Opening Shock and Shape of the Drag-vs-Time Curve

Jean Potvin

Physics Department, Saint Louis University, St. Louis MO

Contact: potvinj@slu.edu 314-977-8424

Talk presented at the 19th AIAA Aerodynamic Decelerator Systems Conference
Williamsburg, VA, May 22-24, 2007

Work funded by Natick Soldier Center (Natick, MA)
U.S. Army contract W9124R-06-P-1068

The material presented here was (and will be) published in the *Journal of Aircraft* by this speaker:

“Universality Considerations for Graphing Parachute Opening Shock Factor Versus Mass Ratio "; ***JOA,*** 44, No. 2, pp. 528 - 538, 2007.

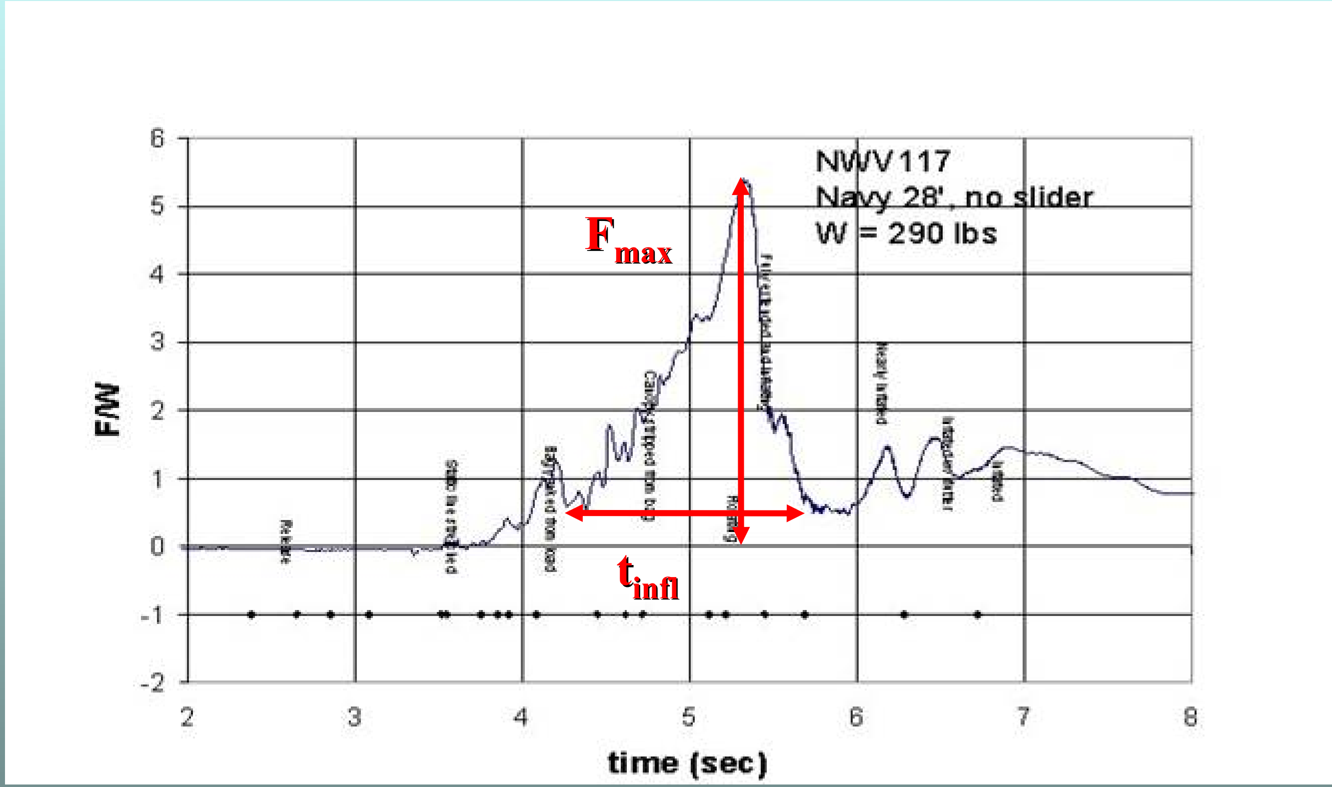
"Momentum-Impulse Balance and Parachute Inflation: Clusters "; ***JOA,*** 44, No. 2, pp. 687-691, 2007.

