

Characterization of Bridle and Riser Elastic Properties of the Dragonfly Parachute Decelerator Subsystem through Full-Scale Testing

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The Dragonfly team conducted testing of the flight-like drogue parachute bridle and riser to characterize the elastic properties of the elements. These tests provide the highest-fidelity elastic data used to-date to inform planetary parachute properties. An overview of heritage elastic modeling approaches are discussed. A test concept, plan, and execution summary for directly measuring the elastic properties of full-scale, flight-like specimens is presented. Findings include a non-linear, load-dependent stiffness and dynamic damping properties derived from transverse and axial pluck test techniques. Recommendations for implementing and verifying these test results into the modeling workflows for the Dragonfly mission are also discussed.

I. Nomenclature

Symbols

As	=	Area of a spring element
a_n	=	Polynomial coefficients
c	=	Damping coefficient
E	=	Young's modulus
f_d	=	Damped frequency
f_n	=	Natural frequency
F_c	=	Viscous damping force
F_s	=	Spring force
F_{ext}	=	External force
k	=	Spring stiffness
L	=	Length of spring
L_0	=	Nominal length of spring
m	=	Mass of the system
n_{plies}	=	Number of plies
t	=	Time
T	=	Period
U_n^M	=	Multiplier dispersion of quantity n
α, β	=	Arbitrary coefficients
δ	=	Decrement ratio
ϵ	=	Strain
σ	=	Stress
ζ	=	Damping ratio
ω_d	=	Damped oscillation frequency
ω_n	=	Natural oscillation frequency

Acronyms

ASNA	=	Airborne Systems North America
DAC	=	Design Analysis Cycle
DF	=	Dragonfly
DIC	=	Digital Imaging Correlation
LandIR	=	Landing and Impact Research Facility
LaRC	=	Langley Research Center
MSL	=	Mars Science Laboratory
M2020	=	Mars 2020
ODE	=	Ordinary Differential Equation
PDS	=	Parachute Decelerator Subsystem
SEBM	=	Simplified Elastic Bridle Model
TMT	=	Tension Member Technology

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II. Introduction

The Dragonfly entry, descent, and landing (EDL) sequence is unique due to its two-hour duration [1], which is considerably longer than the seven minutes of a typical Mars entry trajectory. After hypersonic and supersonic entry, the Genesis-derived aeroshell will use a mortar to deploy an 8.25 m diameter disk-gap-band (DGB) drogue parachute at a nominal condition of Mach 1.5 roughly 150 km about the surface of Titan. As the parachute reaches suspension line stretch and begins supersonic inflation, the elastic triple-bridle and riser elements will be subjected to a dynamic loading environment. It is probable that the elastic bridle and riser lines will experience dynamic overloading such that the loads applied to hardware within the Parachute Decelerator System (PDS) may exceed the peak aerodynamic inflation load predicted at drogue parachute full-inflation.

Recent Monte Carlo simulations of the Dragonfly EDL sequence, co-published by Pensado et al. [2] alongside this paper, have predicted elastic loads that could exceed design tolerances and requirements of critical hardware within the PDS system. Prior to this work, the Dragonfly program utilized heritage approaches, developed for use in MSL and M2020, to characterize the elastic properties of elements within the parachute system. These methods produce largely conservative estimations and use minimal dedicated test data of the flight-like elastic elements. Therefore, a test campaign was developed and executed to characterize the elastic properties of flight-like bridle and riser elements at the loading conditions expected during drogue parachute inflation specific to the Dragonfly EDL.

This paper will first introduce the Dragonfly PDS drogue parachute as well as provide a general overview of heritage approaches to modeling elastic elements for planetary parachutes. This paper will then showcase the test plan and execution of tests at the Tension Member Technologies (TMT) facility and an updated physics-based workflow to determine bounds for estimated elastic properties of the bridle and riser. Finally, recommendations to improve the elastic modeling parameter inputs to better inform Monte Carlo simulations of the PDS system will be provided. Additional information regarding simulation of the Dragonfly PDS and subsequent Monte Carlo results incorporating results from this paper can be found in Pensado et al. [2].

III. Analysis Background

A. Dragonfly Drogue Parachute Geometry

The drogue parachute is an 8.25 m diameter DGB parachute as shown in Figure 1, a scaled version of the *Viking* canopy. The parachute is mortar deployed at a nominal Mach number of 1.5 and is used to stabilize and decelerate the aeroshell at supersonic, transonic, and subsonic speeds. After descending for approximately 110 minutes, the drogue parachute serves as a pilot parachute to deploy the main parachute. This occurs nominally at an altitude of 4 km above the Titan surface. More details about the Dragonfly PDS system are discussed in Lowry et al. [3].

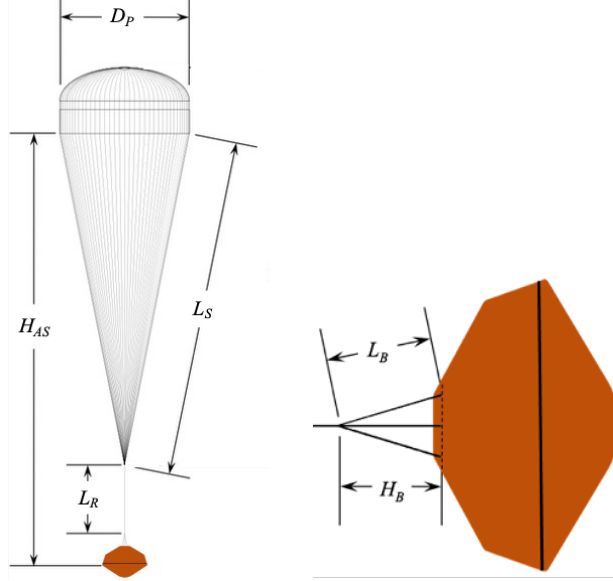


Fig. 1 Labeled schematic of the Dragonfly PDS drogue parachute (left) and close-up of the capsule attachment (right).

The drogue parachute has 32 suspension lines that attach to a single riser. The riser connects to the backshell of the entry vehicle through a swivel and triple bridle assembly. Tabulated geometric parameters are provided in Table 1.

Table 1 Drogue parachute geometric parameters

Feature	Value
Canopy type	Disk-Gap-Band
Geometric porosity (λ_g)	12.5%
Nominal diameter (D_0)	8.25 m $\pm$ 0.05 m (1.0 D_0)
Projected diameter (D_P)	6.06 m (0.734 D_0)
Riser length (L_R)	26.64 m (3.23 D_0)
Suspension lines length (L_S^*)	14.03 m (1.7 D_0)
Number of suspension lines	32
Nondimensional parachute trailing distance (H_{AS}/D_A)	10
Bridle length (L_B)	3.06 m
Bridle height (H_B)	3.04 m
Aeroshell diameter (D_A)	4.5 m

The main elastic elements discussed in this document are the bridle elements and riser. The bridle is made of two-ply of two-turn (four-ply total) 7250-lbf Kevlar material with a nominal length of 3.063 m. The riser consists of eight parallel plies of 3800-lbf Kevlar with a nominal length of 26.640 m.

B. Dynamic Overloads

Current Monte Carlo simulations of the Dragonfly EDL sequence predicts the loads on triple bridle legs to be higher than the applied aerodynamic loads. These elastic phenomena are referred to as overloads, but since they occur during highly dynamic events, mostly during drogue parachute inflation and the subsequent transient, they are more commonly called dynamic overloads. The Dragonfly mission uses the peak inflation load as a stressing design load case for PDS hardware and requires that all components shall survive this load, with margin. However, the peak inflation load is derived from the maximum aerodynamic and inertial loads at full-inflation and does not account for dynamic

overloading induced by elastic elements. Therefore, it is possible that dynamic overloads exceed PDS load requirements.

C. Heritage Elastic Properties Modeling (Planetary Parachutes)

Past planetary parachute missions have modeled the triple bridle legs as linear, massless, spring-dampers [4]. For simplicity, past missions such as MSL and M2020 only modeled the triple bridle geometries as elastic, assuming that the riser, suspension lines, and canopy act as a singular rigid body. In this modeling approach, the elastic system is accelerated by external forces countered only by a spring force, F_s , and viscous damping force, F_c .

