}^{\text{net mouth}} \sim \pi(\tau D_0/2)^2$. Here τ is the so-called reefing ratio, defined as the ratio of the diameter of the circle created by the reefing line to that of the parachute's nominal diameter D_o [1]. A reefing line that yields $\tau \leq 0.2$ is usually considered a "short" reefing line and will result in the spherical reefed shape discussed here. With these remarks in mind, using (7) will give

$$n_{\text{fill}}^{\text{phase-2}} = \frac{(1/2)[(4\pi/3)(X_p D_0/2)^3] - [(4\pi/3)(D_0/2\pi)^3]}{\pi(\tau D_0/2)^2 D_0} \tag{9}$$

Equations (8) and (9) can be compared with the filling time associated with the inflation of the same canopy but without reefing whatsoever:

$$n_{\text{fill}}^{\text{unreefed}} \sim \frac{(1/2)[(4\pi/3)(X_p D_0/2)^3]}{S_{\text{init}}^{\text{tube-mouth}} D_0} \tag{10}$$

Note that (10) yields $n_{\text{fill}} \sim 9$ for a $D_0 = 28$ ft low-porosity canopy of the USAF C-9 type, with $X_p \sim 0.7$ [1] and $S_{\text{init}}^{\text{tube mouth}} \sim 4\ \text{ft}^2$, a filling time value to be compared with $n_{\text{fill}} \sim 6$–8 for the real canopy [1,2,11]. Taking the ratio of Eqs. (9) and (10) yields the following comparison:

$$\frac{n_{\text{fill}}^{\text{phase-2}}}{n_{\text{fill}}^{\text{unreef}}} = \frac{4}{\pi\tau^2} \frac{S_{\text{init}}^{\text{tube-mouth}}}{D_0^2} \left[1 - \frac{2}{\pi^3 X_p^3}\right] \tag{11}$$

In cases where $\tau \sim 0.20$, $X_p \sim 0.70$, and $S_{\text{init}}^{\text{tube mouth}} \sim 0.01 D_0^2$ one has

$$\frac{n_{\text{fill}}^{\text{phase-2}}}{n_{\text{fill}}^{\text{unreef}}} \sim 26 \frac{S_{\text{init}}^{\text{tube-mouth}}}{D_0^2} \sim 0.26$$

which for highly reefed flat circular canopies would yield nondimensional disreefing times in the ballpark of $\sim 8 \times 0.26 \sim 2.1$. This follows from the fact that the volume-to-fill during disreefing inflation, i.e., from a sphere to a hemisphere of comparable *radii*, is much smaller than the volume required for unreefed inflation, where the canopy evolves from a tube of almost no volume, to a hemisphere of substantial volume.

A similar ratio is obtained when comparing the filling time associated with reefed inflation (i.e., phase 1) to that of a completely unreefed configuration. Assuming similar initial tube mouth areas,

$$\frac{n_{\text{fill}}^{\text{phase-1}}}{n_{\text{fill}}^{\text{unreef}}} = \left[\frac{2}{\pi^3 X_p^3}\right] \tag{12}$$

With $X_p \sim 0.70$ one gets a filling time ratio of $n_{\text{fill}}^{\text{phase-1}}/n_{\text{fill}}^{\text{unreef}} \sim 0.2$, a proportion that is also due to the smaller "to fill" volume of the reefed state. Note that (12) is only valid at small reefing ratios τ; in fact, this n_{fill} ratio exceeds unity when τ is large enough, namely, $\tau > 0.6$, as the reefed canopy is then shaped like a hemisphere, but one with a mouth constrained to a smaller area [1].

IV. Maximum Drag Sustained

The value of $F_{\max}$ can now be obtained from (1–3) for a scenario in which the first inflation phase takes place along the horizontal, and the second along the vertical and after a long enough freefall under the reefed configuration. This example features several interesting comparisons.

A. Reefed Inflation Versus Unreefed Inflation

Skirt reefing is often used as a strategy to reduce $F_{\max}$, as compared to unreefed inflation. A ratio of the maximum forces involved in both processes can be constructed out of Eqs. (1) and (2) as follows:

$$\frac{F_{\max}^{\text{phase-1}}}{F_{\max}^{\text{unreef}}} = \left[\frac{n_{\text{fill}}^{\text{unreef}}}{n_{\text{fill}}^{\text{phase-1}}}\right]\left[\frac{I_F^{\text{if/unreef}}}{I_F^{\text{if/phase-1}}}\right]\frac{[1-(V_f^{\text{phase-1}}/V_i)]}{[1-(V_f^{\text{unreef}}/V_i)]} \tag{13}$$

In this comparison the total parachute-payload mass m is the same in both cases, as well as the deployment altitude and atmospheric density ρ and the parachute-payload speed at the beginning of inflation V_i. Note that (13) is the result of the fact that $[(SC_D)_{\text{sd}}]^{3/2}/R_m = m/\rho$ and is thus explicitly independent of drag area. Note that at this point Eq. (13) is valid for all values of the filling time n_{fill}, canopy size and porosity [i.e., $(SC_D)_{\text{sd}}$], and reefing ratio τ.