"Momentum-Impulse Balance and Parachute Inflation: Dis-Reefing"; ***JOA,*** 44, No. 2, pp. 691-694, 2007.

Momentum-Impulse Balance and Parachute Inflation: Rocket-Propelled Payloads"; to appear in ***JOA,*** 2007.

"Momentum-Impulse Balance and Parachute Inflation: Fixed-Point Drops "; to appear in ***JOA,*** 2007.

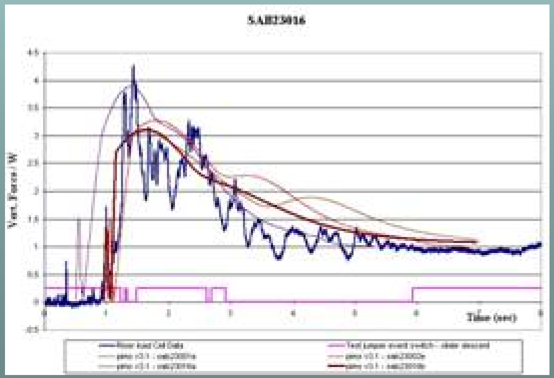
Simple estimators for parachute inflation performance
F_{max} and t_{fill}



But there is another important dimension to consider:

The shape of the drag-vs-time curve

Another type of shape



Jump-to-jump shape variations on same canopy (slider-reefed sport parafoil)

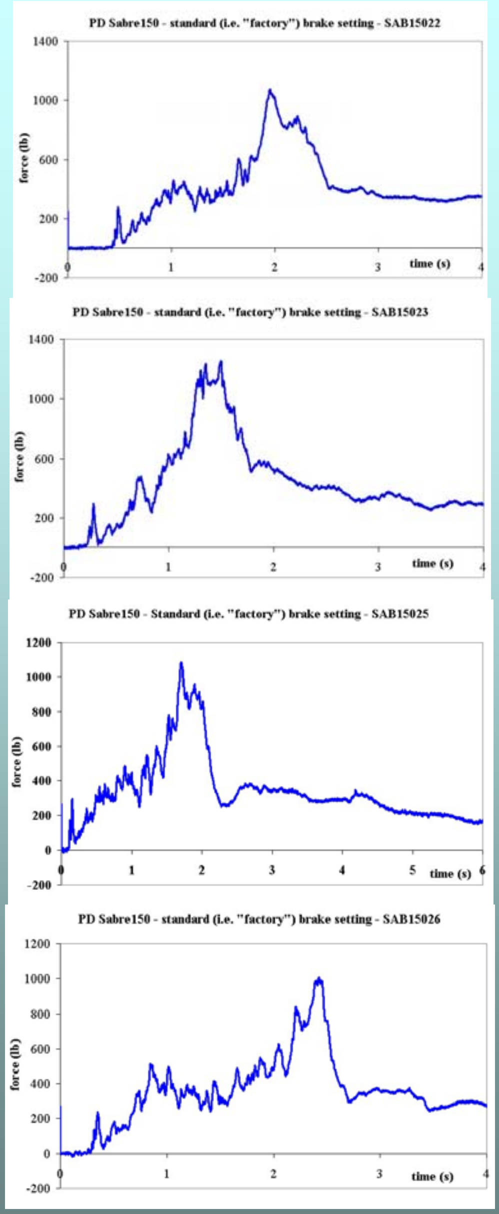


Figure 1.23. Drag evolution experienced by a Performance Designs Sabre 150 parafoil (slider-reefed) [42]. From top to bottom, the drag integral (equation 3.9) has the following values: I_F^{if} = 0.48, 0.50, 0.47 and 0.44.

Is the value of F_{max} connected to the shape of the curve? You bet!

How?

