Testing Without Load Cells - Can Opening Shock Be Estimated From Video Data Only?

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Gary Peek & Jean Potvin

Physics Department, Saint Louis University, St. Louis MO

Contact: peek@industrologic.com 800-435-1975

potvinj@slu.edu 314-977-8424

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Executive Summary

- The maximum drag force F_{max} generated by an inflating parachute can be *estimated* via these two formulas:

Horizontal trajectories

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i}\right]$$

Vertical trajectories (downwards)

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i} + \frac{g(t_f - t_i)}{V_i}\right]$$

- Note the dependence on $(t_f - t_i) \equiv$ *inflation duration* (obtained from video)
- Such estimate will work with most parachute and reefing types
- Works *only* for slow-descending parachute-payload systems (i.e. $V_{descent} < 30ft/sec$)
- Paper shows the large database that was used to check the range of validity

Executive Summary

- **NOT DISCUSSED IN THIS TALK OR PAPER:**
  The maximum drag force F_{max} generated by an inflating parachute used at infinite-mass conditions (i.e. low mass ratios/wind tunnels,etc.), can be *estimated* via this formula:

$$F_{\max} \approx U_{ck} \frac{\rho (SC_D)_{sd}^{3/2} V_i}{2(t_f - t_i)}$$

$$U_{ck} \approx 20$$

For both
low- and high porosity
hemisphericals - **unreefed**

(Horizontal trajectories)

More details can be found in:
"Universality Considerations for Graphing Parachute Opening Shock Factor Versus Mass Ratio "; ***JOA***, 44, No. 2, pp. 528 - 538, 2007.
Paper-copy available on request.

Why is this a big deal?

- The value of the maximum drag force F_{max} is a standard measurement during the testing phase of most parachute systems (involving load cells and/or accelerometers)

- But what about finding out F_{max} during service use, say after unusual deployments and/or unusually hard openings? Typically such parachutes are not equipped with force-measuring devices.

- The method discussed here proposes an estimate, based on general deployment and parachute characteristics AND on inflation duration, which obtained from the video coverage of the opening

Main ingredient – 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 MI-theorem has been used extensively to study the maximum force on many types of systems. See references [1 – 5] in paper. Paper copies of refs. [1] and [4, 5] are available here!

Main ingredient – the Momentum-Impulse Theorem

- **Reformulate in terms of F$_{\max}$**

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

$$\Downarrow$$

Inflation duration

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

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

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

Main ingredient – the Momentum-Impulse Theorem

- **Focus on either vertical trajectories ($\theta(t)$ = 0°) and on horizontal downwards trajectories ($\theta(t)$ = 90°)**

- **Assume $V_f \sim V_{descent}$ (i.e. steady-state descent under fully inflated canopy)**

- **Assume drag integral $I_F^{if} \sim 1/2$**

Extracting F_{max} from the MI-theorem under these conditions yields the main results of this paper

Horizontal

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i}\right]$$

$2 = 1/\mathbf{I}_\mathbf{F}^{\mathbf{if}}$

Vertical

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i} + \frac{g(t_f - t_i)}{V_i}\right]$$

Obtained from video coverage

“Froude term”

Which parachute-payload system satisfy the condition $V_f \sim V_{descent}$?

- One can get $V_f \sim V_{descent}$ if the drag force is large enough and lasts long enough to generate the required *deceleration*

- In particular this constraint applies to high mass ratio (R_m) systems!

$$R_m \equiv \frac{\rho_{high}\,(SC_D)_{sd}^{\;3/2}}{m}$$

- Why? Consider Netwon's 2nd law again (horizontal trajectory) and reformulate in terms of the mass ratio

$$ma(t) = -\frac{1}{2}\rho_{high}\,(S(t)C_D(t))V^2(t)$$

We get: $$\delta(t) \equiv \frac{(SC_D)_{sd}^{\;1/2}}{V^2(t)}a(t) = -\left(\frac{1}{2}R_m\right)\left(\frac{(S(t)C_D(t))}{(SC_D)_{sd}}\right)$$

$$\delta(t) \equiv \frac{(SC_D)_{sd}^{1/2}}{V^2(t)} a(t) = -\left(\frac{1}{2} R_m\right)\left(\frac{(S(t)C_D(t))}{(SC_D)_{sd}}\right)$$

- **This means that the higher the mass ratio R_m, the more deceleration; "high-R_m" typically means $R_m > 0.1$**