1. Spring Force Formulation

The spring stiffness, k , of an elastic element can be derived using Hooke's law, which relates the spring force on a linear, undamped system as shown in Equation 1.

$$F_s = k\Delta L \quad (1)$$

The formal derivation of Hooke's law states a linear relationship between stress, σ , and strain, ϵ , such that Equation 2 holds true.

$$\sigma = E\epsilon \quad (2)$$

The stress on a spring element can also be defined as spring force divided by area of the spring as shown in Equation 3. Therefore, the value of Young's modulus can be determined by the force acting over an area and the resulting strain of a specimen as formulated in Equation 4. The stiffness of a material can then be characterized using area, Young's modulus, and the nominal material length in the form of Equation 5.

$$\sigma = \frac{F_s}{A_s} \quad (3)$$

$$E = \frac{\sigma}{\epsilon} = \frac{F_s}{A_s\epsilon} \quad (4)$$

$$k = \frac{A_s E}{L_0} \quad (5)$$

The more common formulation of stiffness is derived as Equation 6 by substituting Equation 4 into Equation 5 to define the stiffness of an element using applied force, resultant strain, and the nominal length; all quantities that can be directly measured experimentally.

$$k = \frac{F_s}{\epsilon L_0} \quad (6)$$

The key assumption in the formulation of stiffness in Equation 6 is that the specimen exhibits purely linear elasticity (Hooke's law). This is often not sufficient to describe the behavior of elastic cordage such as that used in the Dragonfly PDS. If the linear assumption is relaxed, then the generalized definition of stiffness is as shown in Equation 7 such that stiffness is the length-normalized partial change of force per partial change in strain elongation. For ease of experimental determination, stiffness can be approximated as Equation 8: the length-normalized change in force for a given change in elongation. This approximate form can further be expanded to Equation 9 to enable a finite-difference approximation of stiffness in a point-wise manner, enabling non-linear values of stiffness.

$$k = \frac{\partial F_s}{\partial \epsilon} \frac{1}{L_0} \quad (7)$$

$$k \approx \frac{\Delta F_s}{\Delta \epsilon} \frac{1}{L_0} \quad (8)$$

$$k \approx \frac{F_2 - F_1}{\epsilon_2 - \epsilon_1} \frac{1}{L_0} \quad (9)$$

Note, the linear approximation of stiffness in Equation 6 is recovered in Equation 9 when assuming zero force at zero strain, (i.e., $F_1 = 0$ when $\epsilon_1 = 0$).

2. Damping Force Formulation

The damping force of the elastic system is modeled as a viscous force such that it scales with the velocity of the element. A damping coefficient, c , is introduced such that viscous damping force, F_c , is modeled by Equation 10.

$$F_c = c\dot{L} \quad (10)$$

3. Damping Ratio and Natural Frequency

For common elastic and vibrational applications, the 2nd-order ODE describing the equations of motion is formulated in Equation 11 to include the effects of stiffness and damping [5].

$$m\ddot{x} + c\dot{x} + kx = F_{\text{ext}} \quad (11)$$

The fundamental quantities of damping ratio, ζ , and system natural frequency, ω_n , are respectively defined by Equations 12 and 13. Note the damping ratio is defined as the ratio of damping coefficient to critical damping of the system, $c_c = 2\sqrt{km}$.

$$\zeta = \frac{c}{2m\omega_n} \quad (12)$$

$$\omega_n = \sqrt{\frac{k}{m}} \quad (13)$$

4. The Rayleigh Damping Assumption

Parachute modeling for MSL [4] and M2020 elected to treat the elastic elements as massless-spring-dampers, thus invalidating the functional form of damping coefficient shown in Equation 12. To accommodate a massless system, the heritage models use Rayleigh damping [6] with general form shown in Equation 14. A Rayleigh damper models viscous damping with a linear combination of mass and stiffness proportionality.

$$c = \alpha k + \beta m \quad (14)$$

While the formulation of damping coefficient in Equation 12 becomes infinite for a massless system, the Rayleigh damping model of Equation 14 remains defined for a massless elastic element and simplifies to stiffness-proportional damping shown in Equation 15.

$$c = \alpha k \quad (15)$$

The physical value of coefficient α can be solved for by combining Equation 15 with the definition of damping ratio, Equation 12, such that Equation 15 becomes:

$$\alpha = \frac{2\zeta}{\omega_n} = \frac{\zeta}{\pi f_n} \quad (16)$$

D. Heritage Elastic Model Parameter Estimation

Historically, only the triple bridle has been modeled as elastic elements with all upstream components such as the riser and suspension lines modeled as a single rigid body [4]. It is important to document the sources of heritage spring stiffness and dynamic damping estimations to establish a baseline of best practices that the findings in this work seeks to improve upon.

1. Bridle Spring Stiffness Estimation

The spring stiffness was previously extracted from data documented in seam and joint test reports with no dedicated tests performed to specifically assess the . Numerous specimen were pulled to failure to assess the strength and the average breaking force was used in Equation 6 to estimate spring stiffness.

2. Bridle Dynamic Damping Estimation

The dynamic damping terms were determined using the Rayleigh damping formulation with stiffness-dependence as defined. MSL/M2020 parachute models used the damping coefficient in the form of Equation 15. The damping ratio and natural frequency were not measured by test. The damping ratio of 0.01 was chosen as a conservative estimate as it is more in-family with damping characteristics of rigid, inelastic elements. The natural frequency was used to apply a filtering operation on the EDL simulation of MSL and M2020. A natural frequency of 5 Hz mitigated high-frequency, non-physical simulation dynamics.

IV. Test Execution

A. Test Objectives

The objective of the test campaign was to characterize the stiffness and viscous damping properties of the drogue parachute triple bridle and riser at conditions relevant to drogue parachute inflation at Titan. Specifically, the goal of the test was to provide insight into the static and dynamic behavior (i.e., load-displacement, cyclic conditioning, dynamic response, etc.) of the bridle and riser of the drogue parachute.

A general outline of test activities conducted to achieve the test objectives is shown in Table 2. Details of the relevant test setups are provided later in this section.

Table 2 Test Campaign Outline

Test Program	Activity	Objective
Pathfinder (NASA LaRC)	Static cycling	Kevlar Material Stiffness
Pathfinder (NASA LaRC)	Transverse pluck	Kevlar Material Damping
Pathfinder (NASA LaRC)	Pull-to-failure	Kevlar Material Strength
Full-Scale, Flight-Like (TMT)	Static cycling	Bridle & Riser Stiffness
Full-Scale, Flight-Like (TMT)	Transverse pluck	Bridle & Riser Damping
Full-Scale, Flight-Like (TMT)	Axial pluck	Supplemental Added Scope

The tests used for informing modeling parameters were the static cycling and transverse pluck of the full-scale, flight-like bridle and riser. The Pathfinder tests utilized single-ply strands of the Kevlar material as a low-cost exploratory program to refine the procedures and test points selected for the full-scale, flight-like testing. Additionally, the axial pluck testing was done as a feasibility demonstration and was exclusively used for gathering data trends. The analysis of the large dataset generated by the axial pluck testing will remain future work, pending a mission justification to pursue it.

B. Facility

Tests were performed at Tension Member Technologies Laboratories located in Huntington Beach, California. TMT Laboratories describes itself as a large-scale mechanical test facility with a 24,000-square-foot laboratory that houses several large test machines with load frames, cylinders, and load cells that range in capacity from a few pounds to several million. Unlike traditional tensile test stands, these machines and their auxiliary equipment can be configured in various combinations to simulate a wide variety of mechanical service situations. TMT also keeps a large suite of electrical and optical test equipment in-house that can be used to monitor various test parameters during mechanical or stand-alone tests [7].



Fig. 2 Large tensile test stand for testing of full-scale elastic elements at Tension Member Technologies (TMT) Laboratories in Huntington Beach, CA. Hydraulic driver with 40-kip load cell (left) and full 110-ft test segment available for use (right).

Due to the large size of the full-scale specimens (3.063 m bridle and 26.640 m riser), traditional laboratory tensile test stands could not accommodate this test program. A gantry would have been required to support vertical tensile testing. The modularity of the TMT horizontal test setup enabled tensile and dynamic testing of the elastic elements with the known tradeoff being small gravitational forces. However, the gravitational forces acting on the test specimens would be on the order of tens of Newtons, which were deemed insignificant compared to the operational test loads of tens of kilo-Newtons applied during the test campaign.

C. Test Specimen

A flight-like bridle and riser were manufactured by Airborne Systems (ASNA) to support testing. The bridle has a nominal length $L_{BL} = 3.063$ m and the riser has a length of $L_R = 26.640$ m. The triple bridle is made of four-pplies of 7250-lbf Kevlar strands while the riser is made of eight parallel plies of 3800-lbf Kevlar strands. More details regarding the design of the confluence junctions is described in Lowry et al. [3]. Figure 3 shows the as-tested specimens.

