

Modeling and Simulation of the Dragonfly Drogue Parachute Opening Loads using POST2

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The Dragonfly project is a New Frontiers Program mission that will launch in 2028 and deliver a rotorcraft to Titan, Saturn’s largest moon. The entry, descent, and landing (EDL) phase is highly dependent on the drogue and main parachute subsystem due to Titan’s dense atmosphere and relatively low gravity. As such, the deployment of the drogue parachute represents a critical event to ensure a successful descent. This study provides an overview of the modeling and simulation efforts to quantify the drogue opening loads using a heritage method and by evaluating the bridle elastic loads to assess hardware risk. The elastic loads yielded a more representative estimate for quantifying the loads that the parachute and entry vehicle will undergo. This study showed that the inflation models drive these loads more so than the elastic properties of the bridles, and tuning the drogue deployment timing can minimize the opening loads.

I. Nomenclature

D_0	=	Nominal parachute diameter
S_0	=	Nominal parachute area
D_p	=	Projected parachute diameter
S_p	=	Projected parachute area
F_{sd}	=	Force generated by a spring-damper system
k_{BL}	=	Spring constant of a bridle leg
ΔL_B	=	Change in length of a bridle leg
c_{BL}	=	Coefficient of viscous damping of a bridle leg
dt	=	Time step
F_{BL}	=	Force on triple bridle leg
t_{FI}	=	Time at parachute full inflation
t_{LS}	=	Time at parachute line stretch
d_{inf}	=	Inflation distance
$V_{aeroshell}$	=	Entry vehicle atmosphere relative velocity
K_{I1}	=	time-dependent scaling multiplier
F_{Peak}	=	Peak force on the parachute
q_∞	=	Dynamic pressure of the entry vehicle
C_T	=	Axial or tangential force coefficient
$(C_T)_I$	=	Inflation Axial or tangential force coefficient
$(C_T)_{Int}$	=	Interpolated axial or tangential force coefficient
C_N	=	Normal force coefficient
$(C_N)_I$	=	Inflation Normal force coefficient
$(C_N)_{Int}$	=	Interpolated Normal force coefficient
C_{m_0}	=	Pitching moment coefficient

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$(C_{m0})_I$	=	Inflation pitching moment coefficient
$(C_{m0})_{Int}$	=	Interpolated pitching moment coefficient
K_P	=	Momentum peak opening load factor
K_{I2}	=	drogue inflation multiplier
MEF	=	Mach Efficiency Factor
ΣF_{BL}	=	Total elastic load
$U_{parameter}$	=	Uncertainty of a parameter
$U_{parameter}^M$	=	Uncertainty multiplier of a parameter
ζ	=	Damping ratio
f_n	=	Natural frequency
P	=	Pearson Correlation Coefficient
σ	=	Standard deviation

II. Introduction

The Dragonfly mission, a NASA New Frontiers mission to Titan, will need to execute a safe entry, descent, and landing (EDL) to deliver a rotorcraft lander to the surface of Saturn's biggest moon. The EDL profile is dominated by the parachute descent phase due to Titan's high atmospheric density and relatively low gravity. The Dragonfly EDL sequence, including the parachute decelerator subsystem (PDS), is modeled using the Program to Optimize Simulated Trajectories II (POST2) [1]. POST2 simulations are used to analyze the parachute loads, perform trajectory analyses, and characterize system dynamics with the goal of evaluating the PDS performance, informing the subsystem design, developing requirements, and supporting verification and validation efforts. The Dragonfly PDS is designed to deliver the Dragonfly rotorcraft to acceptable flight conditions in a given time frame. The PDS consists of a two-stage parachute system: a mortar-deployed Disk-Gap-Band (DGB) drogue parachute of 8.25 m nominal diameter and a drogue deployed 16.66 m conical ringslot main parachute. The drogue parachute is sized to stabilize the entry vehicle in the low-supersonic and transonic flight regimes while maintaining acceptable opening loads and the descent timeline. The ringslot main parachute is designed to be robust when opening at low dynamic pressures, provide an adequate ballistic coefficient differential to allow heatshield separation, and achieve the required terminal velocity while maintaining acceptable system attitude and attitude rates for mid-air rotorcraft release. More details of the EDL concept of operations are in reference [1].

A critical event in the EDL sequence is the deployment and inflation of the drogue parachute at supersonic conditions. Quantifying the peak opening loads experienced by the drogue parachute is key to ensuring that the PDS hardware and structural interfaces with the entry vehicle are not at risk of failure. This paper provides an overview of the simulation framework and analysis used to assess the peak opening load and associated transients for the Dragonfly drogue parachute.

III. Parachute Models

The parachute models used for Dragonfly are adapted from models originally developed for Mars Science Laboratory (MSL). These models have been used for flight projects such as Mars InSight[2], ASPIRE [3][4] and Mars 2020[5]. A more detailed discussion of heritage parachute models, including those not included in this document (Area Oscillations), is contained in reference [6].

A. Basic Modeling Assumptions

The parachute and entry vehicle are modeled in POST2 as two distinct, rigid bodies attached by three bridle legs as shown in Figure 1. The canopy, suspension lines, and riser are treated as a single rigid body with six degrees-of-freedom (6-DOF). The parachute's wind angles (i.e. angle of attack, angle of sideslip, and/or equivalents) are calculated at the parachute's center of volume as shown in Figure 2. The Mach number and dynamic pressure for the parachute models, however, is that of the aeroshell's center of mass to avoid artificial numerical oscillations due to interactions between the elastic bridle and other parachute models [6].