- **Note that high-mass ratio also means *slow-descending***

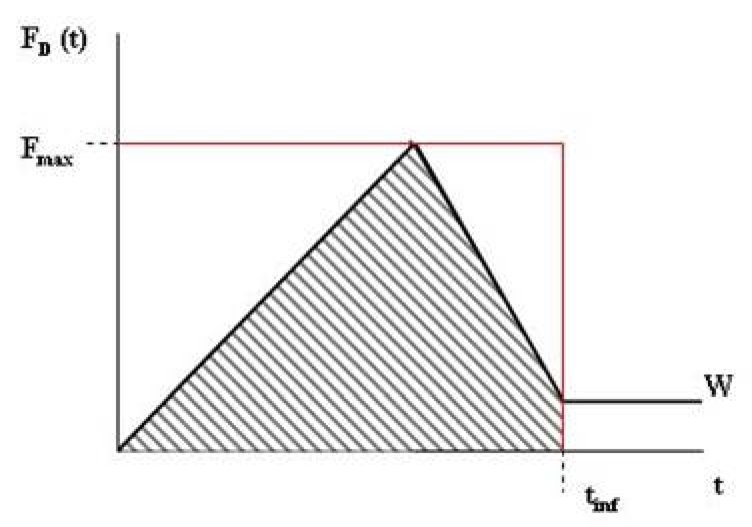
$$R_m = \frac{2g(SC_D)_{sd}^{1/2}}{\left(V_{descent}^{high}\right)^2}$$

- **So $R_m \sim 1.7$ means $V_{descent} \sim 25$ *ft/sec* for US. Army T-10, or $R_m \sim 6.0$ means $V_{descent} \sim 25$ *ft/sec* for US Army G-11 (one canopy)**

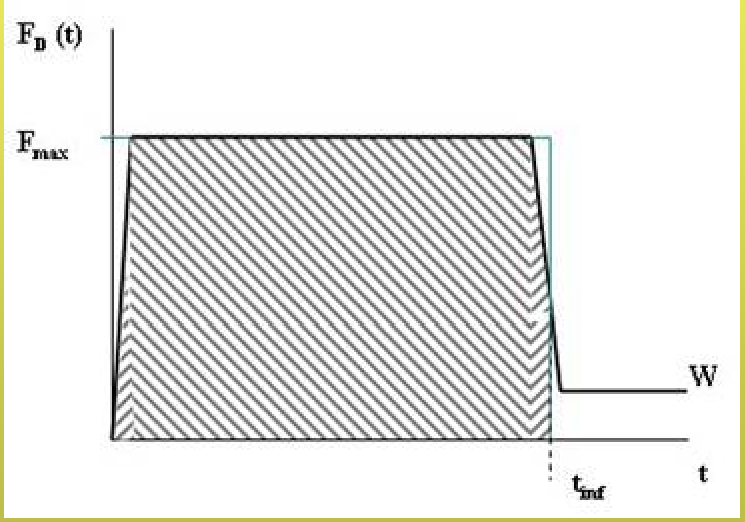
- **In what follows we consider $V_{descent} < 30$ ft/sec as a necessary constraint for the estimate to work**

Which parachute-payload system satisfy the condition I_F^{if} ~ ½ ?