B. Large Reefing Ratio Regime

This regime shall be defined loosely as representing the values of the reefing ratio τ for which the reefed canopy has roughly the shape of a hemisphere or a cap. On many canopies, this means $\tau > 0.6$. In such cases, data from Knacke's design manual [1] indicates that $n_{\text{fill}}^{\text{phase-1}}/n_{\text{fill}}^{\text{unreef}} \geq 1$. To the extent that $R_m^{\text{phase-1/reefed}} \sim R_m^{\text{unreef}}$ here, the drag integrals are also likely to be similar, namely, $I_F^{\text{if/phase-1}} \sim I_F^{\text{if/unreef}}$ [6]. Finally, given that one always has $\varepsilon \equiv (SC_D)_{\text{sd}}^{\text{phase-1/reefed}}/(SC_D)_{\text{sd}}^{\text{unreef}} < 1$, it is expected that $(V_i - V_f^{\text{phase-1/reef}}) < (V_i - V_f^{\text{unreef}})$. According to (13), the maximum opening force should indeed be reduced by reefing.

C. Small Reefing Ratio Regime

Here the reefing ratio τ involves short skirt reefing lines that yield reefed canopies shaped like spheres. In this case Eq. (13) hints at the fact that *using permanent reefing may not always guarantee lower opening forces*. This can be explained by the fact that at $\varepsilon \sim 0.2$–0.3, one has $\tau \sim 0.20$, as documented in [1] (see Figs. 5-71–5-73). Like in the large-τ regime, the momentum loss factors would still be such that $(V_i - V_f^{\text{phase-1/reef}}) < (V_i - V_f^{\text{unreef}})$ (because $\varepsilon < 1$). But the difference arises first from the mass ratios being related as $R_m^{\text{phase-1/reefed}}/R_m^{\text{unreef}} = (\varepsilon)^{3/2} \ll 1$ (at equal mass m), or $R_m^{\text{phase-1/reefed}} \ll R_m^{\text{unreef}}$. According to [6] the drag integrals would then compare as $I_F^{\text{if/phase-1}} < I_F^{\text{if/unreef}}$. Secondly, given the earlier estimate in which $n_{\text{fill}}^{\text{phase-1}}/n_{\text{fill}}^{\text{unreef}} \sim 0.2$ [as performed with (12)], the force ratio $F_{\max}^{\text{phase-1/reef}}/F_{\max}^{\text{unreef}}$ will be less than unity *only* if the ratio $(V_i - V_f^{\text{unreef}})/(V_i - V_f^{\text{phase-1/reef}})$ is much greater than the product $(n_{\text{fillunreef}}/n_{\text{fill}}^{\text{phase-1/reef}})(I_F^{\text{if/unreef}}/I_F^{\text{if/phase-1/reef}})$. In other words, the details of the design and value of the total mass shall determine the efficiency of (tight) skirt reefing in reducing $F_{\max}$.

D. Comparing the Maximum Forces of Phases 1 and 2

Considering disreefing only after a long freefall offers the one simplifying assumption that the value of V_i is nearly equal to the steady descent fall rate of the system under the reefed configuration, a number that can be calculated from the steady descent fall rate formula as $V_{\text{sd}}^{\text{reef}} = [2W/\rho(SC_D)_{\text{sd}}^{\text{phase-1/reefed}}]^{0.5}$. Noting that the altitude at which disreefing/phase 2 is initiated will be different from that of phase 1, the atmospheric densities shall be distinguished, i.e., with "ρ_{high} and "ρ_{low}" for phases 1 and 2, respectively. Noting also that the initial speed V_i in both inflation sequences will be different, the following notation shall be used as well: $V_i = V_{\text{stretch}}$ (phase 1) and $V_i = V_{\text{sd}}^{\text{reef}}$ (phase 2), where typically $V_{\text{stretch}} \gg V_{\text{sd}}^{\text{reef}}$ (the term "stretch" stands for "suspension line stretch"). The maximum forces sustained during each phase are as follows:

$$F_{\max}^{\text{phase-1}} = \left(\frac{1}{2}\rho_{\text{high}}V_{\text{stretch}}^2\right)\frac{[(SC_D)_{\text{sd}}^{\text{phase-1}}]^{3/2}}{D_0} \times \left[\frac{2}{R_m^{\text{reef}} n_{fill}^{\text{phase-1}} I_F^{\text{if/phase-1}}}\right]\left(1 - \frac{V_f^{\text{phase-1}}}{V_{\text{stretch}}}\right) \tag{14}$$

$$F_{\max}^{\text{phase-2}} = \left(\frac{1}{2}\rho_{\text{low}}(V_{\text{sd}}^{\text{reef}})^2\right)\frac{[(SC_D)_{\text{sd}}^{\text{no-reef}}]^{3/2}}{D_0}\left[\frac{2}{R_m^{\text{unreef}} n_{\text{fill}}^{\text{phase-2}} I_F^{\text{if/phase-2}}}\right] \times \left(1 - \frac{V_f^{\text{phase-2}}}{V_{\text{sd}}^{\text{reef}}} + \frac{gD_0}{(V_{\text{sd}}^{\text{reef}})^2} n_{\text{fill}}^{\text{phase-2}}\right) \tag{15}$$

The ratio of these two forces can be evaluated also, after neglecting the term in gD_0 in (15) because of the small inflation times involved in disreefing (this is the gravitational impulse term), and after taking advantage of the fact that the same mass m is being used in both mass ratio factors in (14) and (15):

$$\frac{F_{\max}^{\text{phase-1}}}{F_{\max}^{\text{phase-2}}} = \left[\frac{\rho_{\text{high}}V_{\text{stretch}}^2}{\rho_{\text{low}}(V_{\text{sd}}^{\text{reef}})^2}\right]\frac{\rho_{\text{low}}}{\rho_{\text{high}}}\left[\frac{n_{\text{fill}}^{\text{phase-2}} I_F^{\text{if/phase-2}}}{n_{\text{fill}}^{\text{phase-1}} I_F^{\text{if/phase-1}}}\right] \times \left[\frac{1-(V_f^{\text{phase-1}}/V_{\text{stretch}})}{1-(V_f^{\text{phase-2}}/V_{\text{sd}}^{\text{reef}})}\right] \tag{16}$$

Once again the force ratio shows that the maximum force sustained in phase 1 is greater or lower than that of phase 2, depending on the details of the parachute design and drop conditions. Considering the example of current cargo airdrop applications, one may have phase 1 and phase 2 occurring at altitudes of 20,000 ft mean sea level (MSL) and 5000 ft MSL, respectively, where $V_{\text{stretch}} \sim 250$ ft/s and $V_{\text{sd}}^{\text{reef}} \sim 60$ ft/s, i.e., conditions that yield ratio of dynamic pressure in the 7–10 range. At *small reefing ratios*, Eqs. (11) and (12) suggest the filling time ratio being near unity (for the type of reefed canopy discussed here) and the ratio of drag integrals is expected to also be near unity (because of the swift inflation in both cases); the force ratio would thus stand at being somewhat high, even though the velocity ratio in (16) is in the 10^{-1}–10^0 range, as $V_f^{\text{phase-1}}/V_{\text{stretch}}$ is likely to be closer to unity than $V_f^{\text{phase-2}}/V_{\text{sd}}^{\text{reef}}$. At *large reefing ratios*, on the other hand, it is expected that $n_{\text{fill}}^{\text{phase-2}}/n_{\text{fill}}^{\text{phase-1}} \sim (0.2$–$0.3)$ and the velocity ratio be near unity. Here the expectation is that the force ratio $F_{\max}^{\text{phase-1}}/F_{\max}^{\text{phase-2}}$ be still greater than unity, but smaller than the value of the force ratio sustained at very small reefing ratios. In the context of the high-/low-altitude two-phase drops discussed in the example, the designer has almost no choice but to go with reefing the canopy at moderate-to-large reefing ratios.

V. Conclusions

Compared to unreefed parachutes, parachutes that are disreefing via the removal of a skirt reefing line will experience faster inflation times and potentially higher opening loads, depending on mass ratio, time of disreefing, etc. The results derived here show whether and when such higher loads shall arise. But note that they apply only to (reefed) parachute-payload systems falling freely under the influence of gravity. Reefed parachutes opening while their payload is being subjected to a propulsion force, such as ejection seats and their stabilization drogues, will also involve equations like (1–3) but modified to accommodate the extra impulse contributed by the rocket motor. This and other issues shall be discussed in more details in [12].

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