Use the Momentum-Impulse Theorem (MI-Theorem)

The Momentum-Impulse Theorem

- Integration of Newton's 2nd law of motion

$$mV_f - mV_i = \int_i^f F_D(t)\,dt + \int_i^f W\cos\theta(t)\,dt$$

Momentum change of parachute-payload | Parachute drag impulse | Gravitational impulse

- V_f = descent rate @ end of inflation
- V_i = descent rate @ the beginning of inflation (i.e. @ line stretch)
- $\theta(t)$ = flight angle

The Momentum-Impulse Theorem

- **Reformulate in terms of F_{max}**

$$mV_f - mV_i = \int_i^f F_D(t)\,dt + \int_i^f W\cos\theta(t)\,dt$$

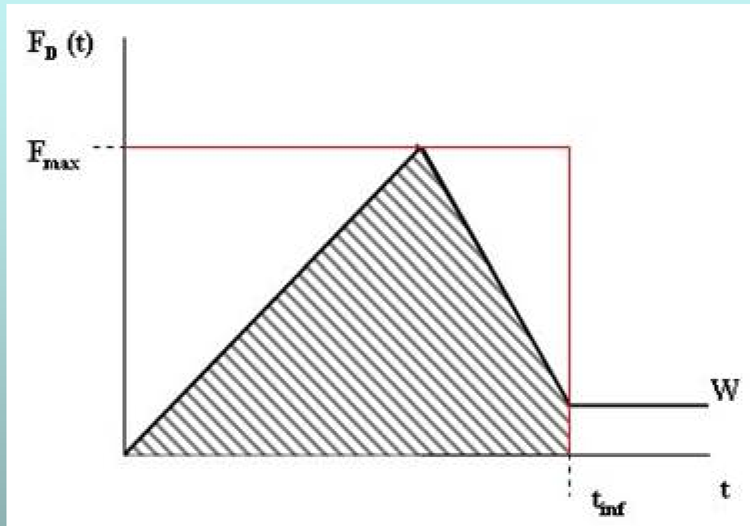
$$\left(mV_f - mV_i\right) = -F_{\max}(t_f - t_i)I_F^{if} + \int_i^f W\cos\theta(t)\,dt$$

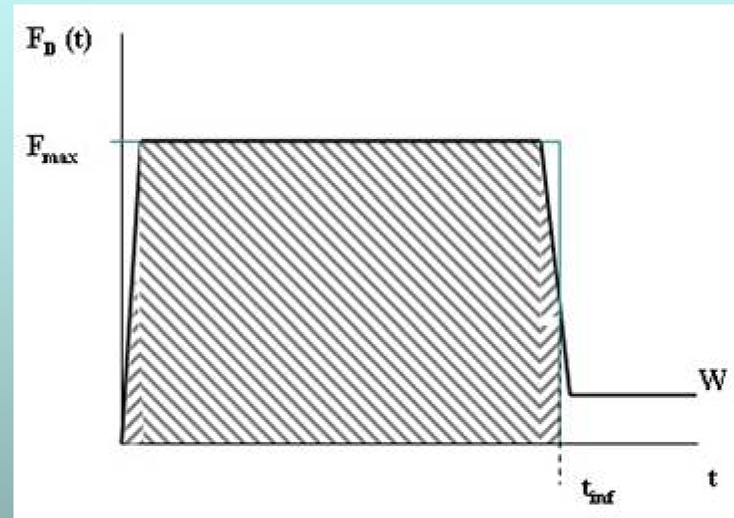
Inflation duration

$$I_F^{if} = \int_i^f \frac{\left|F_D(t)\right|dt}{F_{\max}(t_f - t_i)}$$

Drag integral; gauges the *shape* of the drag vs. time curve

The drag integral measures the area under the drag-vs-time curve in units of ($F_{max}\, t_{fill}$)