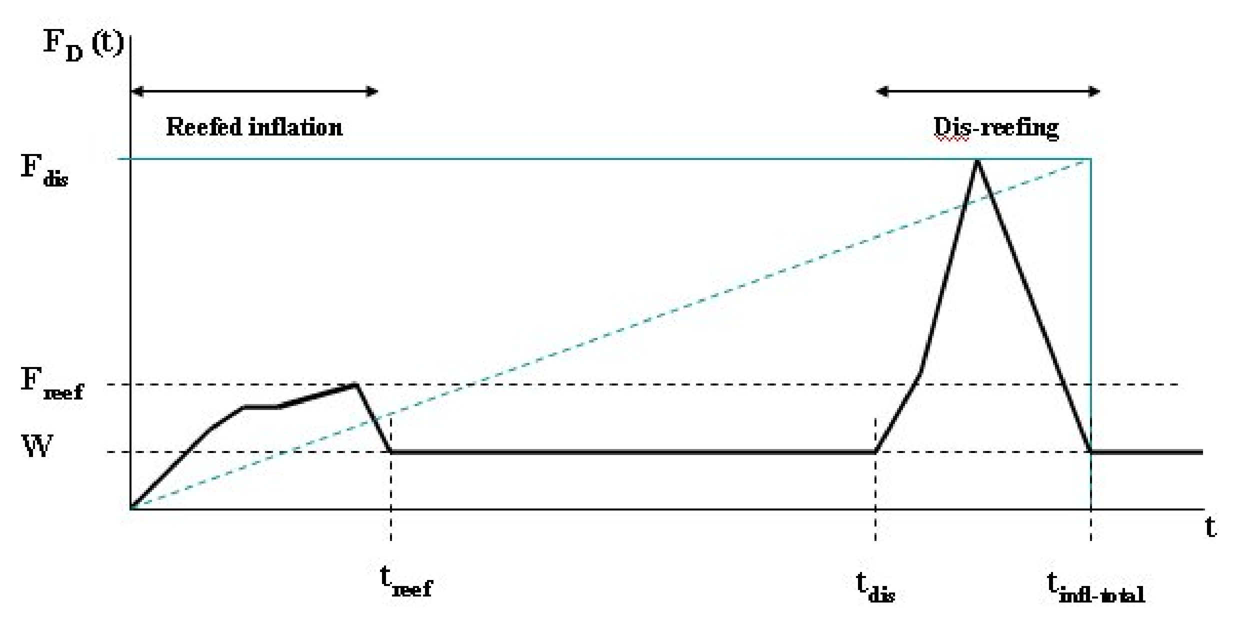
- **One can get I_F^{if} ~ ½ if the mass ratio is large enough, again $R_m > 0.1$. Why?**
- **The drag integral measures the area under the *(normalized) drag vs. time* curve**



Drag integral ~ ½



Drag integral ~ 1



Dis-reefing case (long after reefed inflation) – Drag integral ~ ¼.
Note: drag integral → 0 as $t_{dis} - t_{reef} \rightarrow W/F_{dis} << 1/2$

When is $I_F^{if} \sim \tfrac{1}{2}$?

- Reference [1] showed the first experimental data suggesting this value whenever $R_m > 0.1$ (or so), on
  - Slider-reefed parafoils
  - Permanently reefed or un-reefed hemispherical canopies

- More experimental data analyzed here show the same trend to be working also on
  - ringslot types
  - slider-reefed rounds
  - deep cones
  - unreefed parafoils (not always though; depends on lift)

- Reference [1] also shows that $I_F^{if} < 1/3$ when $R_m < 0.1$, at least for disk-gap-band types and hemispherical types

- *Exception:* it seems that $I_F^{if} < 1/3$ at both small- and large-R_m with chutes that dis-reef long after reefed inflation

Validation

- **Based on a large database (next slide)**
- **Data must include load cell data (to calculate I_F^{if} and F_{max})**
- **Must also include video coverage of each test, in order to obtain the inflation time $t_f - t_i$ (via frame-counting)**

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i}\right]$$

video

Calculated via standard descent formula

$2 = 1/I_F^{if}$

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i} + \frac{g(t_f - t_i)}{V_i}\right]$$

Load cell

Calculated, simulated or measured

Database: 14 canopy-reefing combos & 67 drops total

Hemispherical and spherical types

US Army T-10C (Table 4-1)
USAF C-9, unreefed & permanently skirt-reefed (Table 4-2)
½-scale C-9, unreefed & permanently skirt-reefed (Table 4-3)
Butler HX-600 (hemispherical canopy with slider reefing) (Table 4-4)
Cruciform, with and without slider-reefing (Table 4-5)
US Army 26ft ringslot extraction parachute (Table 4-6)

Deep-conical types

Truncated Cone Decelerator (Table 4-7)

Parafoil types

Unreefed parafoils (Table 4-8)
BLM Trilobe (Table 4-9)
PD Sabre230 (Table 4-10)
PDSabre120 (Table 4-11)
PD Sabre150 (Table 4-12)
PD Stiletto150 (Table 4-13)
+ repeat jumps/drops

Results

- Hard to plot this data on a single graph
- Data shown in tabular form

US. Army T-10C

Table 4-1. US Army T-10C (hemispherical canopy)
Canopy specs: 35.0ft nominal diameter. Construction details can be found in reference [8].
Deployment method: static line.