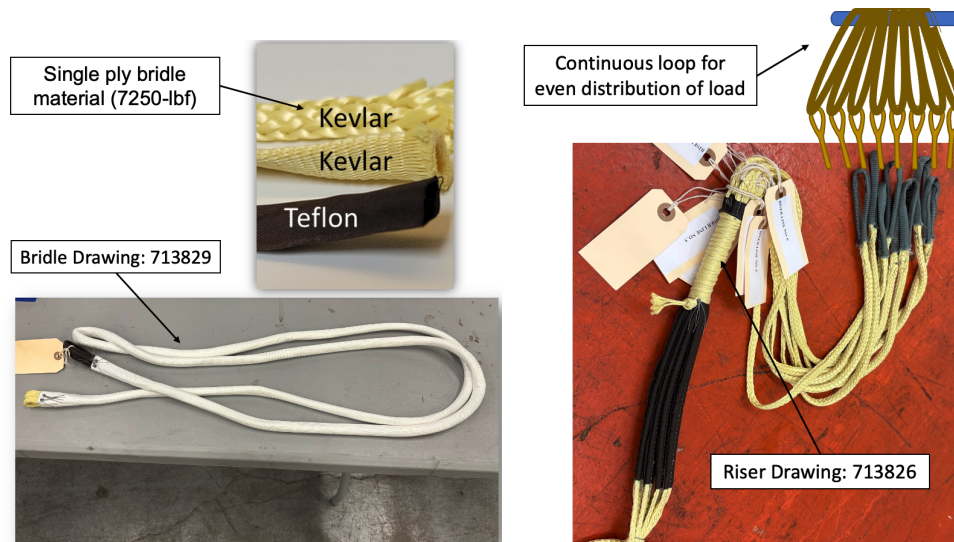


Fig. 3 Flight-like bridle (left) and riser (right) used for the full-scale, flight like test campaign.

Since the bridle is connected by single loop ends on either side, it was expected that load sharing across the equivalent four-pplies would be near equal when attached to pin grips. However, the same would not be true for the eight loop ends

of the riser specimen since even a 0.1% difference in overall length would result in over 2.5 cm of length difference. Therefore, a continuous loop end was developed, schematized on the right of Figure 3 and shown as-tested in Figure 4.

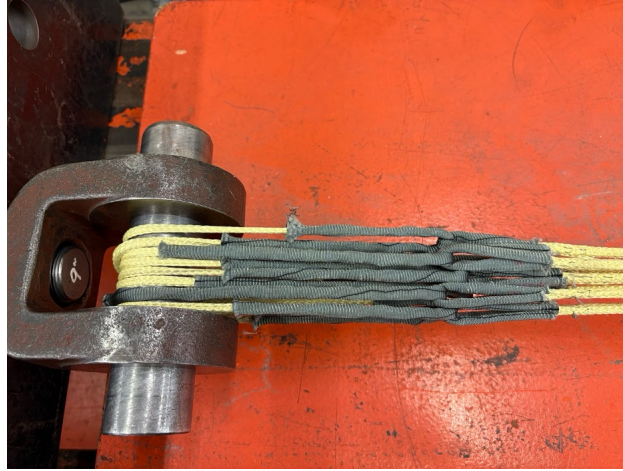


Fig. 4 Continuous loop end strung through the eight loop ends of the flight-like riser and pin grip to provide equal load sharing across the eight strands.

The continuous loop end is a simple replacement for a traditional whippletree setup. This continuous loop end was made from a single strand of riser material looping through each of the eight ends of the riser and the pin grip to ensure equal load sharing across the plies. Since the continuous loop had an effective eight-ply of riser material, it did not introduce new material properties to the system. The continuous loop added approximately an additional 6-inches of overall length to the full-scale riser, which corresponds to a 0.60% increase in overall length.

D. Test Matrix and Setups

Two main test setups were used to support elastic element testing at TMT: static testing and transverse pluck testing. The full test matrix is provided in Table 3 at the end of this section. The following are descriptions of each test type conducted:

1. Flight-Like Static Testing

Static cycle testing was performed on the flight-like bridle and riser. The general con-ops is provided in Figure 5 where the specimen is attached to a dead end and pulled by a hydraulic system at a prescribed cyclic load.

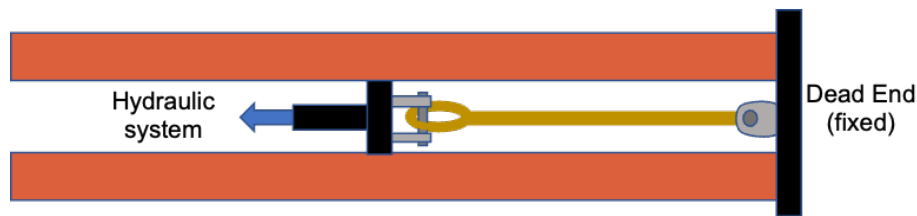


Fig. 5 Static cycle testing setup.

The hydraulic actuator cycles 20 times per load condition using a sinusoidal load-control that averages approximately 3 kN/s. The 20 cycles were selected based on findings from the Pathfinder test series which showed the Kevlar material is fully preconditioned after the initial 10 cycles. This led to at least 10 cycles of post-conditioning elastic characterization data for extracting stiffness information of the specimen.

Figures 6 and 7 show test-day images of the static cycle setup for both the flight-like bridle and riser respectively. For each test, the hydraulic actuator position remained fixed and the dead end was moved along the length of the fixture to accommodate the specimen length. Small metal and wood supports were used to null the gravitational loads acting on

the specimens when under low loads. Heights of the supports were chosen such that even at 1% target load application, the specimens were pulled taught such that there was no residual contact with the supports.



Fig. 6 Flight-like bridle mounted to the test stand for static cycle testing. Full test setup (left) with close-ups of the dead end side pin attachment (top right) and the hydraulic side pin attachment (bottom right).



Fig. 7 Flight-like riser mounted to the test stand for static cycle testing. Full test setup (bottom) with close-ups of the dead end side continuous loop attachment (top left) and the hydraulic side pin attachment (top right).

2. *Flight-Like Transverse Pluck Testing*

Transverse pluck testing was performed on the flight-like bridle and riser per the test matrix in Table 3. For each specimen, the transverse pluck testing occurred directly after static cycle testing such that the static cycling served as a preconditioning operation prior to dynamic testing. The schematic for the transverse pluck operations is shown in Figure 8. The specimen is pulled using the hydraulic arm to the desired axial pre-load. Then, the system is plucked transversely like a guitar string.

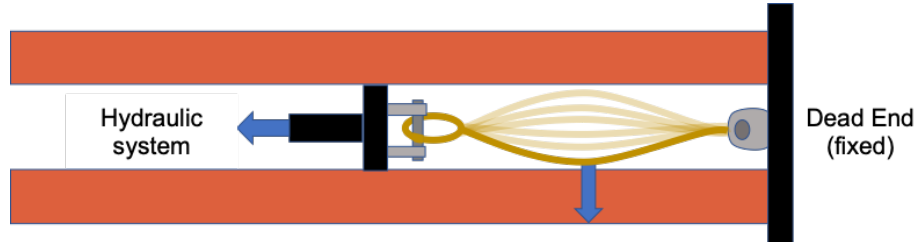


Fig. 8 Transverse pluck testing setup.

A manual gantry crane with a quick release hook was attached to the center of each specimen to create the desired transverse displacement for each test point as shown in Figure 9. The initial transverse displacement specified in Table 3 is set by the test operator. Then the quick release hook is actuated to initiate the transverse pluck operation.



Fig. 9 Flight-like riser mounted to the horizontal test stand. The gantry crane with quick release hook is attached at the center of the specimen.

Table 3 Full-Scale, Flight-Like As-Tested Matrix

Test Article	Test Type	Load (kN)	# Cycles / Tests	Configuration Notes
Bridle	Static	32	20	Sinusoidal force control ~3 kN/s
		40	20	Sinusoidal force control ~3 kN/s
		24	20	Sinusoidal force control ~3 kN/s
	Transverse Pluck	32	3	[3", 2", 1"] initial condition
		24	3	[3", 2", 1"] initial condition
		16	3	[3", 2", 1"] initial condition
Riser	Static	32	20	Sinusoidal force control ~3 kN/s
		40	20	Sinusoidal force control ~3 kN/s
		24	20	Sinusoidal force control ~3 kN/s
	Transverse Pluck	32	3	[12", 18", 36"] initial condition
		24	3	[12", 18", 36"] initial condition
		16	3	[12", 18", 36"] initial condition

V. Data Products

To keep the test campaign simple, a minimal instrumentation package was put together to acquire the necessary data products to characterize the stiffness and dynamic damping of the full-scale, flight-like bridle and riser. Table 4 specifies the data recording rates for both the static and pluck test series.

