(Preprint) AAS 16-115

ORION GN&C DETECTION AND MITIGATION OF PARACHUTE PENDULOSITY

Mark A. Kane,[*] Roger Wacker[†]

New techniques being employed by Orion guidance, navigation, and control (GN&C) using a reaction control system (RCS) under parachutes are described. Pendulosity refers to a pendulum-oscillatory mode that can occur during descent under main parachutes and that has been observed during Orion parachute drop tests. The pendulum mode reduces the ability of GN&C to maneuver the suspended vehicle resulting in undesirable increases to structural loads at touchdown. Parachute redesign efforts have been unsuccessful in reducing the pendulous behavior necessitating GN&C mitigation options. An observer has been developed to estimate the pendulum motion as well as the underlying wind velocity vector. Using this knowledge, the control system maneuvers the vehicle using two separate strategies determined by wind velocity magnitude and pendulum energy thresholds; at high wind velocities the vehicle is aligned with the wind direction and for cases with lower wind velocities and large pendulum amplitudes the vehicle is aligned such that it is perpendicular to the swing plane. Pendulum damping techniques using RCS thrusters are discussed but have not been selected for use onboard the Orion spacecraft. The techniques discussed in this paper will be flown on Exploration Mission 1 (EM-1).

INTRODUCTION

Late in the Orion parachute development program, Capsule Parachute Assembly System (CPAS) drop tests exhibited pendulous swing mode of the crew module (CM). Motion induced by pendulosity increases touchdown impact loading to the structure and crew and can saturate the reaction control system (RCS) during final alignment of the CM. A multidisciplinary team was created to mitigate risk for future Orion missions. Redesign efforts of the parachutes and CM structure were unsuccessful in reducing the likelihood, or consequence, of pendulous motion necessitating modification of the landing guidance, navigation and control (GN&C) system. Parachute aerodynamics were analyzed extensively from four CPAS drop tests with 2-main parachute clusters. Based upon successful re-construction of flight data, high-fidelity parachute models were developed and integrated in Orion GN&C descent and landing simulations allowing design of new control strategies.

[*] Control Engineer, NASA-JSC Aerosciences and Flight Mechanics Division, 2101 NASA Pkwy, Houston TX 77058
[†] Orion GN&C Lead, Lockheed Martin Corporation, M/S H3B, P.O. Box 58487, Houston TX 77258

PENDULOSITY

Description. The Orion spacecraft deploys three ring sail parachutes for final landing designed to slow vertical descent for survivable water impact. The parachutes are attached at an offset to the vehicle center line which causes a natural hang angle allowing the CM to ‘toe-in’ at water landing when in the direction of horizontal travel.

The main parachutes inherently exhibit unstable side force aerodynamics which cause an oscillatory motion of the parachutes and CM with respect to the local vertical axis. The pendulum mode is present with three deployed main parachutes, however due to the chaotic nature of main parachute dynamics the pendulum mode does not grow to large swing amplitudes. When only two main chutes are present a weak axis of rotation persists allowing for the pendulum mode to grow to large swing amplitudes and reach limit cycle. This motion occurs in the plane perpendicular to that created when the chutes are aligned as shown in Figure 1.