Good matches

Acft ID Drop#	Acft speed Deploy altitude (feet; MSL)	W (lbs)	R_m Mass ratio	Estimated V_i (true airspeed at line-stretch; ft/sec)	Calculated $V_{descent}$ (ft/sec) $V_i/V_{descent}$	I_F^{if} (Drag integral; calculated from data)	$t_f - t_i$ (sec)	Traject. type during inflation	Calculated F_{max}^{horiz} Horizontal trajectory (lbs)	Measured F_{max} (lbs)	Calculated F_{max}^{vert} Vertical trajectory (lbs)
UH-1 Helo Test 06-456	80 KIAS 1000	300	4.52	104	18.5 5.6	0.57	2.10	ballistic	756	1036	1356
UH-1 Helo Test 06-457	80 KIAS 1000	300	4.42	104	18.5 5.6	0.65	2.18	ballistic	728	857	1329
UH-1 Helo Test 06-458	80 KIAS 1000	200	2.46	85	14.8 5.7	0.50	2.14	ballistic	405	759	804

Table 4-4. Butler HX-600 slider-reefed hemispherical canopy

Canopy specs: 27.64ft nominal diameter (low porosity fabric). More construction details can be found in [16].

Slider specs: span = 67in (Sombrero slider - rim diameter).

Deployment method: static line.

Good matches

	Acft speed (KIAS) Deploy altitude (feet; MSL)	W (lbs)	R_m Mass ratio	Estimated V_i (true airspeed at line-stretch; ft/sec)	Calculated $V_{descent}$ (ft/sec) ($C_D \sim 0.75$) $V_i/V_{descent}$	I_F^{if} (Drag integral; calculated from data)	$t_f - t_i$ (sec)	Traject. type during inflation	Calculated F_{max}^{horiz} Horizontal trajectory (lbs)	Measured F_{max} (lbs)	Calculated F_{max}^{vert} Vertical trajectory (lbs)
Beech King Air NWV144	95 KTSI 1000-1500	300	2.45	120	23.8 5.0	0.51	2.8	ballistic	641	1167	1241
Beech King Air NWV158	95 KTSI 1000-1500	300	2.45	120	23.8 5.0	0.52	2.4	ballistic	805	1064	1405
Cessna Super Caravan YPG016	95 KTSI 1000-1500	165	4.45	107	17.6 6.1	0.46	3.1	ballistic	316	553	646
Cessna Super Caravan YPG019	95 KTSI 1000-1500	165	4.45	107	17.6 6.1	0.52	2.7	ballistic	332	546	662

Slider-reefed parafoil - note the drop-to-drop variations in inflation time BUT not in I_F^{if}

Table 4-9. US Bureau of Land Management "Trilobe" slider-reefed, seven cell parafoil
Wing specs: span = 25.7ft & chord = 12.8.
Slider specs: span = 2.08ft by 1.83ft .
Deployment: after freefall by parachutist (at least 10secs of freefall) – Reference [13].
NA = not applicable

Good matches

Deploy altitude (feet; MSL)	W (lbs)	R_m Mass ratio	Measured V_i (true airspeed at line-stretch; ft/sec)	Calculated $V_{descent}$ (ft/sec) $V_i/V_{descent}$	I_F^{if} (Drag integral; calculated from data)	$t_f - t_i$ (sec)	Trajectory type during inflation	Calculated F_{max}^{horiz} Horizontal trajectory (lbs)	Measured F_{max} (lbs)	Calculated F_{max}^{vert} Vertical trajectory (lbs)
2500-3500	220	1.23	191	25 7.6	0.48	4.9	vertical	NA	801	903
2500-3500	220	1.23	184	25 7.4	0.38	3.8	vertical	NA	1168	1007
2500-3500	220	1.23	191	25 7.6	0.39	3.4	vertical	NA	1399	1102
2500-3500	220	1.23	188	25 7.5	0.44	6.8	vertical	NA	743	769
2500-3500	220	1.23	176	25 7.0	0.46	6.3	vertical	NA	704	771
2500-3500	220	1.23	191	25 7.6	0.48	4.9	vertical	NA	834	903
2500-3500	220	1.23	194	25 7.8	0.45	3.9	vertical	NA	1251	1028
2500-3500	220	1.23	179	25 7.2	0.45	4.0	vertical	NA	948	966

USAF C-9 – unreefed (yields hemispherical shape)

Table 4-2. Full-scale USAF C-9 (unreefed and hemispherically-shaped canopy;
Canopy specs: 28.0ft nominal diameter. See reference [8] for details.
Deployment method: static line, from Cessna Caravan.