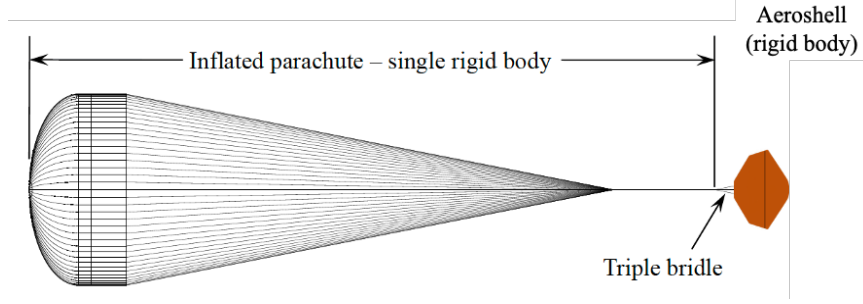


Fig. 1 Multibody model of the drogue parachute and entry vehicle

B. Geometric Parameters

The key geometric parameters are shown in Table 1. The nominal parachute diameter and the ratio of projected to nominal parachute diameter is used to determine all geometric properties relevant to this assessment.

Table 1 Geometric Properties of the Dragonfly Drogue Parachute

Item	Symbol	Value
Nominal parachute diameter	D_0	8.25 m
Nominal parachute area	S_0	$S_0 = \pi D_0^2/4$
Ratio of projected to nominal parachute diameter	D_p/D_0	0.735
Projected parachute area	S_p	$S_p = \pi D_p^2/4$

C. Elastic Properties

The triple bridle legs are the only elastic elements in the simulation. Each bridle leg is modeled as a massless, tension-only spring-damper. The force of each bridle is calculated using Equation 1 found in reference [6]. The logical gate in Equation 2 is used to enforce that bridles exert positive loads (tension). Negative loads (compression) do not impart any force on the parachute or the entry vehicle. A bridle with zero (or negative) loads is referred to as a "slacked" bridle. All three bridle legs use the same spring constant (stiffness) and damping coefficient. These elastic properties become active at the suspension lines stretch event (drogue deployment) and are constant through the simulation. The modeled elastic properties for each triple bridle leg are defined in the following section.

$$F_{sd} = k_{BL}\Delta L_B + c_{BL}\frac{d(\Delta L_B)}{dt} \quad (1)$$

$$\text{if } F_{sd} > 0 \text{ then } F_{BL} = F_{sd}; \text{ else } F_{BL} = 0; \text{ endif} \quad (2)$$

D. Parachute Deployment

1. Flight Conditions

The drogue is deployed using an inertial measurement unit (IMU) sensed accelerator trigger. This acceleration is tuned to correspond to a drogue deployment below Mach 1.5. A predictive logic algorithm is used to ensure the mortar fire occurs at a low total angle of attack. The requirement is set that the drogue must deploy at a total angle of attack less than 15 degrees (99 %-tile). This is set to minimize the risk of high opening loads at high pull angles. There is a backup timer of five seconds from when the logic algorithm is initialized to ensure the drogue deploys if the conditions of the predictive logic algorithm are not met in time.

As noted in reference [6] and in previous flight experience, DGB parachutes experience large force oscillations at Mach numbers above 1.4. As such, the deployment condition is also designed to ensure the time above Mach 1.4 does not exceed 10 seconds (99 %-tile). Additionally, for overall EDL requirements, the entire descent time is constrained to

be less than 150 minutes to meet power and thermal challenges. These two requirements define the upper bound of the deployment condition.

2. Parachute Initialization

Deployment is defined as the events occurring from mortar firing to suspension lines stretch. Suspension lines stretch, t_{LS} , is defined as the time at which the skirt of the canopy starts to emerge from the deployment bag. The parachute is not explicitly modeled during the time interval from mortar firing up to (but not including) suspension lines stretch. The time at suspension lines stretch is calculated from the stretched-out parachute geometry and the average deployment bag speed [6]. The Dragonfly drogue parachute deployment occurs on the order of one second.

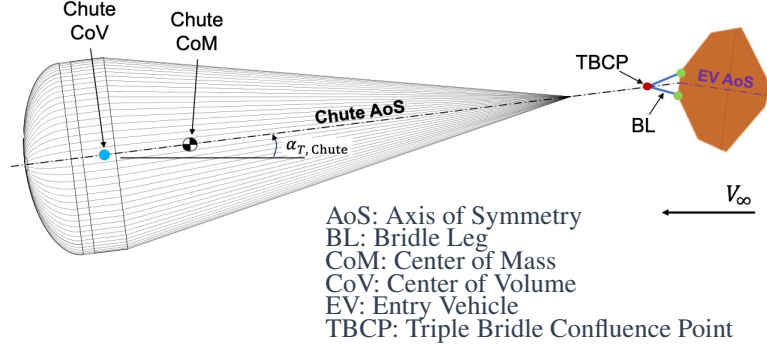


Fig. 2 Drogue Parachute Geometry as modeled in POST2

At suspension lines stretch, the un-inflated parachute spawns in the simulation and its aerodynamic and inertial characteristics become active. The following initial conditions define the state of the parachute (position, velocity, attitude and rates) at t_{LS} .

- The parachute's airspeed vector at its center of mass is equal to the aeroshell's airspeed vector at its center of mass.
- The parachute appears at a perturbed (random) total angle of attack and total angle of attack clock angle as defined in [6].
- The parachute body rotation rate vector is zero.
- The axis of symmetry of the parachute passes through the midpoint of the three bridle attachment points on the entry vehicle.
- None of the triple bridle legs can be stretched beyond their unloaded length (at most two of three legs may be slack).