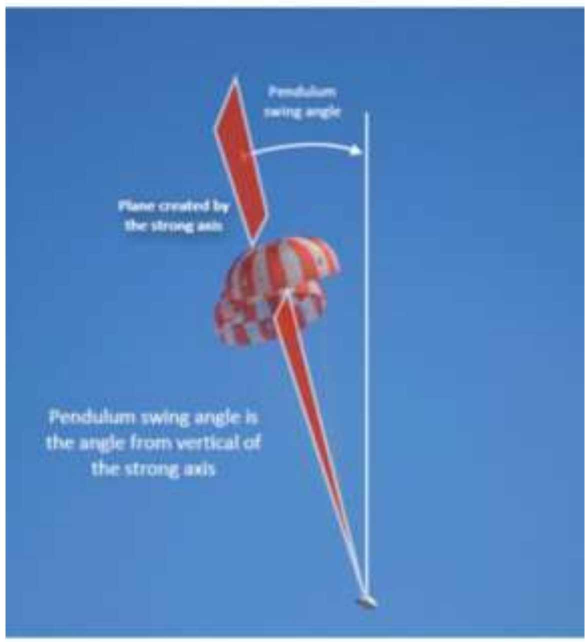

Figure 1. Definition of Pendulum Swing

Effects. During final alignment GN&C issues RCS jet firing commands that rotate the spacecraft about the local vertical axis and point a configurable vehicle body axis (V_b^{NED}) projected on the local horizontal plane (V_b^{NE}) towards a desired reference heading direction (V_d^{NED}) that is also projected on the local horizontal plane. Heading (ψ) is the angle between the two projected vectors. In the example, shown in Figure 2, the vehicle alignment axis is the Z-body axis.

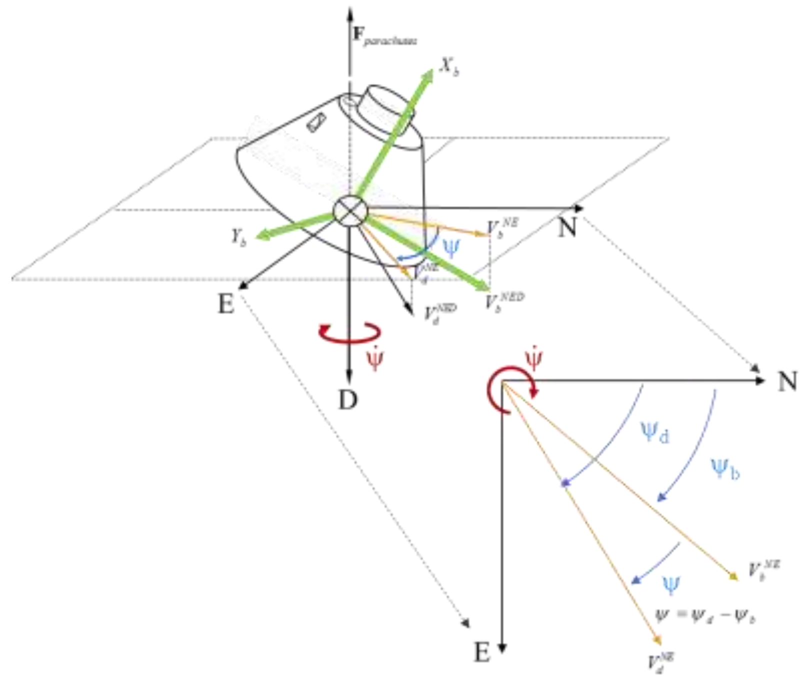

Figure 2. Definition of Heading and Heading Rate

The desired reference heading direction is chosen to mitigate landing loads experienced by the crew and CM structure. The reference heading direction has been in the direction of travel in the local horizontal plane. Under main parachutes, the horizontal velocity (V_{CM}) is driven primarily by wind velocity (V_{Attach}) on the main parachutes and pendulum motion (V_{Pend}). An example velocity signal in a single direction is given in Figure 3.

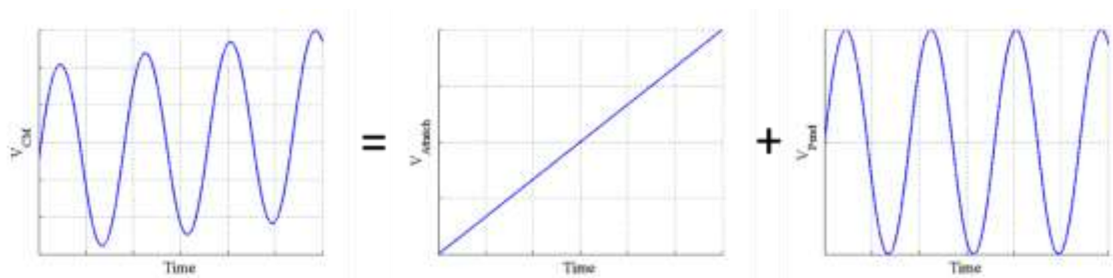

Figure 3. Components of Velocity

The velocity induced by the pendulum mode introduces undesirable response in the heading. Low steady-state wind velocity magnitudes paired with large magnitude pendulum induced velocities lead to a heading direction change of 180 degrees twice during the pendulum period as seen in Figure 4. This cannot be tracked by the RCS system and results in excessive propellant usage and undesirable behavior.