Good matches

Drop# Reefing type	Acft speed (KIAS) Deploy altitude (feet; MSL)	W (lbs)	R_m Mass ratio	Estimated V_i (true airspeed at line-stretch; ft/sec)	Calculated $V_{descent}$ (ft/sec) $V_i/V_{descent}$	I_F^{if} (Drag integral; calculated from data)	$t_f - t_i$ (sec)	Traj. type during infl.	Calculated F_{max}^{horiz} Horizontal trajectory (lbs)	Measured F_{max} (lbs)	Calculated F_{max}^{vert} Vertical trajectory (lbs)
YPG001 No reefing (80-20 “Mea West”)	95 1000-1500	165	4.45	101	17.6 5.74	0.55	0.87	ballistic	982	1083	1313
YPG004 No reefing	95 1000-1500	165	4.45	101	17.6 5.74	0.76	2.20	ballistic	389	453	719
YPG005 No reefing	95 1000-1500	165	4.45	101	17.6 5.74	0.62	1.67	ballistic	545	700	875
YPG008 No reefing	95 1000-1500	165	4.45	101	17.6 5.74	0.74	1.67	ballistic	512	500	842

USAF C-9 – reefed (tight reefing - yields spherical shape)

Good matches

Table 4-2. Full-scale USAF C-9 (~~unreefed and hemispherically-shaped canopy~~; and permanently reefed and spherically-shaped canopy)
Canopy specs: 28.0ft nominal diameter. See reference [8] for details.
Deployment method: static line, from Cessna Caravan.

YPG011 24%reefing	**95 1000-1500**	**165**	**0.61**	**101**	**34.1 2.96**	**0.63**	**2.01**	**ballistic**	**411**	**600**	**741**
YPG014 24%reefing	**95 1000-1500**	**165**	**0.61**	**101**	**34.1 2.96**	**0.59**	**1.60**	**ballistic**	**429**	**540**	**759**
YPG020 24%reefing	**95 1000-1500**	**165**	**0.61**	**101**	**34.1 2.96**	**0.74**	**1.62**	**ballistic**	**423**	**472**	**753**
YPG024 24%reefing	**95 1000-1500**	**165**	**0.61**	**101**	**34.1 2.96**	**0.55**	**1.49**	**ballistic**	**490**	**912**	**820**

Half-scale C-9 – unreefed (yields hemispherical shape)

Good to fair matches

Table 4-3a. 1/2-scale C-9 canopy (hemispherical canopy; unreefed)
Canopy specs: 14.0ft nominal diameter. Construction details can be found in reference [17]
Deployment method: Very wide payload container; static line; exit from side door of Cessna 402 (NWV12) and Cessna 411 (all others).

Drop#	Acft speed (KIAS) Deploy altitude (feet; MSL)	W (lbs)	R_m Mass ratio	Estimated V_i (true airspeed at line-stretch; ft/sec)	Calculated $V_{descent}$ (ft/sec) $V_i/V_{descent}$	I_F^{if} (Drag integral; calculated from data)	$t_f - t_i$ (sec)	Traj. type during infl.	Calculated F_{max}^{horiz} Horizontal trajectory (lbs)	Measured F_{max} (lbs)	Calculated F_{max}^{vert} Vertical trajectory (lbs)
NWV12	90 800-1000	105	0.79	135	29 4.65	0.51	0.35	Mostly horiz.	1975	1619	2185
NWV15	90 800-1000	105	0.79	135	29 4.65	0.27	0.60	Mostly horiz.	1152	1774	1362
NWV17	90 800-1000	105	0.79	135	29 4.65	0.57	0.57	Mostly horiz.	1686	1539	1896
NWV19	90 800-1000	105	0.79	135	29 4.65	0.41	0.69	Mostly horiz.	1002	1174	1212

Half-scale C-9 – reefed (tight reefing - yields spherical shape)

Table 4-3b. 1/2-scale C-9 canopy (permanently skirt-reefed; spherically-shaped canopy)
Canopy specs: 14.0ft nominal diameter (unreefed) [17].
Deployment method: static line, from Cessna Caravan.

NO match!