E. Inflation

Inflation accounts for the events occurring from suspension lines stretch up to, but not including, the full inflation of the canopy. The time at first full inflation is calculated from Equation 3, defined in terms of the drogue parachute inflation distance, d_{inf} , and the aeroshell velocity, $V_{aeroshell}$. The inflation time of the drogue parachute is estimated to be 0.2 seconds based on expected mortar performance.

$$t_{FI} = t_{LS} + \frac{d_{inf}}{V_{aeroshell}} \quad (3)$$

F. Opening Loads

1. Opening Loads

The parachute forces and moments are minimal at parachute suspension lines stretch, (t_{LS}), but are expected to grow until achieving full inflation (FI). This effect is modeled by two multipliers, the first being a time-dependent scaling multiplier, K_{I1} , defined in terms of the times at suspension lines stretch, the time at full inflation, and the inflation exponent, n_I , which has a value of four for the Dragonfly drogue parachute.

$$K_{I1} = \left(\frac{t - t_{LS}}{t_{FI} - t_{LS}} \right)^{n_I} \quad (4)$$

The second multiplier, K_{I2} , is defined by the K_{I1} multiplier and the peak aerodynamic opening load in the numerator, F_{peak} . The denominator normalizes the peak opening load using the dynamic pressure of the entry vehicle, the nominal parachute area, and the root sum mean square of the tangential and normal force coefficients. The dynamic pressure is queried at the center of mass of the entry vehicle. This multiplier is used to modulate the static aerodynamic coefficients during inflation.

$$K_{I2} = \frac{K_{I1} F_{Peak}}{q_{\infty} S_0 \sqrt{(C_T)_{Int}^2 + (C_N)_{Int}^2}} \quad (5)$$

2. Peak Opening Loads

The drogue parachute peak opening load is estimated using a momentum-based indicator as described in reference [7]. This method has heritage from the Mars 2020 project [5]. The peak opening loads are calculated using Equation 6. The model uses the momentum peak opening load factor (k_p), defined at a nominal value of 0.8 dispersed using a normal uncertainty distribution with three standard deviations (3σ) of 0.1 around the nominal. The dynamic pressure (q_{∞}) is calculated at the center of mass of the entry vehicle to avoid artificial transients that would be introduced by calculating the dynamic pressure at a point along the parachute. The projected parachute area (S_p) is calculated as indicated in the drogue parachute geometric parameters. The peak opening load factor is used in defining the Drogue inflation multiplier in Equation 5.

$$F_{peak} = 2k_p q_{\infty} S_p \quad (6)$$

G. Mach Efficiency Factor

The Mach Efficiency Factor (MEF) is used as a scaling factor for the static aerodynamic coefficients to take into account variations in parachute drag across the supersonic and transonic regimes. This model, originally developed for MSL [6], was adapted for the Dragonfly drogue parachute. The MEF is also used to scale the parachute static aerodynamic coefficients during inflation, thereby influencing opening loads as discussed in Section VI.C.

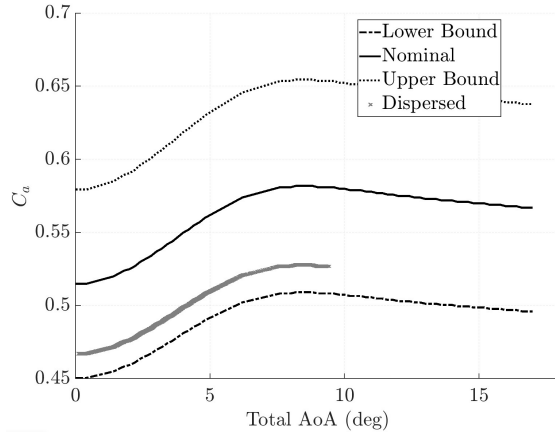
H. Aerodynamic Coefficients

The aerodynamic coefficients are modeled using the tangential (C_T or C_a), normal (C_N), and pitching moment coefficients (C_{m_0}) which are defined as functions of the total angle of attack, α_T . The three coefficients can be used to describe the static aerodynamics of an axisymmetric parachute. The static aerodynamic coefficients for the Dragonfly drogue parachute, along with their uncertainty bounds, are shown in Figure 3. For a given Monte Carlo analysis the nominal curve is shifted within the defined bounds using a triangular distribution. A single dispersed case is shown in gray in Figure 3. The dispersed curve is used for the entire simulation and using total angle of attack, α_T , as the independent variable for interpolation. During inflation, the interpolated static aerodynamic coefficients are modulated by the MEF and K_{I2} inflation multiplier (see below). After full inflation, the interpolated coefficients are only modulated by the MEF .

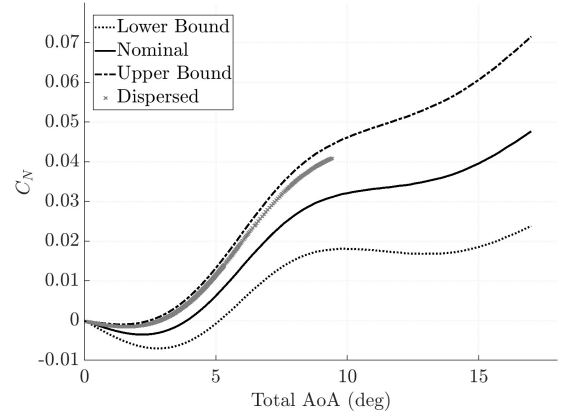
$$(C_T)_I = K_{I2} MEF (C_T)_{Int} \quad (7)$$

$$(C_N)_I = K_{I2} MEF (C_N)_{Int} \quad (8)$$

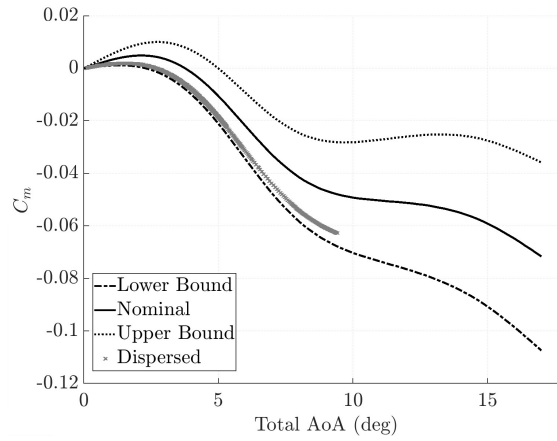
$$(C_{m_0})_I = K_{I2} MEF (C_{m_0})_{Int} \quad (9)$$