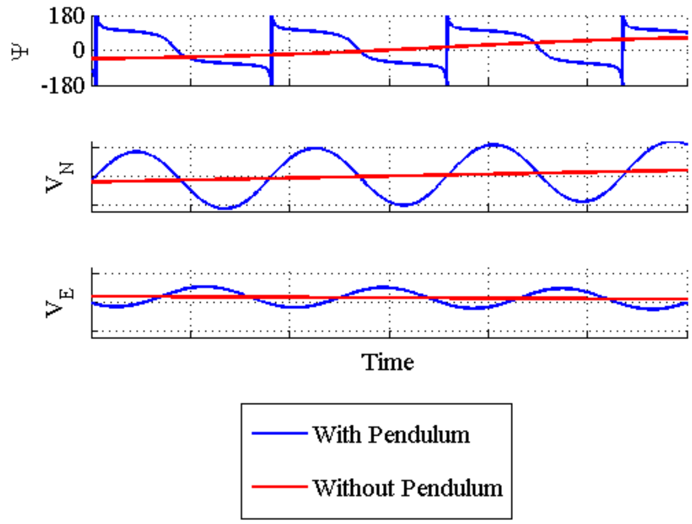

Figure 4. Pendulum Effect on Heading

In addition to introducing translational dynamics, pendulum motion causes attitude rotation of the CM spacecraft. The rotation of the CM alters the touchdown impact angle affecting how landing loads are imparted on the structure. Change in the impact angle can move the touchdown impact point radially towards the heat shield center, or outwards towards the leading edge. The CM is sensitive to low impact angle points that result in impact points near the heat shield center. Pendulum swing can occur in an arbitrary direction resulting in a circular probability of locus impact points on the heat shield. Loading severity with respect to impact location is shown notionally in Figure 5. The nominal impact point with no pendulum (or other attitude) motion would be located in the center of the distribution shown as a white X.

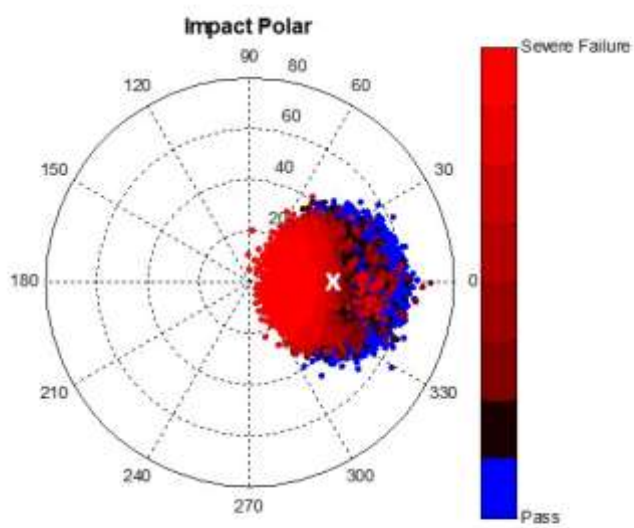

Figure 5. Load Severity with Respect to Landing Impact Point

PENDULOSITY OBSERVATION

Reducing pendulum effects with GN&C may be accomplished by translation of the CM using RCS thrusters or by altering the impact angle by rotating the CM about the parachute riser to an orientation that reduces the probability of low impact angles. Both of these options require onboard estimation of pendulum motion to facilitate correct pointing and control decisions.

Pendulum observation as described in this paper consists of three parts:

1. 2D Pendulum observer used in estimating states in the N-D plane
2. 2D Pendulum observer used in estimating states in the E-D plane
3. Generation of 3-dimensional states using the 2-dimensional observations

The coordinate system used to describe pendulum motion is given in Figure 6.