Drag integral ~ ½

Drag integral ~ 1

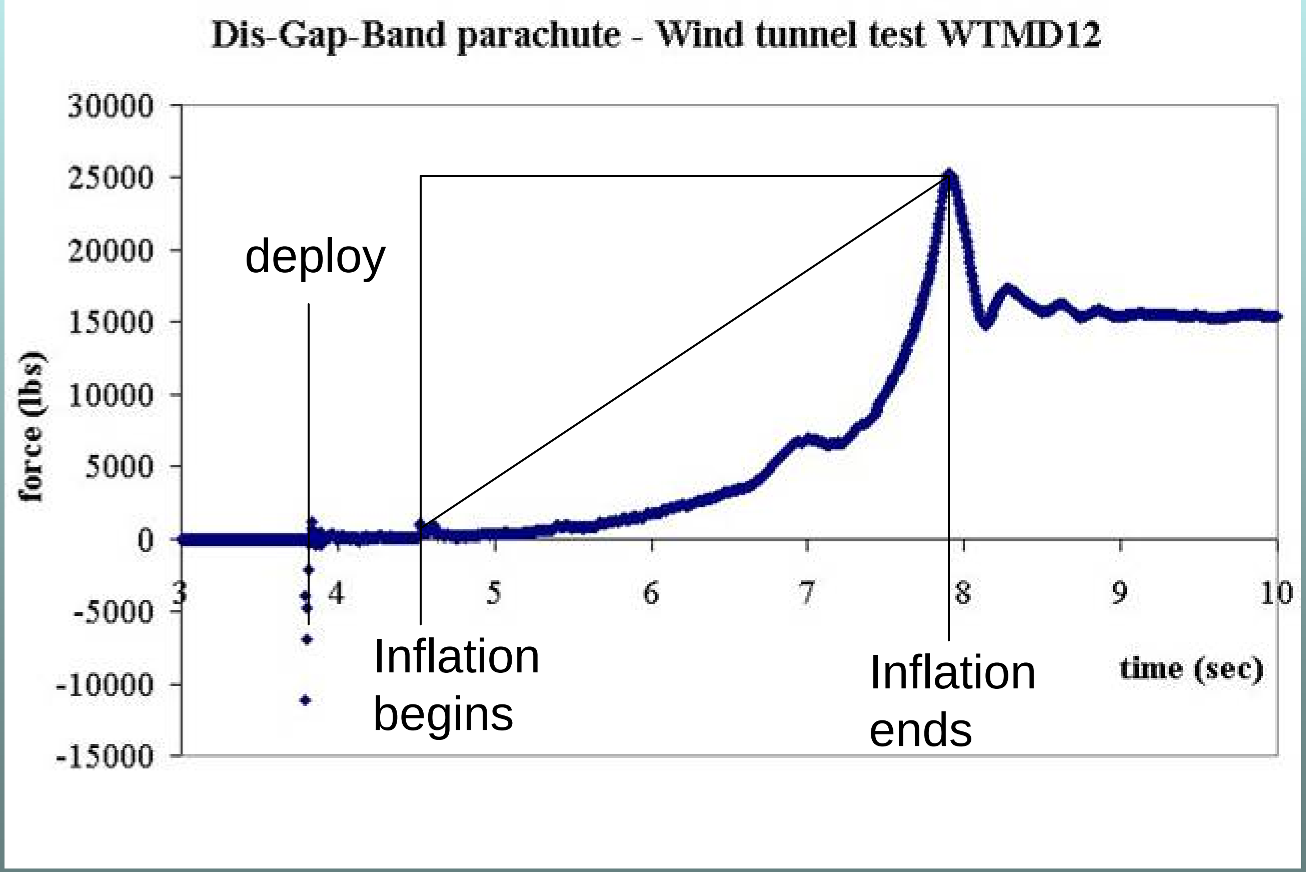
Most common case at high mass ratio
(i.e. personnel and slow-descent cargo)

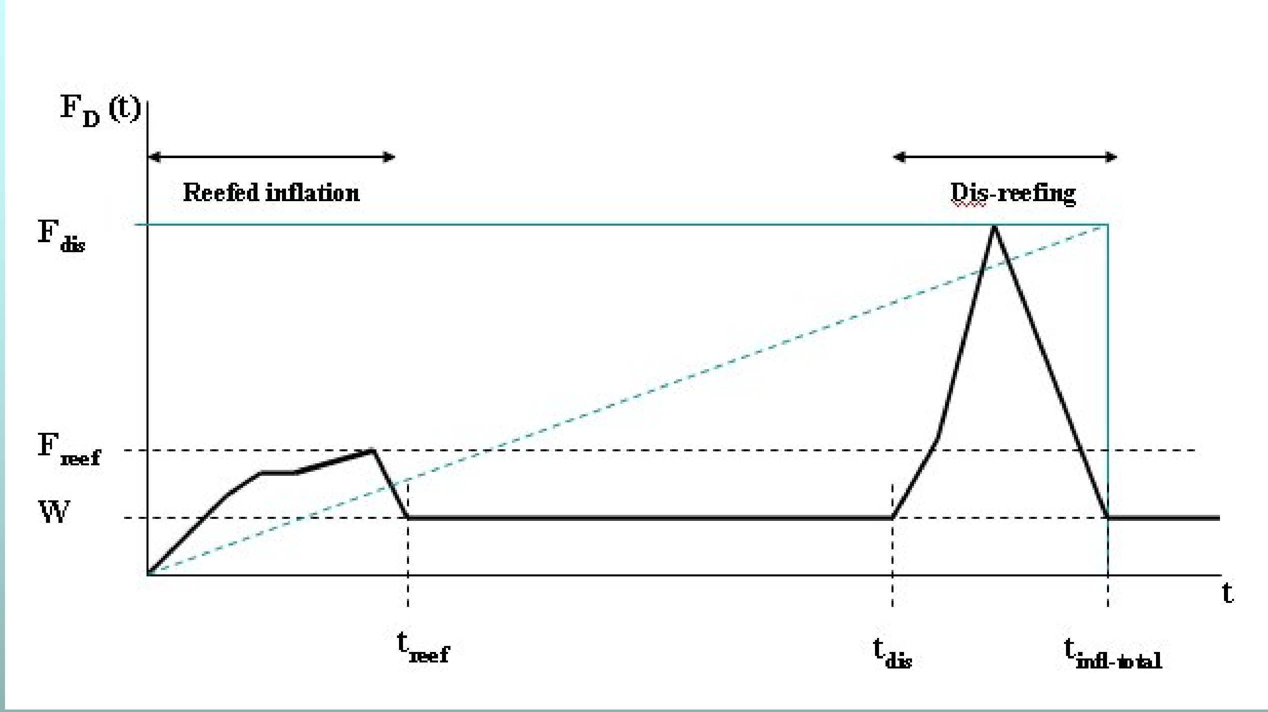
How about at low-mass ratio?