(a) Axial or Tangential force coefficient



(b) Normal force coefficient



(c) Pitching moment coefficient

Fig. 3 Parachute static aerodynamic coefficients

IV. Entry Vehicle

A. Aerodynamics

The entry vehicle aerodynamics in the supersonic regime of Dragonfly's EDL trajectory are modeled by a combination of computational fluid dynamics (CFD) solutions and heritage test data. Static aerodynamic characteristics of the entry vehicle are informed by a combination of steady-state Reynolds-Averaged Navier-Stokes (RANS) and time-accurate Detached Eddy Simulation (DES) CFD solutions of the standalone Dragonfly entry vehicle outer mold line (OML) at Titan entry and descent conditions for a total angle of attack up to 60 degrees [8]. The unsteady aerodynamic damping models use data obtained from ballistic range testing of the Genesis sample return capsule (GSRC), which the Dragonfly entry vehicle OML is based on. GSRC testing characterized increasing dynamic instability as the vehicle decelerates through Mach numbers relevant to Dragonfly drogue deploy and no apparent limit cycle below 40 degrees total angle of attack [9]. However, models derived from GSRC ballistic range testing data are also suspected of producing conservative supersonic damping behavior [10]. Additional Dragonfly ballistic range testing is being conducted to improve characterization of the entry vehicle in the drogue deploy Mach regime, where data available from GSRC testing is sparse. As the entry vehicle continues to decelerate through and after drogue deploy, dynamic stability continues to be an important factor and is closely coupled to the drogue parachute design [11]. The dynamic stability of the entry vehicle drives the lower bound of the deployment conditions, as it will be more challenging to ensure mortar fire occurs at a low total angle of attack, increasing the risk of an unsuccessful drogue deployment.

A detailed description of all the subsystem models including atmosphere, gravity model, and entry vehicle can be found in reference [1].

V. Assessing Elastic Overloads

Evaluating the bridle line loads or the elastic loads is done to quantify the risk to hardware failure. An independent analysis was completed to evaluate the load path from the bridle attachments to the canopy to define the load limits. As a result, a requirement was set that the peak loads shall not exceed 32 kN (95 %-tile).

This section gives an overview of how the elastic loads are characterized using the heritage method developed for previous Mars missions such as MSL and various methods derived for Dragonfly. In order to improve the modeling fidelity and characterize the elastic loads a test campaign was completed to derive the modeling parameters for the bridles and riser. Reference [12] discusses the test campaign and the derivation of the parameters used for this analysis.

A. Heritage Elastic Bridle Modeling

The elastic properties are described in Table 2. All three bridle lines stiffness and damping parameters are constant. The total elastic loads on the bridle are defined as the summation of the three line forces. This is due to the concern of the loads that the swivel, the joint above the triple bridle confluence point, will experience. The individual bridle line loads are tracked to quantify the forces the entry vehicle attachment points will undergo, but do not drive the requirements.

Table 2 Triple bridle elastic properties

Parameter	Heritage Values	Experimentally Derived Values
k_{BL}	$9.5215 \times 10^5 \text{ N/m}$	$1.298 \times 10^6 \text{ N/m}$
c_{BL}	$606.16 \text{ N}\cdot\text{s/m}$	$956.2 \text{ N}\cdot\text{s/m}$

$$\Sigma F_{BL} = F_{BL_1} + F_{BL_2} + F_{BL_3} \quad (10)$$

B. Load Independent Stiffness and Stiffness Dependent Damping

An immediate alteration to that model that can be made is the inclusion of dispersions that are derived from the experimental data. Eqn 11 defines the stiffness from the derived nominal stiffness, k_{nom} , and disperses the value by a scale factor $(1 + U_k)$. The dispersion on the stiffness term is held at $\pm 30\%$ from the nominal values in a uniform distribution.

$$k_{BL} = k_{nom} \cdot (1 + U_k) \frac{N}{m} \quad (11)$$

Two different damping coefficient derivations are presented in this work. Eqn 12, calculates the damping coefficient of the bridle using the same method as the stiffness and is dispersed independently.

$$c_{BL} = c_{nom} \cdot (1 + U_c) \frac{N * s}{m} \quad (12)$$

However, a more realistic model was created that correlates the damping coefficient to the stiffness coefficient. This is applied using Eqn 13.

$$c_{line} = \frac{\zeta}{\pi \times f_n} k_{line} \quad (13)$$

In this model, the inputs are the stiffness coefficient that is specified for a given case, the damping ratio, ζ , that is dispersed uniformly $\pm 35\%$, and the natural frequency, f_n , which is dispersed uniformly by $\pm 12\%$ using Eqn 14-15.

$$\zeta_{BL} = \zeta_{nom} \cdot (1 + U_{\zeta}^M) \quad (14)$$

$$f_n = f_{n,nom} \cdot (1 + U_{f_n}^M) \quad (15)$$

All three bridle lines use the same dispersed stiffness and damping parameters for each independent case in the Monte Carlo, i.e. for a specific case, bridle line one will have the same elastic properties as bridle line three.