Table 4 Data Sources for static and dynamic testing

Static Testing	Rate
10-kip load cell	10 Hz
Stringpot	10 Hz
Pluck Testing	Rate
10-kip load cell	1 kHz

For static cycle testing a 10 Hz data acquisition rate was more than sufficient given the intentionally slow (quasi-static) cycling of the material. A load cell measured force applied by the hydraulic actuator, and a stringpot measured the specimen displacement. The initial pin-to-pin length for static cycle testing was measured and recorded.

The pluck testing only required load versus time data. Since the specimen would be displaced out of plane of the stringpot, there was no justifiable rationale to develop a reliable method of mounting the strain pot during the pluck testing. To ensure high-frequency dynamics were captured during the pluck testing series, the data acquisition rate was increased to 1 kHz.

A. Static Cycle Testing

Static cycle testing was performed on both the flight-like bridle and riser, per the test matrix in Table 3. An example of the load as a function of time and strain (normalized stringpot displacement) is shown in Figure 10.

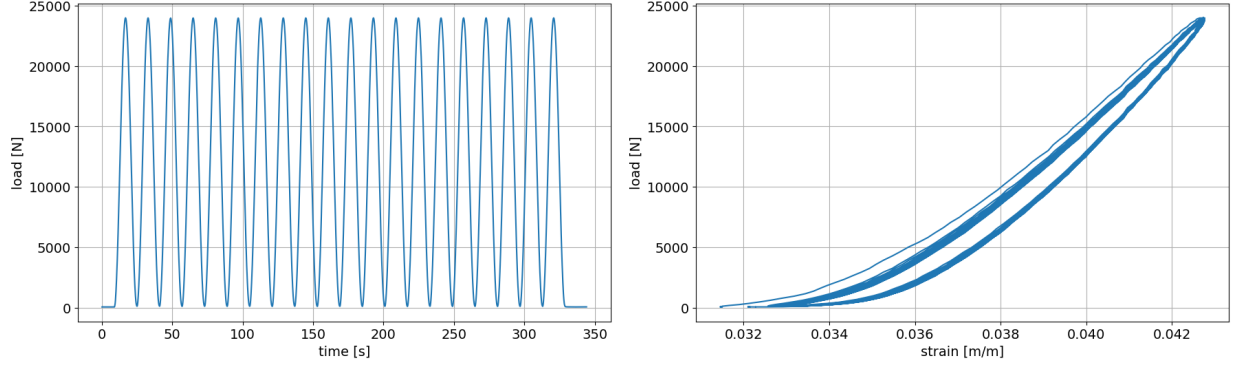


Fig. 10 Full-scale, flight-like bridle specimen cycle testing data at 24 kN with applied load versus time (left) and versus strain (right).

The load condition of most interest to the Dragonfly program is the 32 kN setpoint. The PDS hardware and entire EDL assembly both carry requirements that the loads experienced by the system at drogue parachute deployment shall not exceed 32 kN. Since the PDS system will be packed and stowed for over seven years during Dragonfly's journey to Titan, the conditioning data, or hysteresis most elastic elements experience when energized for the first few times, was of interest at the 32 kN load. Therefore, the 32 kN test point was scheduled to be the first static cycle condition of each specimen.

B. Transverse Pluck Testing

Transverse pluck testing was performed on both the flight-like bridle and riser per the Table 3 test matrix. Figure 11 shows an example load versus time data-stream for the bridle (left) and riser (right) specimens. The signal begins after the release hook is mechanized. Both the bridle and riser exhibit exponentially decaying oscillations from the load induced by the initial transverse displacement back to the test point pre-load, which was 16 kN for both of these cases.

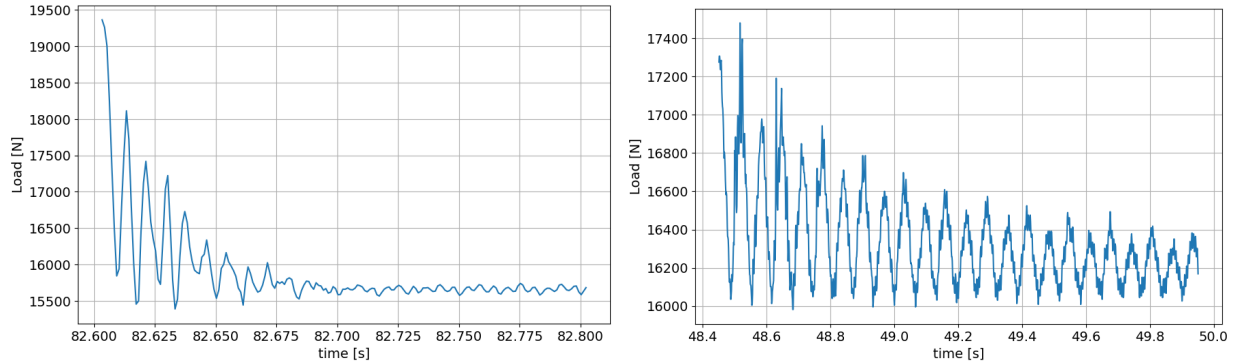


Fig. 11 Transverse pluck load versus time data for the bridle (left) and riser (right) specimens at a pre-load of 16 kN.

Due to the high stiffness and short length of the bridle compared to the riser, the signal to noise ratio in the bridle transverse pluck tests is significantly lower. Additionally, the number of cycles before returning to the test point pre-load is less than for the riser, indicating higher damping characteristics.

VI. Results

The full-scale, flight-like test campaign occurred over one and a half test days in October of 2025 at TMT Laboratories [7]. This section highlights the major steps required to extract elastic modeling parameters, namely the spring stiffness, k , the damping ratio, ζ , and the natural frequency, ω_n .

A. Spring Stiffness

The spring stiffness is extracted from the tensile cycle test data. For each specimen at each cycle load test point, only the tensioning measurements are used (i.e. when $dF/dt > 0$). For the 32 kN cycle tests where the first few cycles condition the material, data is truncated to only include post-conditioned tension data. As discussed in Section III.C.1, heritage analysis approaches assumed a linear load-strain relationship. All linear assumptions levied on the behavior of the specimen strain versus applied force are relaxed by solving Equation 9 at each discrete measurement point. For a given load measurement, at discrete point, n , the spring stiffness defined in Equation 9 is evaluated using Equation 17.

$$k(n) = \frac{F_2 - F_1}{(\epsilon_2 - \epsilon_1) \times L_0} = \frac{F(n) - F(n-1)}{(\epsilon(n) - \epsilon(n-1)) \times L_0} \quad (17)$$

The end result is a force-dependent estimation of spring stiffness at each measurement along the tensioning operation of the cycle test such that the non-linear behavior of the elastic element is preserved.

The aggregate point cloud extracted from a set of cycle test data is shown in Figure 12 as a function of applied load and resultant stiffness. Each point in the cloud is colored by the temporal duration of the test to monitor any potential signs of material conditioning in the data. The example point cloud shown in Figure 12 has no discernible temporal trends indicating that the cycles from which the stiffness was extracted from represent a fully conditioned specimen.

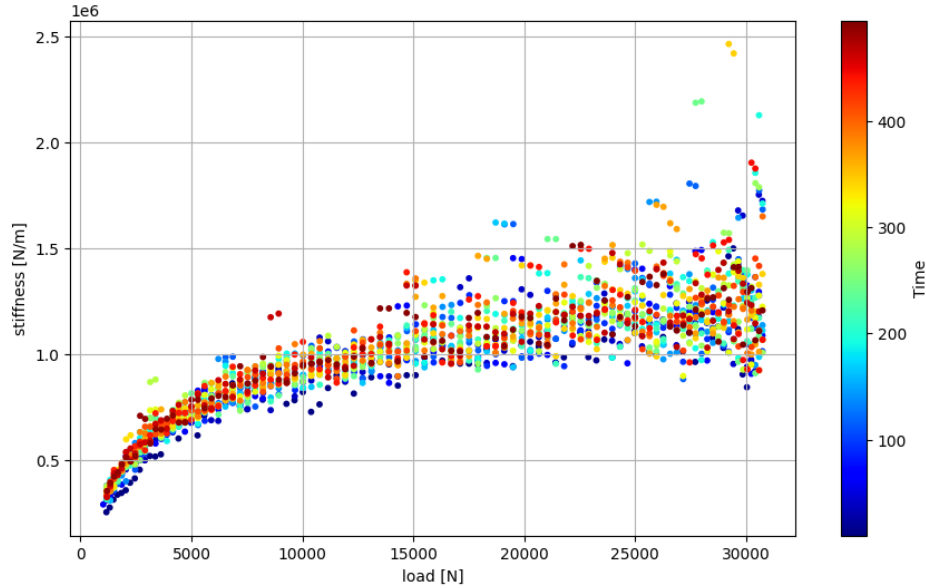


Fig. 12 Point cloud of discrete spring stiffness estimations throughout static cycle testing of the bridle specimen. Points are colored by time of measurement.