Out of validity range

Drop# Reefing type	Acft speed (KIAS) Deploy altitude (feet; MSL)	W (lbs)	R_m Mass ratio	Estimated V_i (true airspeed at line-stretch; ft/sec)	Calculated $V_{descent}$ (ft/sec) $V_i/V_{descent}$	I_F^{if} (Drag integral; calculated from data)	$t_f - t_i$ (sec)	Traj. type during infl.	Calculated F_{max}^{horiz} Horizontal trajectory (lbs)	Measured F_{max} (lbs)	Calculated F_{max}^{vert} Vertical trajectory (lbs)
YPG006 16%reefing	95 1000-1500	66	0.15	121	47 2.57	0.65	0.47	Mostly horiz.	679	403	811
YPG009 16%reefing	95 1000-1500	66	0.15	121	47 2.57	0.76	0.39	Mostly horiz.	789	288	930
YPG012 24%reefing	95 1000-1500	66	0.19	121	43 2.81	0.70	0.35	Mostly horiz.	912	239	1044
YPG015 24%reefing	95 1000-1500	66	0.19	121	43 2.81	0.39	0.47	Mostly horiz.	679	628	811
YPG018 24%reefing	95 1000-1500	66	0.19	121	43 2.81	0.68	0.39	Mostly horiz.	819	224	951

Cruciform parachute (3:1 Aspect ratio)

Matches good only b/c of error cancellation (next slide); out of validity range!

Table 4-5. Cruciform parachutes
Full-scale specs: built from two 24.84ft –by- 9.25ft rectangular panels (zero-porosity fabric);
Half-scale specs: built from two 12.24ft-by-4.37ft rectangular panels (zero-porosity fabric);
Both versions were made of 200 denier nylon fabric (permeability: 30-45cfm).
Deployment method: static line.

Chute ID Acft ID Drop#	Acft speed Deploy altitude	W (lbs)	R_m Mass ratio	Estimated V_i (true airspeed at line-stretch; ft/sec)	Calculated $V_{descent}$ (ft/sec) $V_i/V_{descent}$	I_F^{if} (Drag integral; calculated from data)	$t_f - t_i$ (sec)	Traject. Type during inflation	Calculated F_{max}^{horiz} Horizontal trajectory (lbs)	Measured F_{max} (lbs)	Calculated F_{max}^{vert} Vertical trajectory (lbs)
Full scale C-130 Test 01-470 (no slider)	130KIAS 18,000ft MSL	1,477	0.13	220-234	75 2.9 – 3.1	0.26	1.19	Ballistic (mostly horiz.)	11,960 See sect. 4.2.3	11,416	14,910
Full scale C-130 Test 01-470 (with slider)	130KIAS 10,000ft MSL	1,042	0.27	166	60 2.8	0.21	1.26	Ballistic (mostly horiz.)	5,544	7,000	7664
Half scale UH-1 Helo Test 06-459 (no slider)	80 KIAS 1000ft MSL	200	0.15	142	57 2.5	0.36	0.62	ballistic	1705	964	2105

Error cancellation in $R_m < 0.2$ regime

$2 = 1/I_F^{if}$ here;
"2" -factor should be replaced by a higher value, since in reality I_F^{if} is smaller