C. Load Dependent Stiffness and Stiffness Dependent Damping

From the elastic bridle test campaign, a non-linear relationship between the stiffness coefficient and the loading on the line was observed [12]. A polynomial estimation was created to model the behavior observed during the pull testing to be implemented into the flight mechanics simulation, shown in Eqn 16.

$$k_{BL}(F) = (a_1 F^4 + a_2 F^3 + a_3 F^2 + a_4 F + a_5) \cdot (1 + U_k^M) \quad (16)$$

However, due to the relationship between force and stiffness, where the loading is a function of the stiffness and the stiffness is a function of the loading, Eqn 16 was implemented using Eqn 11 for the first timestep as shown in Eqn 17.

$$k_{BL}(F) = \begin{cases} k_{experiment} \cdot (1 + U_k^M), & t_{drogue} = 0 \\ (a_1 F(t-1)^4 + a_2 F(t-1)^3 + a_3 F(t-1)^2 + a_4 F(t-1) + a_5) \cdot (1 + U_k^M), & t_{drogue} > 0 \end{cases} \quad (17)$$

The nominal stiffness was defined using the experimentally-derived stiffness coefficient, $k_{experiment}$. This is used as an estimation for the first time step where the lines are active in the flight mechanics simulation. After the first time step, the calculated load from the previous calculation is used as an estimate to circumvent the implicit nature of the problem.

D. Rigid vs Elastic Riser

The baseline simulation assumes the riser is a rigid element that is encapsulated in the parachute rigid body. This is due to the high computational cost of modeling the riser as an elastic element. Adding an elastic riser adds numerical stiffness, requiring a significantly smaller simulation time step. As a sensitivity analysis, the riser was modeled as an elastic element to determine its impact on the resulting elastic loads. For this simulation, the swivel located at the triple bridle confluence point (TBCP) is modeled as a 6-DOF joint (shown in Fig 2). The swivel is then attached to the entry vehicle using the same triple bridles as in the rigid case, and a new tension-only spring-damper connects the swivel to the drogue parachute as seen in Fig 4. In this case, the canopy and suspension lines are treated as a rigid body. The elastic properties of the riser are described in Table 3. Due to the computational cost, the simulation is limited to two seconds after mortar fire.

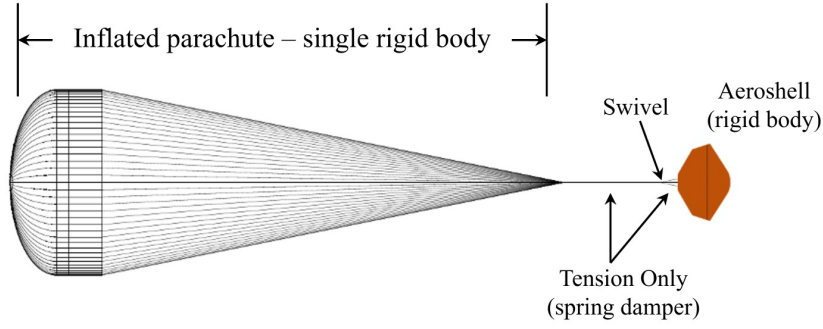


Fig. 4 Multibody model including elastic riser

Table 3 Riser elastic properties

Parameter	Drogue Riser
k_{riser}	$1.0986 \times 10^5 \text{ N/m}$
c_{riser}	$404.12 \text{ N}\cdot\text{s/m}$

VI. Results

A. Rigid Riser

Figures 5 and 6 show the nominal elastic load time history starting at mortar fire. The line stretch and full inflation events are marked with vertical lines. Figure 5 shows the total elastic load with respect to the drogue aerodynamic force. Note behavior and oscillations are a result of elastic bridle modeling and the rigid riser. See Section VI.D for further discussion. The elastic load follows with the aerodynamic forces of the parachute as it inflates and the drop after full inflation. Figure 6 shows the total elastic load, the individual bridle line loads, and the monitor which tracks the max elastic loads. This monitor is used to query the max elastic load across all the Monte Carlo cases. In this particular case the first bridle leg experiences the majority of the load and the other two bridles become engaged after full inflation. Recall from Equation 2 when the forces are 0, it indicates the bridles are slacked. The peak load occurs at full inflation which is similar to behavior seen in reference [13, 14].

B. Monte Carlo Results

The Monte Carlo results for the elastic load methods and the peak opening loads are shown in Figures 7, with the full set of EDL dispersions as outlined in reference [1]. Each Monte Carlo consists of 10,000 cases. The peak opening load, described in Equation 6, is shown in green and was the baseline method to quantify the parachute loads until the implementation of the new metrics and models outlined in this paper.

The elastic bridle models estimate much larger loads, with 95%-tile values nearly 10 kN higher than the peak opening load estimation. The elastic loading is higher than the max opening load because of dynamic overload, where the load seen by the lines are higher than the aerodynamic forces on the parachute. Since the bridles are modeled as a spring-damper system, they are expected to see some overloads higher than one. The offset between the elastic and momentum-based predictions are due to those overloads, with values of up to about 1.5 observed. Since the elastic prediction is more indicative of the load seen by the hardware, this metric has been carried forward for assessing the 32 kN 95%-tile requirement. As seen in Figure 7 and Table 4 all bridle modeling methods estimate the maximum elastic loads at approximately 30 kN. The maximum loads are insensitive to the elastic model. Based on the current data collected from [12] and the simplicity of the model the stiffness dependent damping method will be used moving forward. However, as can be seen the heritage method suffices for assessing the maximum elastic loads.