The three main sources of experimental uncertainty are the precision of the load cell, the calculation of strain from the stringpot, and the extent to which the overall length of the specimen is known. A summary of these uncertainties and their respective rationales is provided in Table 5. The total experimental uncertainty, U_k^{exp} , is defined in Equation 18 as the normalized sum square of experimental sources of error.

Table 5 Considered experimental sources of error for static testing

Source	Symbol	Value	Rationale
Load Cell	U_F^{exp}	22.22 N	Precision of 0.05% of rated load
Calculated Strain	U_ϵ^{exp}	0.01 m/m	Stringpot agreed with DIC within 1%
Specimen Length	$U_{L_0}^{exp}$	1.00%	Manufactured to within 1% of the drawing

$$U_k^{exp} = \sqrt{\left(\frac{U_F^{exp}}{F}\right)^2 + \left(\frac{U_\epsilon^{exp}}{\epsilon}\right)^2 + \left(\frac{U_{L_0}^{exp}}{L_0}\right)^2} \quad (18)$$

The individual data points from the point cloud are organized into bins of 2 kN. The root mean square of experimental uncertainty of each bin is sum squared with the standard deviation of the points within a bin to generate a combined uncertainty representing both the experimental and repeatability uncertainties. The bins from all three of the static cycle tests for a given specimen are combined with respective uncertainties root sum squared. The end result is a non-linear curve of spring stiffness versus applied load with a total uncertainty bound encompassing both experimental uncertainties and repeatability uncertainties. Figure 13 shows this curve for the bridle (top) and riser (bottom).

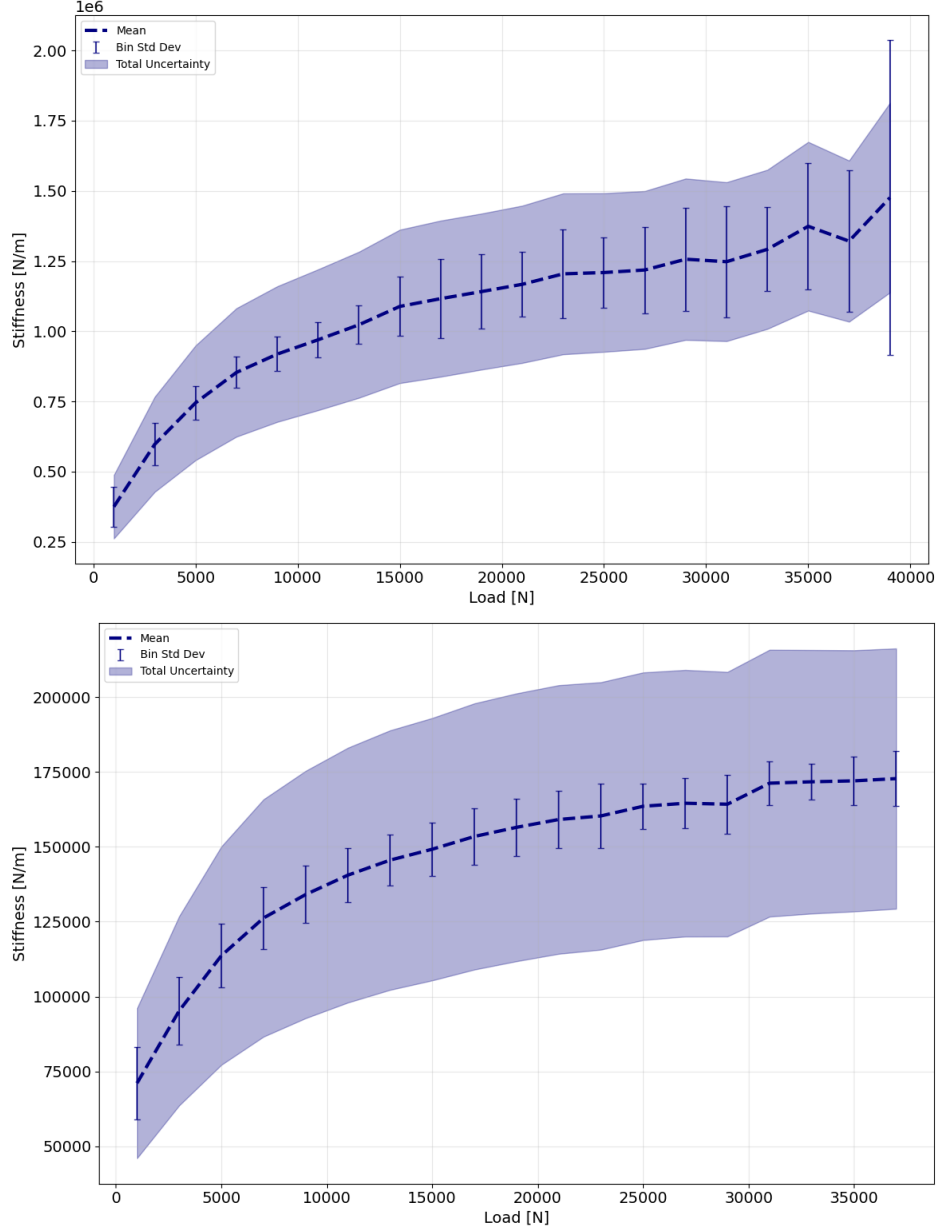


Fig. 13 Binned stiffness measurements of the flight-like bridle (top) and riser (bottom) as a function of load (blue dotted) with total uncertainties (blue band).

B. Dynamic Damping and Natural Frequency

The dynamic damping coefficient is extracted using the transverse pluck data. The extraction of the dynamic damping characteristics of the specimen will be done by utilizing a logarithmic decrement analysis approach. A full detailed accounting for extracting dynamic damping from an experimental signal is summarized in 1981 NASA Contractor Report 3423 “Mechanical Design Handbook for Elastomers” [5]. The formula for the log decrement of a decaying oscillation is shown in Equation 19. It is a measurement of the ratio of amplitudes between any two peaks along an oscillatory signal. The damping ratio can be assessed from a reference peak to n peaks away.

$$\delta = \frac{1}{n} \ln \frac{x(t)}{x(t+nT)} \quad (19)$$

The estimated damping ratio in Equation 19 can then be used to calculate the damping ratio of an elastic element using Equation 20. This damping ratio is the same parameter defined in Equation 12.

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \quad (20)$$

A peak finding algorithm is used on the transverse pluck raw data stream to identify local minima and maxima of the signal. A de-rectifying operation is performed to transform the raw load versus time data into a symmetric decaying oscillation signal to perform logarithmic decay analysis on. The average value of the collection of valleys is used as an axis of revolution applied to only even numbered peaks. The end result is a quasi-symmetric curve of the exponential decay for when the specimen had positive transverse displacement (original peaks) and negative transverse displacement (revolved peaks). This operation effectively projects the transverse pluck load data into an axial pluck to simplify log-decrement analysis.

After the de-rectifying operation is complete, the log-decrement analysis can be performed on the decaying oscillation of the signal using both the peaks and valleys as discrete local maxima. The estimated curve fits of damping ratio from the log-decrement analysis performed across subsequent peaks and valleys of the de-rectified signal is shown in Figure 14.

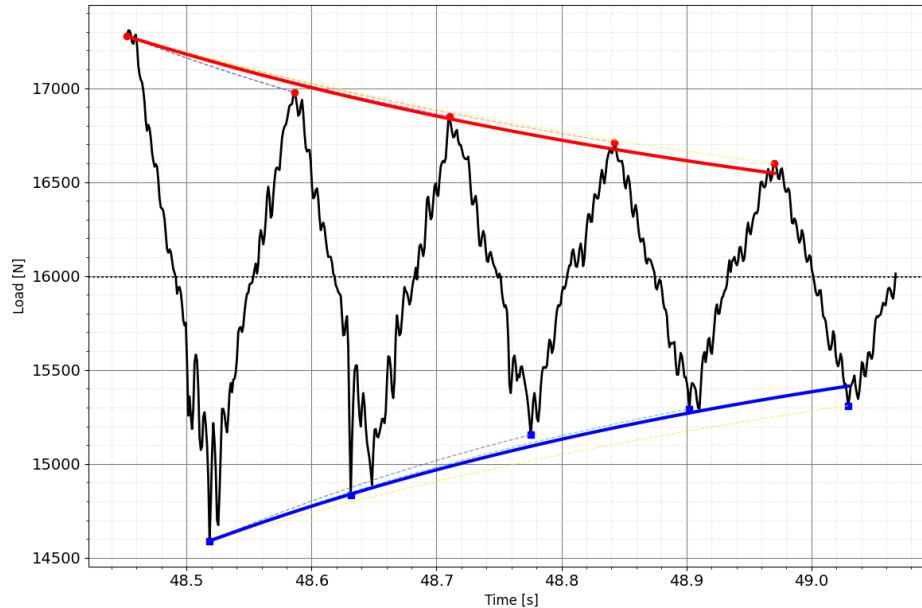


Fig. 14 Log-decrement analysis performed on a de-rectified transverse pluck dataset. Peak-to-peak analysis is performed from the initial peak to subsequent peaks (dashed lines) with the average log-decrement across the first five peaks is shown (solid line).