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i}\right]$$

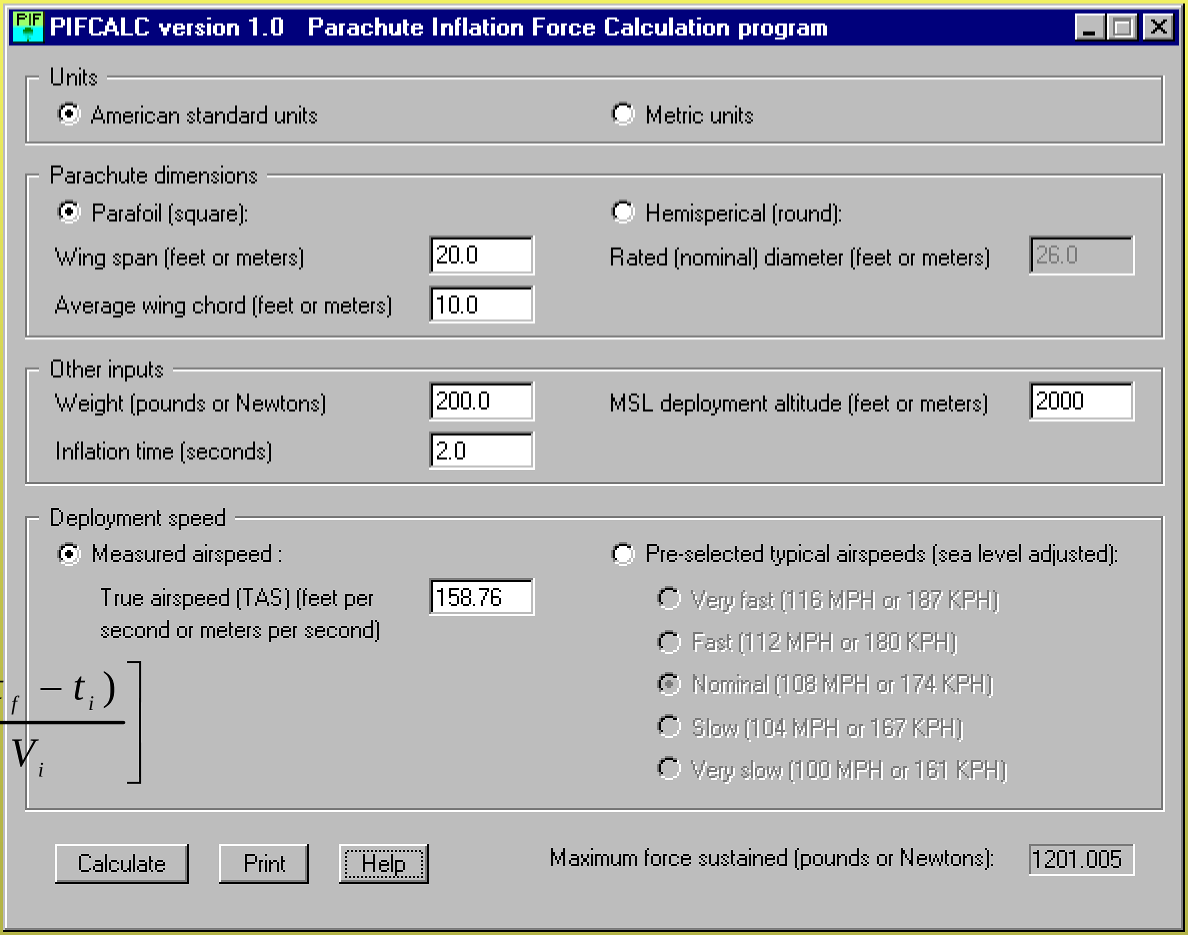
$V_f >> V_{descent}$ in this regime; number inside brackets should be smaller than $1 - V_{descent}/V_i$

Concluding remarks

- **Method works well for almost all parachute/reefing designs**
- **Exception: Parachutes that disreef long after reefed inflation has ended**
- **All validation cases came from cargo drops or skydiving, where $V_i \sim 80 - 200$ ft/sec**
- **What about the cases where $V_i \gg 200$ ft/sec? (ejection seat, etc.) Would the method work if $R_m > 0.1$? Yes, if $t_f - t_i$ measures *inflation +post-inflation deceleration***
- **What about slow deployments? (BASE jumping) Here $V_i \sim V_{descent}$. In principle the method should work but V_i *must be measured very accurately***

Simple Windows-based program for manned parachuting

- Easy to use
- Free download at http://www.pcprg.com/pifprog.htm



Units

● American standard units
○ Metric units

Parachute dimensions

● Parafoil (square):
Wing span (feet or meters): 20.0
Average wing chord (feet or meters): 10.0

○ Hemisperical (round):
Rated (nominal) diameter (feet or meters): 26.0

Other inputs

Weight (pounds or Newtons): 200.0
Inflation time (seconds): 2.0
MSL deployment altitude (feet or meters): 2000

Deployment speed

● Measured airspeed :
True airspeed (TAS) (feet per second or meters per second): 158.76

○ Pre-selected typical airspeeds (sea level adjusted):
○ Very fast (116 MPH or 187 KPH)
○ Fast (112 MPH or 180 KPH)
● Nominal (108 MPH or 174 KPH)
○ Slow (104 MPH or 167 KPH)
○ Very slow (100 MPH or 161 KPH)

Maximum force sustained (pounds or Newtons): 1201.005

$V_{descent}$ calculated with C_{D0} = 0.7 (rounds) or 1.0 (parafoil)

$$F_{\max} \approx \frac{2mV_i}{(t_f - t_i)}\left[1 - \frac{V_{descent}}{V_i} + \frac{g(t_f - t_i)}{V_i}\right]$$

Questions?