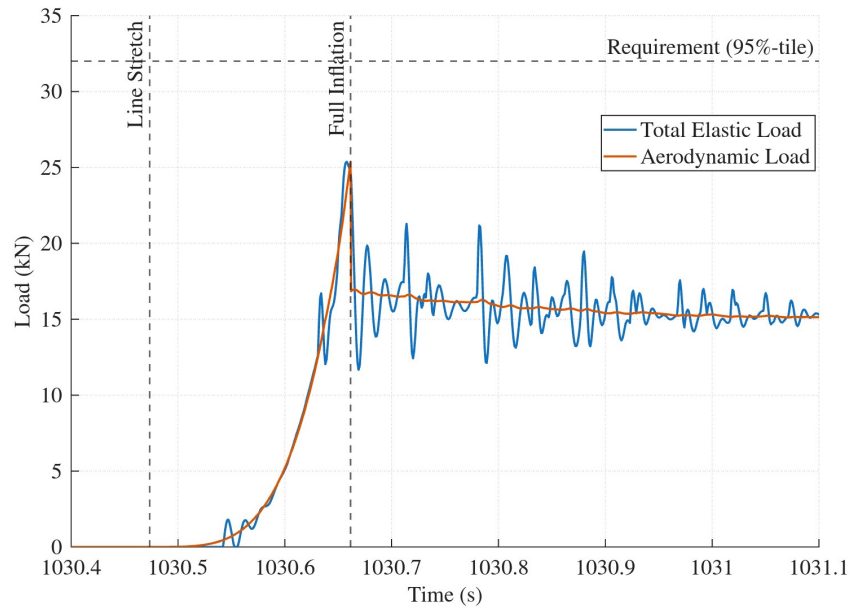


Fig. 5 Time history of nominal total elastic and aerodynamic load from mortar fire

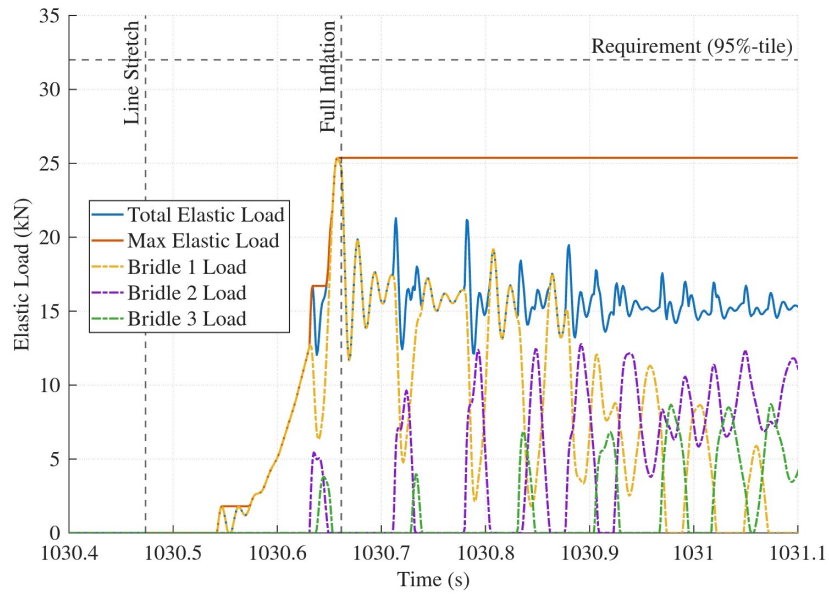


Fig. 6 Time history of nominal total elastic and individual bridle line loads from mortar fire

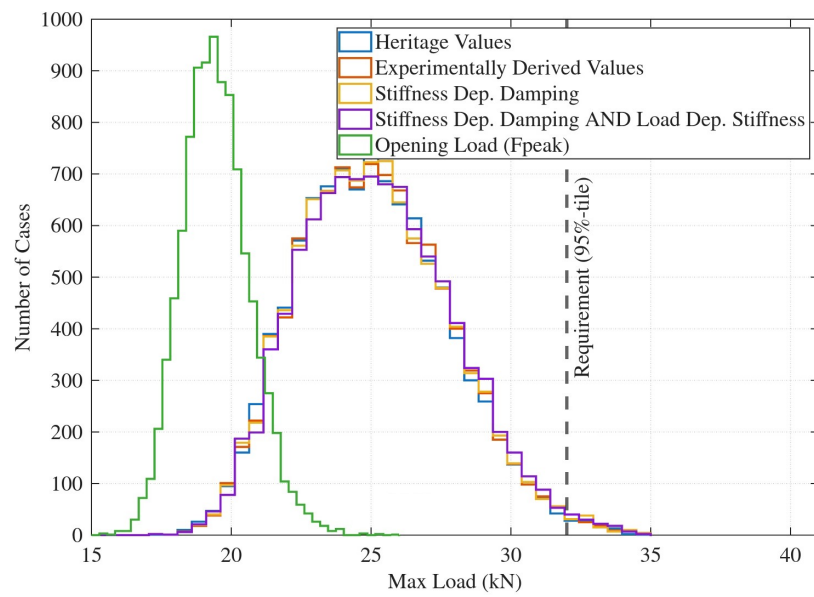


Fig. 7 Monte Carlo results of the total elastic loads using various methods in comparison to the peak opening load method

Table 4 Load Requirement Compliance

Case Name	95%-tile Load (kN)
Opening Load (Fpeak)	21.57
Heritage Values	29.75
Experimentally Derived Values	29.8
Stiffness Dependent Damping	29.83
Load Dependent Stiffness and Stiffness Dependent Damping	30