The data extracted from the raw transverse pluck data using this technique is sufficient for estimating the elastic properties of a specimen, with uncertainties to motivate model parameter inputs. The damping ratio estimates as a function of pre-load applied and initial transverse displacement of the specimen are shown for the flight-like bridle

in Figure 15 and flight-like riser in Figure 16. The red damping ratio values correspond to log-decrement analysis performed on the positive displacement peaks and the blue data points correspond to those extracted from the de-rectified negative displacement peaks.

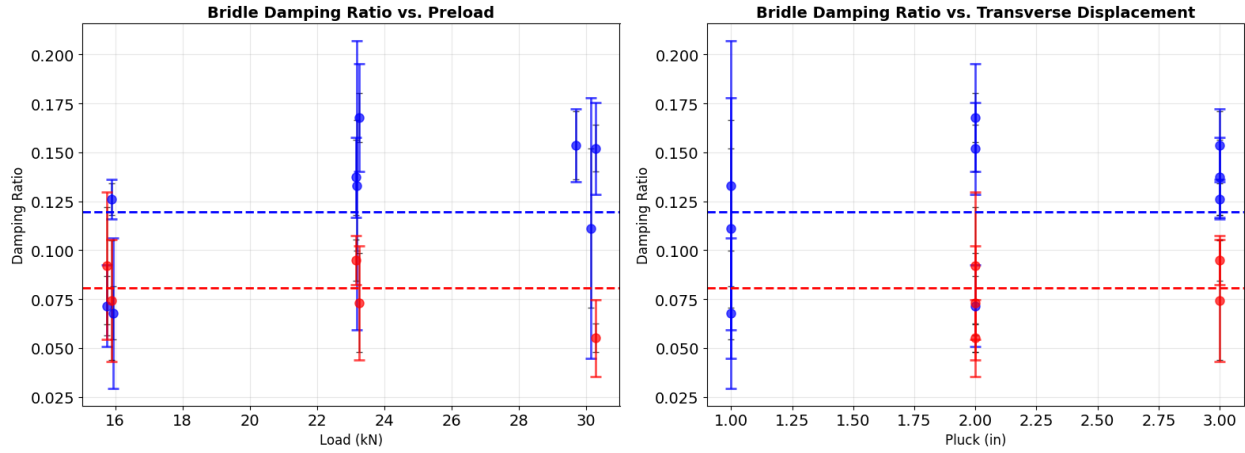


Fig. 15 Assembly of predicted damping ratios and respective uncertainties from transverse pluck testing of the flight-like bridle. Organized by applied pre-load (left) and initial pluck displacement (right).

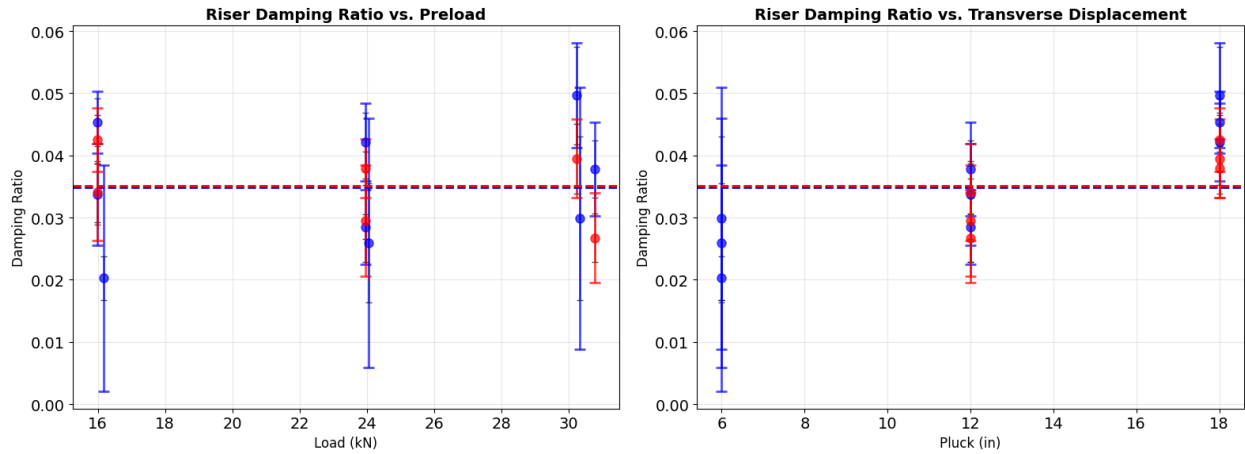


Fig. 16 Assembly of predicted damping ratios and respective uncertainties from transverse pluck testing of the flight-like riser. Organized by applied pre-load (left) and initial pluck displacement (right).

Neither the bridle nor riser specimen exhibited correlation between the observed damping ratio and applied pre-load. The riser specimen did show a linear increase in damping ratio as the initial transverse pluck displacement was increased. This trend was not evident in the bridle specimen damping ratio data. The repeatability of transverse pluck log-decrement analysis on the riser was higher than that of the bridle. Both the shorter length and higher stiffness of the bridle compared to the riser contributed to a more challenging damping ratio extraction process. This resulted in larger uncertainties of the bridle quantities that may have masked a similar correlation between bridle damping ratio and initial transverse displacement.

Figures 17 and 18 show the extracted oscillation period and frequency of the flight-like bridle and riser specimens respectively. The oscillation frequency, which is the inverse of the extracted peak-to-peak period, corresponds to the damped frequency of the system, $f_d = \omega_d / (2\pi)$. The natural frequency of the system is then calculated using the damping ratio and damped frequency.

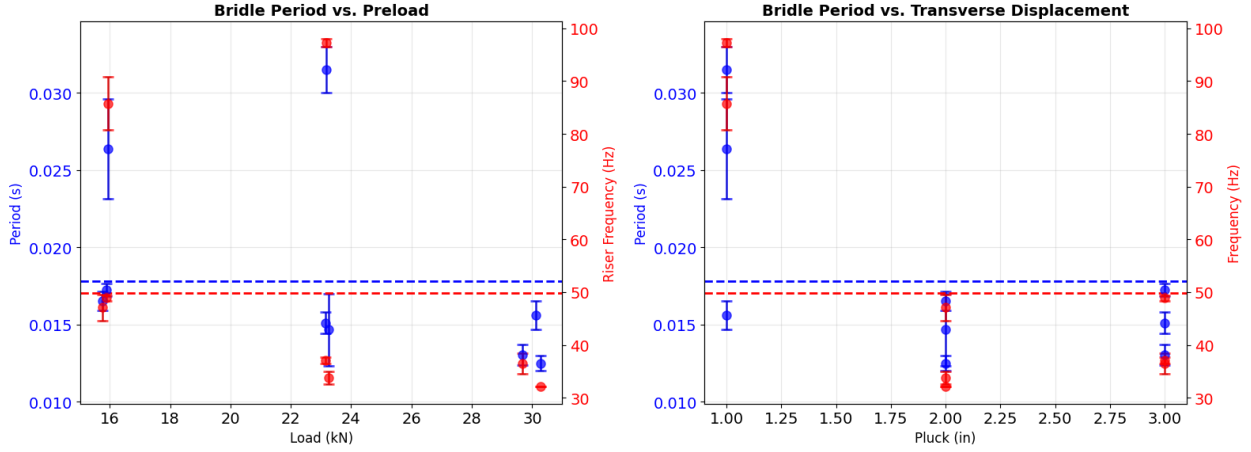


Fig. 17 Assembly of predicted periods and respective uncertainties from transverse pluck testing of the flight-like bridle. Organized by applied pre-load (left) and initial pluck displacement (right).