(drogues; chutes opened in wind tunnels, etc.)

MER disk-gap-band parachute inflating in the NASA Ames full-scale wind tunnel.

The drag integral corresponding to this test is $I_F^{if} = 0.23$ (very typical)





Dis-reefing case (long after reefed inflation) – Drag integral ~ ¼.
Note: drag integral → 0 as $t_{dis} - t_{reef} \rightarrow W/F_{dis} << ½$

Solving the MI-Theorem gives F_{max} in terms of the drag integral I_F^{if}

$$F_{\max} = \frac{mV_i}{(t_f - t_i) I_F^{if}} \left[1 - \frac{V_f}{V_i} + \frac{1}{V_i} \int_i^f g \cos\theta(t) dt \right]$$

Applying to specific trajectory types:

Speed @ end of inflation

Horizontal

$$F_{\max} = \frac{mV_i}{(t_f - t_i) I_F^{if}} \left[1 - \frac{V_f}{V_i} \right]$$

Froude term

Inflation duration

Vertical

$$F_{\max} = \frac{mV_i}{(t_f - t_i) I_F^{if}} \left[1 - \frac{V_f}{V_i} + \frac{g(t_f - t_i)}{V_i} \right]$$

Speed @ line-stretch

Solving the MI-Theorem gives F_{max} in terms of the drag integral I_F^{if}

$$F_{max} = \frac{mV_i}{(t_f - t_i) I_F^{if}} \left[1 - \frac{V_f}{V_i} + \frac{1}{V_i} \int_i^f g \cos\theta(t) dt \right]$$

<u>Important note</u>

V_i and V_f are pretty much the same for many systems

(Since the speed at line stretch is mostly determined by launch acft speed

(In cases where $V_f \sim$ steady descent speeds, which are pretty much all in the 20-30fps -ballpark)

It follows that the *shape* of the F_D-vs-t curve is as important as inflation duration in determining F_{max}:

What this says also:

$$F_{\max} = \frac{mV_i}{(t_f - t_i) I_F^{if}} \left[1 - \frac{V_f}{V_i} + \frac{1}{V_i} \int_i^f g \cos \theta(t) \, dt \right]$$

The greater the value of the drag integral, i.e. the more "boxy" the shape of drag-vs-time curve, the smaller the value of F_{max} (at similar inflation times), as $I_F^{if} \rightarrow 1$ (compared to the triangular shape where $I_F^{if} \sim ½$)

On the other hand, the more "spiky" the curve, the greater the F_{max} , as $I_F^{if} \rightarrow ¼$ or 1/5

Is this any useful to designers?
Perhaps…more on this later

But there is more!