C. Correlation Analysis

A correlation analysis was completed to understand the major drivers on the elastic loads. This was done by calculating the Pearson Correlation Coefficient, which defines the ratio of the covariance of model inputs and outputs normalized by the standard deviation of both as shown in Eqn 18 [15]. This method highlights strong linear relationships and does not account for non-linear correlations. By sorting the coefficients from highest to lowest, the drivers of the models can be categorized as seen in Table 5. The three key drivers were the inflation dispersion that defines the rate of inflation, the momentum peak opening load factor, and the supersonic axial aerodynamic coefficient of the entry vehicle. Notably, the first line property on the list is the bridle damping ratio, ζ , dispersion at about an order of magnitude lower than the K_P . This shows the inflation model and drogue deployment conditions drive the elastic loads more so than the stiffness and damping properties of the bridles.

$$P(X, Y) = \frac{cov(X, Y)}{\sigma_X \sigma_Y} \quad (18)$$

Table 5 Elastic Load Correlations

Parameter	Correlation Coefficient
MEF	0.72336
K_P	0.37578
Entry Vehicle Supersonic C_A Multiplier	-0.29649
[...]	[...]
ζ_{Disp}	-0.04

Figure 8 shows the scatter plot of the MEF dispersion from -1 to 1 in the x-axis, the momentum peak opening load dispersion on the y-axis, and the elastic load from line stretch to full inflation in the z-axis. The high elastic loads are driven by a high inflation dispersion with a high momentum peak open load factor. This result was used to inform the stress case to evaluate for the elastic riser analysis.

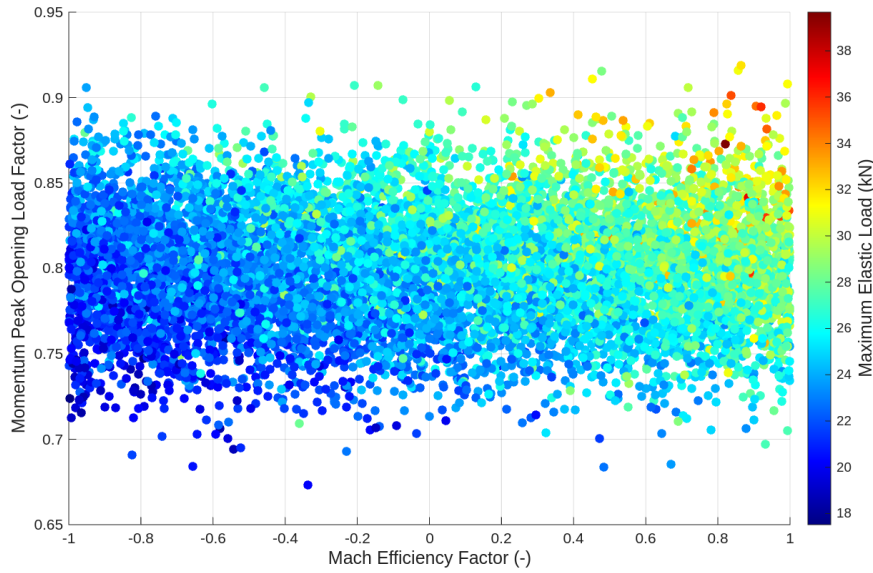
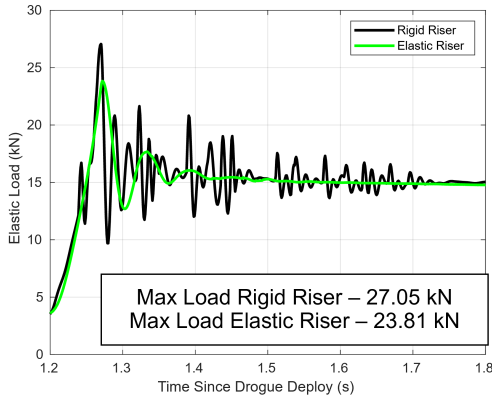


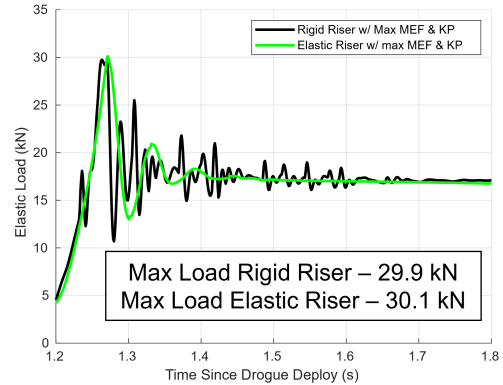
Fig. 8 Elastic Loads Correlation

D. Elastic Riser Analysis

It is typical for multi-body parachute simulations to model the riser as a rigid element. This analysis was done to confirm if there are any dynamics that are not predicted conservatively in the rigid riser case. The elastic riser was evaluated using nominal elastic properties and a dispersed stress case with the maximum MEF and K_P . Figure 9 shows the comparison of the elastic load for the rigid riser and elastic riser cases using the heritage values for the line properties, with Figure 9b showing results for stress case comparison.



(a) Heritage Values

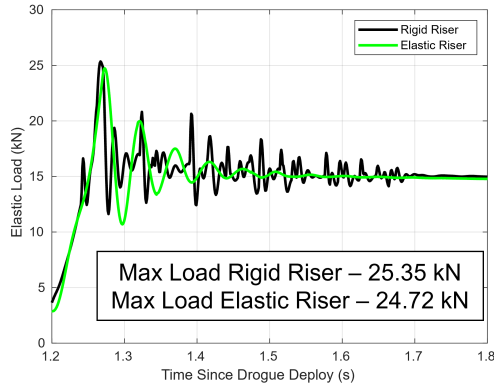


(b) Heritage Values w/ Max MEF and K_P Dispersions

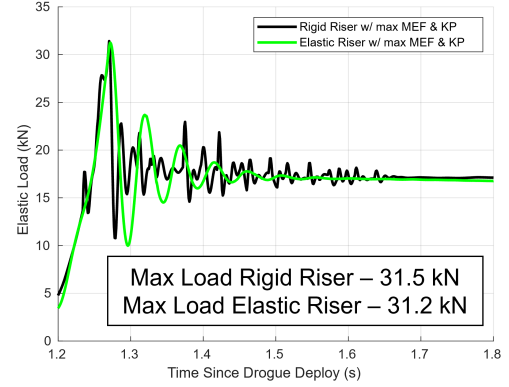
Fig. 9 Elastic Riser Using Heritage Values

As part of the test campaign [12], flight-like riser properties were also obtained and implemented in the same way as the heritage properties, with results for the cases with experimentally derived values shown in Figure 10.