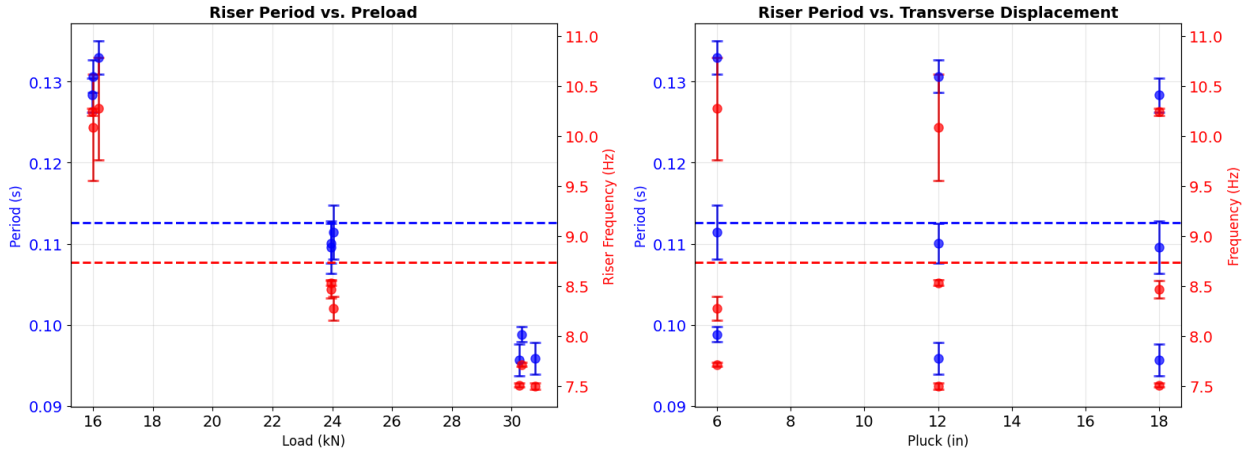


Fig. 18 Assembly of predicted periods and respective uncertainties from transverse pluck testing of the flight-like riser. Organized by applied pre-load (left) and initial pluck displacement (right).

The damped frequency of the riser is nearly an order of magnitude lower frequency than that of the bridle. This is expected given the riser is nearly an order of magnitude longer than the bridle. The riser damped frequency is inversely linearly proportional to the applied pre-load. This trend is less prevalent in the bridle data due to outliers that predict out-of-family damped frequency for the 1-inch initial displacement condition for both the 16 kN and 24 kN pre-loads. Since the number of data points is sparse and a robust outlier rejection process was not developed, these data points were included in the formulation of the bounds of uncertainty for the bridle natural frequency.

It is almost certain that each elastic element has a load-dependent natural frequency, akin to the string of a musical instrument. While it is unclear in the bridle transverse pluck data (17), the load-dependent nature of frequency is evident in the riser data (18). Since the transverse pluck data encompassed most of the distributions of possible opening loads of the drogue parachute, and varies by approximately 10% of the average value, it was decided to simply rollup the load-dependent natural frequency trends into propagated uncertainty instead of developing a load-dependent natural frequency model.

VII. Elastic Modeling Parameter Recommendations

Based on the extracted spring stiffness and dynamic damping quantities of interest from the experiments, formal modeling input recommendations were presented to the Dragonfly program. These recommendations included options

for both load-dependent and load-independent modeling inputs for spring stiffness as well as stiffness-correlated and stiffness-uncorrelated dynamic damping values. Additionally, formal uncertainty bounds on all modeling inputs are recommended to be added as dispersion bounds in the Monte Carlo simulations of the Dragonfly EDL sequence. A full evaluation of the implementation of the final modeling input parameters chosen based on these recommendations is provided in Pensado et al. [2].

A. Spring Stiffness

The static cycle data collected during the full-scale, flight-like bridle and riser specimen tests conducted at TMT show that the spring stiffness of the material depends on the force applied. Therefore, it is recommended that the spring stiffness of the system be modeled as a load-dependent 4th-order polynomial fit of the test data. If a load-dependent model of stiffness is unrealizable for a given simulation tool, or the complexity is deemed not worthwhile, then a semi-conservative load-independent spring stiffness is recommended.

Figure 19 summarizes the recommended spring stiffness modeling inputs for each bridle leg (left) and riser line (right). The baseline spring stiffness value for the bridle legs is included as a black line. The spring stiffness of the riser has no baseline value at the time of these recommendations.

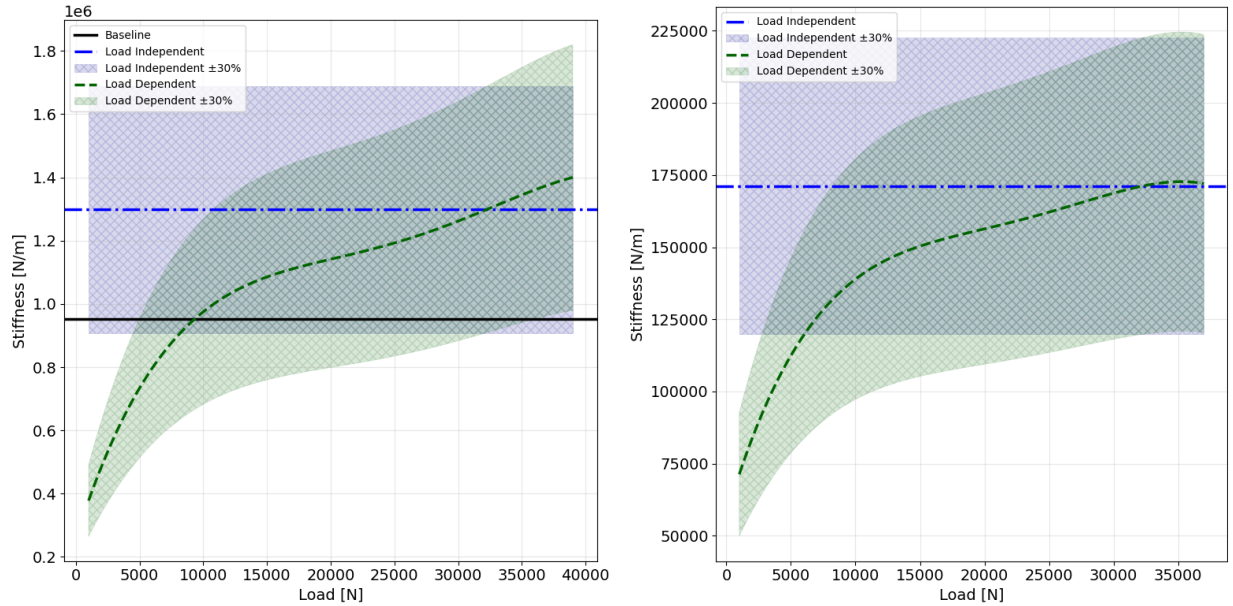


Fig. 19 Recommended functional forms of spring stiffness for the bridle (left) and riser (right). A load-independent nominal value (blue line) and uncertainty (blue hash) as well as a load-dependent curve (green line) and uncertainty (green hash) are included. For the bridle, the baseline stiffness with no dispersion is shown (black line).

1. Load-Dependent Spring Stiffness

The recommended formulation for the load-dependent spring stiffness is a 4th-order polynomial of the form shown in Equation 21, with an applied multiplicative uniform dispersion.

$$k(F) = (a_1 F^4 + a_2 F^3 + a_3 F^2 + a_4 F + a_5) \cdot (1 + U_k^M) \text{ N/m} \quad (21)$$

The polynomial coefficients a_1 through a_5 for the bridle and riser are provided in Table 6. The recommended uncertainty of U_k^M is also defined.

Table 6 Spring stiffness load-dependent functional form coefficients

Coefficient	Bridle Value	Riser Value
a_1	-1.802×10^{-12}	-2.863×10^{-13}
a_2	1.923×10^{-7}	2.706×10^{-8}
a_3	-7.259×10^{-3}	-9.329×10^{-4}
a_4	1.269×10^2	1.509×10^1
a_5	2.582×10^5	5.713×10^4
U_k^M	$U(-0.3, 0.3)$	$U(-0.3, 0.3)$

2. Load-Independent Spring Stiffness

A load-independent estimate for spring stiffness should be the evaluation of Equation 21 using the required peak inflation load, $F_{p,\text{limit}}$, specified by mission requirements. Given that the spring stiffness test data non-linearly increases with applied load, choosing the stiffness at the maximum allowable load would be a conservative estimate for any lower load condition. Equation 22 is Equation 21 with the requirement-specified load substituted for the force acting on the elastic element.

$$k(F_{p,\text{limit}}) = \left(a_1 F_{p,\text{limit}}^4 + a_2 F_{p,\text{limit}}^3 + a_3 F_{p,\text{limit}}^2 + a_4 F_{p,\text{limit}} + a_5 \right) \cdot \left(1 + U_k^M \right) \quad \frac{\text{N}}{\text{m}} \quad (22)$$

The nominal stiffness values for the bridle and riser elastic elements of the Dragonfly drogue parachute system are provided in Table 7.