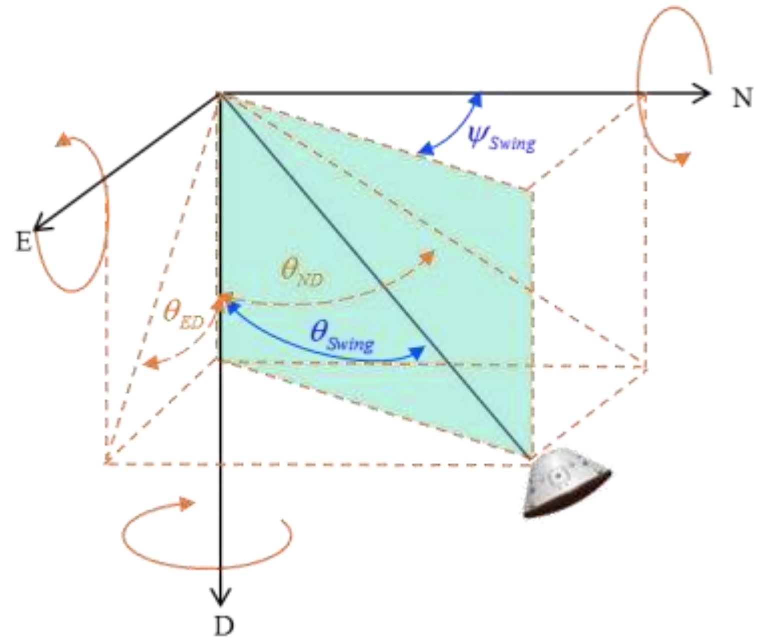

Figure 6. Pendulum Coordinate System

2D Pendulum Observer. 2-dimensional pendulum state observation is based upon a classic control theory, Luenberger Observer, given in Equation (1)

$$\dot{x} = Ax + Bu + G(y - Cx) \tag{1}$$

The measurement used to correct the estimated state is the Navigated CM total velocity. As described previously, total vehicle velocity in the local horizontal plane is assumed to consist primarily of two components when under parachutes and is given in Equation(2). Additional inputs into velocity are assumed to be negligible.

$$V_{CM} = V_{Attach} + V_{Pend} \tag{2}$$

Pendulum induced velocity in the local horizontal plane is a function of the line length (L), swing angle (θ), and swing angle rate ($\dot{\theta}$):

$$V_{Pend} = L\dot{\theta}\cos(\theta) \tag{3}$$

The measurement equation is given in equation(4).

$$y = V_{Attach} + L\dot{\theta}\cos(\theta) \tag{4}$$

The observer states chosen are the pendulum swing angle, swing angle rate, and the attach point (wind) velocity:

$$x = \begin{bmatrix} \theta & \dot{\theta} & V_{Attach} \end{bmatrix}^T \tag{5}$$

2D Pendulum Model. A simple gravity pendulum is used to model the pendulum mode in a single two dimensional plane. The origin of the system is at the centroid of the main parachute cluster and is represented as a moving attach point. The vehicle is modeled as a suspended point mass. Swing angle is defined as the angle between the line drawn from the point mass to the attach point and the downwards axis. Forces included in the model are those due to gravity, assumed to be downwards, and forces due to RCS firings (F_{RCS}). The system is illustrated in Figure 7.