- Usually F_{max} depends not only on the F_{max}-vs-t curve shape but also on inflation time, initial and final speed etc.
- But there will be situations where curve shape is the most important factor

- **Consider cases where inflation time is large (i.e. Froude term is dominating)**

$$F_{\max} = \frac{mV_i}{(t_f - t_i)I_F^{if}}\left[1 - \frac{V_f}{V_i} + \frac{g(t_f - t_i)}{V_i}\right]$$

$$\rightarrow \frac{mV_i}{(t_f - t_i)I_F^{if}}\left[\frac{g(t_f - t_i)}{V_i}\right] = \frac{mg}{I_F^{if}}$$

$$F_{\max} = \frac{mg}{I_F^{if}}$$

Applies to any canopy/reefing ; Inflation along mostly vertical trajectories

Dependence on filling time
and initial speed has disappeared!

Froude-term domination is particularly relevant to clusters of large parachutes.

- **Consider the case of a *j* –parachute cluster**
- **Express in terms of the inflation properties of one of the cluster members**
- **The MI-theorem yields:**

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

where

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

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

$$S_0^{(j)} = jS_0^{(1)}$$

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

Comparing two clusters, i.e. a *j*-cluster and a *k*-cluster, both carrying the same mass:

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

Where $R_m^{(l)}$ is the mass ratio of the entire cluster:

$R_m^{(l)} = (l\,\psi(l))^{3/2}\,\rho(\,(C_D S)_{sd}^{1\text{-}clute}\,)^{3/2} / m$

Another example: Rocket-propelled payloads (during inflation)

- **Start with the MI-theorem using the definitions shown**

$$mV_f - mV_i = \int_i^f F_D(t)dt + \int_i^f F_R(t)dt + \int_i^f W\cos\theta(t)dt$$

New term – rocket impulse

Pusher rocket

$$< F_R >= \pm\int_i^f \frac{|F_R(t)|dt}{(t_f - t_i)}$$

Retro-rocket

$$m_{eff} \equiv m + \frac{< F_R >}{g}$$

"effective" mass

Solve for F_{max} (horizontal trajectory)

$$F_{\max} \equiv \left(m + \frac{\langle F_R \rangle}{g} \right) \left(\frac{V_i}{(t_f - t_i) I_F^{if}} \right) \times$$

$$\left\{ 1 - \frac{V_f}{V_i} + \left(\frac{V_f}{V_i} - 1 \right) \frac{\langle F_R \rangle}{m_{eff}\, g} + \left[\frac{\langle F_R \rangle}{m_{eff} V_i} (t_f - t_i) \right] \right\}$$

Froude-like term but assoc'd with rocket propulsion

$$\langle F_R \rangle = \pm \int_i^f \frac{|F_R(t)|\, dt}{(t_f - t_i)} \qquad m_{eff} \equiv m + \frac{\langle F_R \rangle}{g}$$

Consider the cases when $<F_R> >> m\,g$ (then $<F_R>/m_{eff}\,g \sim 1$); or when $t_f - t_i$ is large, in which case the Froude term dominates again. We get:

$$F_{\max} \equiv \left(m + \frac{< F_R >}{g} \right) \left(\frac{V_i}{(t_f - t_i) I_F^{if}} \right) \times$$

$$\left\{ 1 - \frac{V_f}{V_i} + \left(\frac{V_f}{V_i} - 1 \right) \frac{< F_R >}{m_{eff}\, g} + \left[\frac{< F_R >}{m_{eff} V_i} (t_f - t_i) \right] \right\}$$

$$F_{\max} \sim \left(\frac{< F_R >}{I_F^{if}} \right)$$

The more spiky the F_D-vs-t curve, the higher the maximum drag

$$m_{eff} \equiv m + \frac{< F_R >}{g}$$

What is this good for?
– a look into the (near-) future

AII (or "AI^2") –Artificial Intelligence for Inflation

"…If we can indeed understand and describe the fluid physics of parachute inflation on a computer, then future operational parachutes will likely feature "electronic canopies" with sensors and controls to measure flight conditions and on-board computers that use the inflation models to tailor the inflation process to meet performance requirements within system constraints…" **Carl W. Peterson; "The Fluid Physics of Parachute Inflation"; *Physics Today*, pp. 32 – 39, August 1993.**

- **"Operational" FSI descriptions of inflation may be a long way off**
- **But inflation-tuning via the changing of the shape of the drag-vs-time curve may provide the first practical instance of AI^2 in the short term**