Table 7 Spring stiffness evaluated at mission limit peak inflation load per requirements

Parameter	Bridle Value	Riser Value
$F_{p,\text{limit}}$	32 kN	32 kN
k_{nom}	$1.298 \times 10^6 \text{ N/m}$	$1.712 \times 10^5 \text{ N/m}$
U_k^M	$U(-0.3, 0.3)$	$U(-0.3, 0.3)$

B. Dynamic Damping

It is recommended that the damping of the system be modeled with the experimentally determined inputs of spring stiffness, k , damping ratio, ζ , and natural frequency, f_n such that the final damping ratio, c , is correlated to the spring stiffness, k , as defined by Rayleigh damping in Section III.C.4. If heritage simulation tools can only accommodate an input of a dynamic damping coefficient, c , rather than damping ratio, ζ , and natural frequency, f_n , then an uncorrelated estimation of dynamic damping is also provided.

The baseline Dragonfly elastic model, with no dispersions, adheres to the conceptual formulation of Rayleigh damping with no mass dependence as explained in III.C.4. However, if the explicit use of a dispersed damping coefficient, c , is used, instead of implicitly formulating through dispersions of k , ζ , and f_n , then there is no correlation between the stiffness and damping. The histogram in 20 is the evaluation of the dispersed dynamic damping coefficient distributions in a 100,000 case Monte Carlo of the bridle (left) and riser (right). The uncorrelated model produces a uniform distribution that encompasses the bounds of the correlated model. The correlated model is in the form of a skewed Gaussian distribution, which is the expected result of a stochastic multiplication of three random variables. In this case, the uncorrelated is unconservative, resulting in a disproportionally higher number of cases with increased damping. Therefore, it is recommended that the model of the damper remains stiffness-correlated.

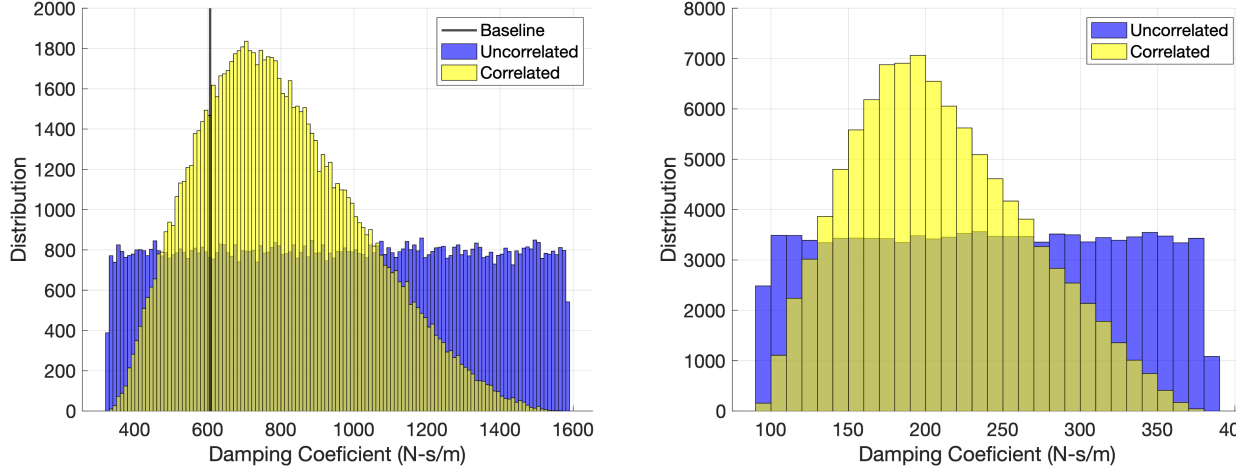


Fig. 20 Histogram comparing the uncorrelated (blue) and correlated (yellow) dynamic damping estimations for a 100,000 case Monte Carlo. The baseline, undispersed value of the damping coefficient (black) is included for the bridle.

1. Stiffness-Correlated Dynamic Damping

The recommended formulation of the damping ratio, ζ , and natural frequency, f_n , are provided in Equations 23 and 24 respectively.

$$\zeta = \zeta_{\text{nom}} \cdot (1 + U_{\zeta}^M) \quad (23)$$

$$f_n = f_{n,\text{nom}} \cdot (1 + U_{f_n}^M) \quad \text{Hz} \quad (24)$$

The recommended nominal value and dispersed uncertainty multiplier for each parameter is provided in Table 8 for both the bridle and riser.

Table 8 Dynamic damping properties

Parameter	Bridle Value	Riser Value
ζ_{nom}	0.108	0.035
U_{ζ}^M	$U(-0.35, 0.35)$	$U(-0.35, 0.35)$
$f_{n,\text{nom}}$	56.0 Hz	9.1 Hz
$U_{f_n}^M$	$U(-0.12, 0.12)$	$U(-0.04, 0.04)$

The recommended values of damping ratio and natural frequency, as listed in Table 8, and spring stiffness, as described in Table 7, should be used. The dynamic damping coefficient, c , used in the parachute elastic model to calculate the elastic forces should be calculated using Equation 25. If the spring stiffness is load-dependent, as recommended in Section VII.A.1, then the damping coefficient will also be load-dependent due to its proportionality to stiffness.

$$c(F) = \frac{\zeta}{\pi f_n} k(F) \quad \frac{\text{N} \cdot \text{s}}{\text{m}} \quad (25)$$

2. Stiffness-Uncorrelated Dynamic Damping

The current Dragonfly model uses the dynamic damping coefficient, c , which is a derived quantity calculated using the spring stiffness, k , damping ratio, ζ , and natural frequency, f_n , as formulated in Equation 16. The mathematically rigorous formulation of the uncertainty of the damping coefficient, c , would follow the probability distribution propagation of three random variables, k , ζ , and f_n , each with uniform distributions. The final distribution would neither be uniform nor normal, but would have an expected value of $E(c) = c_{\text{nom}}$.

For modeling simplicity, the recommended uncertainty bounds for the damping coefficient, c , are determined by assessing the values of k , ζ , and f_n that maximize and minimize damping coefficient, c . The chosen nominal value, c_{nom} , is the average value of these bounds and a uniform distribution is chosen. The functional form of damping coefficient, c , is shown in Equation 26 with specific values provided in Table 9.

$$c = c_{\text{nom}} \cdot \left(1 + U_c^M\right) \frac{\text{N} \cdot \text{s}}{\text{m}} \quad (26)$$

Table 9 Dynamic damping coefficient with symmetric dispersion (recommended if c is used directly)

Parameter	Bridle Value	Riser Value
c_{nom}	956.2 N·s/m	237.9 N·s/m
U_c^M	$U(-0.66, 0.66)$	$U(-0.61, 0.61)$

VIII. Conclusion

The elastic properties of the Dragonfly PDS system, namely the bridle and riser of the drogue parachute system, are measured through experimental testing on flight-like, full-scale elastic hardware. Recommended values with included uncertainties are generated to provide data-informed updates to modeling parameter inputs to be used in Monte Carlo simulations of the Dragonfly EDL sequence. The evaluation of these recommendations are presented in Pensado et al. [2].

The results shown offer an advancement in fidelity of the functional forms used to model elastic elements in the context of planetary parachutes. A parametric understanding of the behavior of these elements was gained through direct experiments conducted on flight-like specimens. This improves upon the heritage approaches of using specimen-failure data to estimate spring stiffness and crafting damping terms such that they aided simulation stability. Additionally, dispersions of elastic properties can now be estimated using test data.

An investigation into the elastic properties of the full-scale bridle and riser of the drogue parachute system for the Dragonfly mission was conducted in response to a risk that dynamic amplification factors induced by the elastic elements of the PDS system may exceed requirements. The specific steps taken to conduct these experiments and synthesize the proper products and their uncertainties was specific to addressing this risk in a timely manner. However, along the way, a large dataset with many opportunities for future exploration has been generated. Future work should include investigating this additional data, namely the axial pluck investigation, as well as using modeling best practices to reconstruct the dynamic tests performed as a verification and validation exercise.

Acknowledgments

The authors would like to thank Juan R. Cruz and the members of the Aeronautics Systems Engineering Branch for their invaluable assistance in preparation of this work. The team at Tension Member Technology (TMT) Laboratories, led by Andy Glasgow, was instrumental in enabling this test campaign to move from conceptualization to completion within just four months.

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