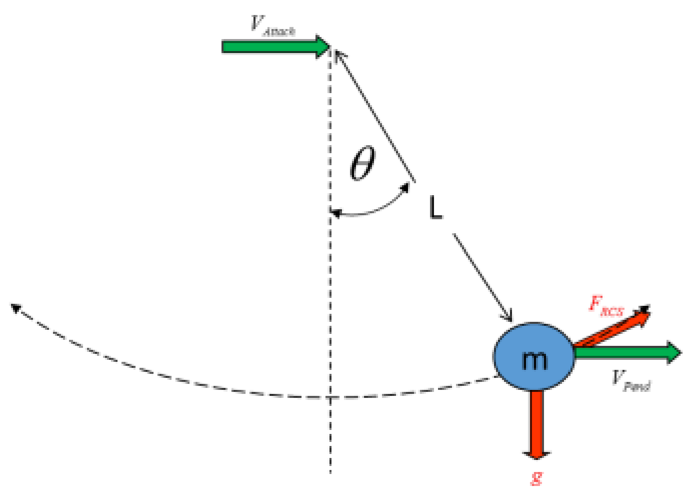

Figure 7: Two-Dimensional Pendulum Model

It should be noted that to simplify the equations the force contribution due to RCS is reduced to a constant (F_{RCS}) and is assumed to be tangential to the swing arc. Actual RCS contribution is a function of the CM attitude, jet mounting location, jet unit thrust vector, and jet thrust magnitude.

Development of the linear system used in the observer requires expressions for swing acceleration ($\ddot{\theta}$) and attach point acceleration (a_{Attach}). Swing acceleration is given in Equation (6).

$$\ddot{\theta} = \frac{1}{L}\left(-g\sin(\theta) - a_{Attach}\cos(\theta) + \frac{F_{RCS}}{m} \right) \tag{6}$$

The derivative of the attach point velocity is acceleration of the attach point (a_{Attach}):

$$\frac{\partial V_{Attach}}{\partial t} = a_{Attach} \tag{7}$$

No further development for attach point acceleration is warranted. State information relating to the attach point (main parachute cluster) velocity cannot be measured by Orion sensors and is not available.

The dynamic equations are put into a state-space form through use of the Jacobian and then linearized about a zero swing angle, zero swing rate, and a non-accelerating attach point:

$$\dot{x} = \begin{bmatrix} \dot{\theta} & \ddot{\theta} & a_{Attach} \end{bmatrix}^T \tag{8}$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{-g}{L} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{1}{L^2 m} \\ 0 \end{bmatrix} \tag{9}$$

$$C = \begin{bmatrix} 0 & -L & 1 \end{bmatrix}, D = \begin{bmatrix} 0 \end{bmatrix} \tag{10}$$

Estimate Quality. A convergence check has been implemented to indicate that the observed pendulum states are ready for use. Convergence is declared 'Passed' once the estimation error (ΔV) magnitude has been below a parameterized threshold (ΔV_{Db}) for a specified number of cycles ($nCycles_{ConvergedDb}$). Logic is shown in Figure 8.

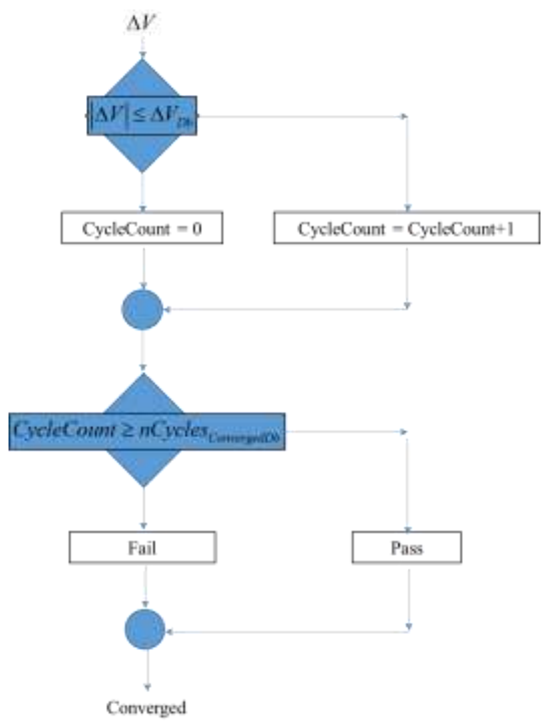

Figure 8: Pendulum Observer Convergence Check

Derived Parameters. Three-dimensional states not produced by the 2D pendulum observers are necessary to fully support methodologies employed by GN&C to negate the effects of pendulum motion. These are the swing plane angle $\left(\psi_{Swing}\right)$ and the pendulum energy (E_{Pend}).