These four cases show that the elastic riser estimated maximum elastic loads are in-family with the rigid riser scenarios while acting as a damper on the high frequency behavior of the system. Both rigid and elastic riser cases reach approximately the same steady state solution. The increase in fidelity with the inclusion of the elastic riser is not seen to be of substantial benefit when factoring in the increase in complexity and run-time of the simulation. As such, the rigid riser assumption is sufficient for assessing the elastic loads.



(a) Experimentally Derived Values



(b) Experimentally Derived Values w/ Max MEF and K_P Dispersions

Fig. 10 Elastic Riser Using Experimentally Derived Values

E. Drogue Release Sensitivity

As noted from the correlation, a key driver for the opening loads is the dynamic conditions under which the drogue parachute is deployed. As discussed in Section III.D and IV.A, the design space is constrained to how early or late the drogue can be deployed. Table 6 shows the sensitivity of the total angle of attack and peak elastic loads with respect to the deploy condition. As discussed, the drogue is released on a sensed acceleration condition tuned to meet a Mach condition. A higher Mach number corresponds to deploying the drogue at a higher altitude or earlier time. Figure 11 shows the 99 %-tile total angle of attack and 95 %-tile peak elastic load with their corresponding requirement. Note the x-axis is reversed where Mach decreases from left to right. The total angle of attack increases the later the drogue is deployed due to the increasing dynamics of the entry vehicle and the performance of the drogue trigger algorithm. There is a non-linear behavior observed at Mach 1.47 with a higher total angle of attack due to the drogue trigger algorithm performance. Inversely, the peak elastic loads decrease as the drogue deploy is delayed. There is a range between the 1.51 - 1.58 Mach deploy conditions in which both the total angle of attack and the peak elastic load requirements can be met. Therefore, the risks on drogue opening loads can be mitigated by tuning the deployment trigger.

Table 6 Parachute deployment performance metrics

G-Trigger Value, Earth-g	99%-tile Mach @ Trigger, -	99%-tile Total AoA @ Deploy, deg	95%-tile Peak Elastic Load, kN
0.31	1.37	17.27	24.20
0.33	1.43	15.63	25.93
0.35	1.47	15.74	27.50
0.37	1.51	14.13	29.05
0.39	1.55	13.13	30.58
0.41	1.59	12.21	32.02

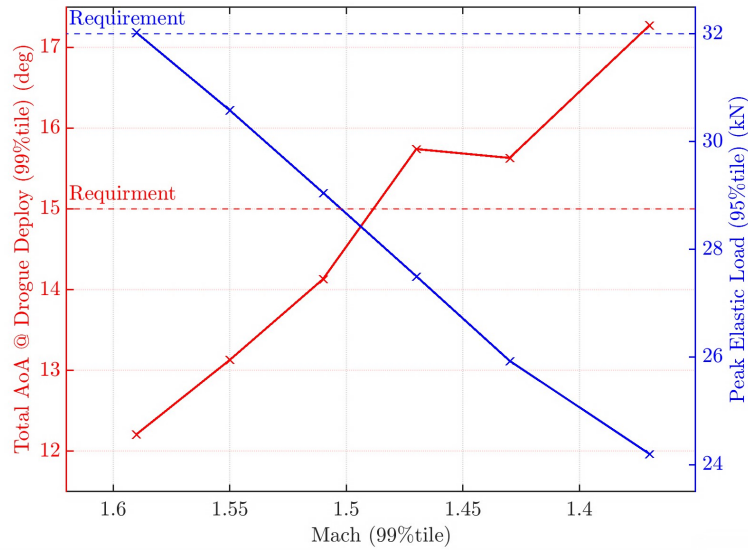


Fig. 11 Deployment condition sensitivity

VII. Conclusion

The EDL phase of the Dragonfly mission is highly dependent on the parachute system. As such, a critical event is the deployment of the drogue parachute. The drogue parachute is designed to withstand the opening loads at low-supersonic and transonic conditions. As part of the design process, the opening loads were modeled and simulated in POST2 using heritage and new methods to assess the risk of hardware failure. Evaluating the elastic loads of the bridles captures the effect of the dynamic overloads that the bridles undergo due to the aerodynamic forces from the parachute. This yields a higher load than estimated by the opening load momentum-based indicator methods used in previous flight missions and provides a more conservative risk assessment for parachute hardware failures. Various methods of modeling the bridles were evaluated, including using elastic properties derived from Dragonfly-specific hardware, and no sensitivity was found with respect to the maximum elastic loads. Assuming the elastic properties are representative of the flight hardware, heritage methods can be used to model the bridles. Modeling the riser as an elastic element produces different transient behaviors, but the maximum elastic loads and the steady-state solution are approximately the same as when modeling the riser as a rigid element. Therefore, the assumption to model the riser as a rigid element is appropriate for evaluating the elastic loads. A sensitivity analysis showed that the elastic loads are driven by the deployment conditions and the inflation model. The risk of high elastic loads can be mitigated by tuning the drogue deployment within the mission constraints.

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