Back to the general result (vertical trajectory)

$$F_{\max} = \frac{mV_i}{(t_f - t_i) I_F^{if}} \left[1 - \frac{V_f}{V_i} + \frac{g(t_f - t_i)}{V_i} \right]$$

- **Goal: control the inflation process so to reduce F_{max}**

- **Principle: Have the computer control the inflation process so to yield the largest possible value of the drag integral; in other words, produce a more "boxy" shape of the drag-vs-time curve so to get $I_F^{if} \sim 1$ (in comparison to the typical $I_F^{if} \sim ½$ at high mass ratios (personnel chutes) or $I_F^{if} \sim 1/4$ at low mass ratio (drogues))**

- **The programming of the computer using the MI-Theorem is easy enough. But how could this be done mechanically?** **Next slide**

- Use load cells on the risers
- Use fall rate sensor

- Use active (computer-controlled dis-reefing)

- **Algorithm (high mass ratio systems):**

  - Start soon after line stretch
  - Measure force at time *t*
  - Increase reefing line radius so to keep the drag force nearly constant (we want the "boxy" F_D vs t curve);

  Since $F_D = \rho\,(S(t)C_D(t))\,V(t)^2/2$ we want the decrease in V^2 be compensated by an increase in drag area

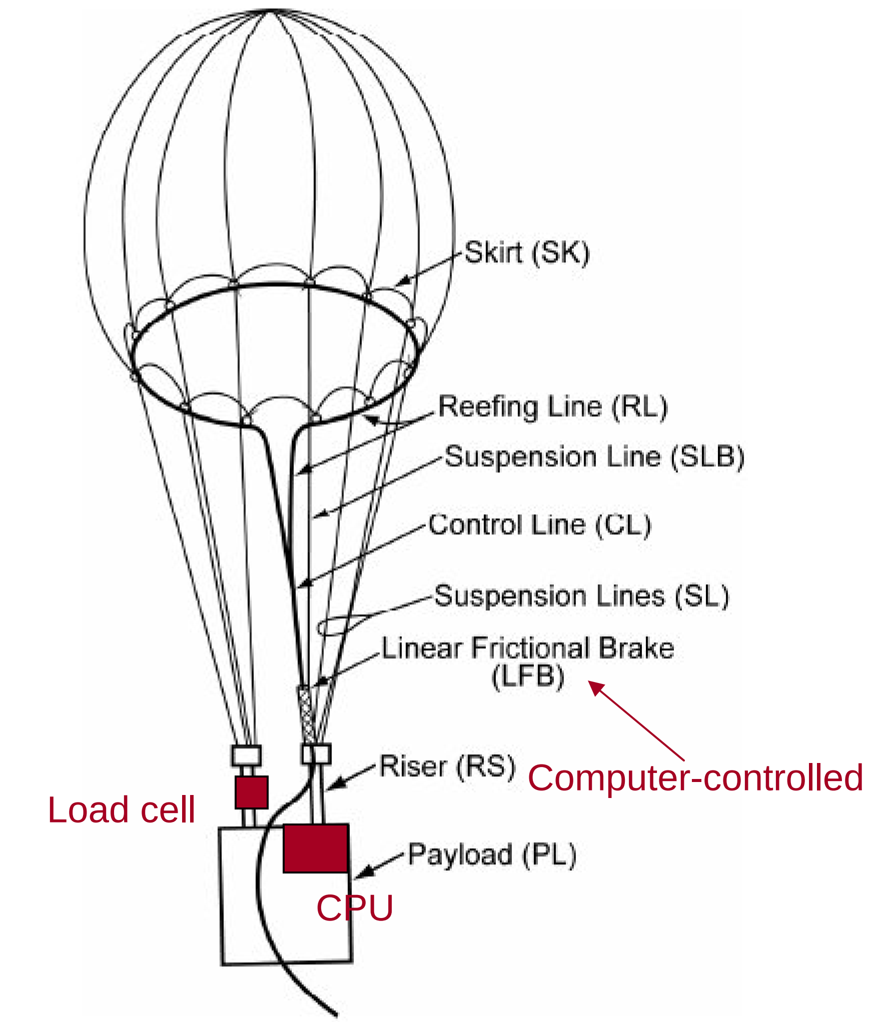


Fig. 1. Schematic showing the implementation of a continuous disreefing system on a round parachute.

Figure by Sadeck and Lee – paper 2007-2513

Realistic?

Only the future will tell.

Questions?