Pendulum energy is given in Equation (11) and is the sum of pendulum kinetic energy (K_{Pend}) and pendulum potential energy (P_{Pend}):

$$E_{Pend} = K_{Pend} + P_{Pend} \tag{11}$$

$$K_{Pend} = \frac{1}{2} mL^2 \left(\dot{\theta}_{ND}{}^2 + \dot{\theta}_{ED}{}^2 \right) \tag{12}$$

$$P_{Pend} = mgL\left(1 - \cos(\theta_{Swing})\right) \tag{13}$$

Swing angle is found geometrically:

$$\theta_{Swing} = \sin^{-1}\left(\sqrt{\sin^2(\theta_{ND}) + \sin^2(\theta_{ED})}\right) \tag{14}$$

The swing plane angle is found geometrically and is limited to be within the range of +/- 90 degrees:

$$\psi_{Swing} = \tan^{-1}\left(\frac{sign(\theta_{ND})\sin(\theta_{ED})}{\left|\sin(\theta_{ND})\right|}\right) \tag{15}$$

Filtering Swing Plane Angle. Due to pendulum swing exhibiting a highly elliptical (near planar) motion, the geometrically produced swing plane angle changes rapidly and is not able to be used by GN&C directly. Fortunately, the system passes through the out-of-plane angles at a high frequency allowing them to be separated from the signal to determine the "plane" of swing.

A conventional low-pass filter is used to remove high frequency content from a signal and allow the low frequency content to pass-through. The filter takes the form shown in Figure 9.

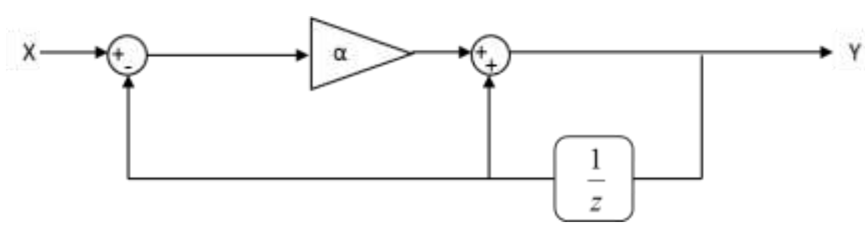

Figure 9: Low-Pass Filter

The design parameter (α) is defined by the time constant (T) and the cut-off frequency (ω_c) in rad/s.

$$\alpha = \frac{T\omega_c}{1 + T\omega_c} \tag{16}$$

Two low-pass filters, configured with design parameters α_1 and α_2, are used in series resulting in the transfer function given in equation(17).

$$\frac{Y}{X}=\frac{\alpha_1\alpha_2 z^2}{z^2+z\left(\alpha_1+\alpha_2-2\right)+\left(1-\alpha_1-\alpha_2+\alpha_1\alpha_2\right)} \tag{17}$$

The filtered swing plane angle is not updated unless the convergence check has passed. This prevents erroneous inputs from corrupting the observer output.

DAMPING PENDULOSITY

Prevention, or reduction, of pendulum motion from the system is desirable as it removes the cause of the increased loads. Pendulum damping is accomplished by issuing RCS thruster commands that result in translation of the CM.

A number of concerns arise when pursuing pendulum damping:

- Limited time for control
  - Pendulum damping occurs during final descent and has a finite time window
- Limited propellant budget
  - Pendulum damping takes place at the end of the mission with the possibility of little propellant remaining
- Pendulum swing occurs in a plane that is not necessarily coincident with velocity
  - Logic must allow for maneuvering to the desired reference heading prior to touchdown impact
- RCS jets are not ideally mounted on the spacecraft to provide forces (F_R, F_{PU}, F_{PD}, F_y) normal to the riser force, see Figure 10.
  - Results in inefficient control (pitch down jets are in the forward bay and are prohibited from use during descent under parachutes)
- Limited RCS authority
  - Increases time necessary to damp motion
  - Increases propellant cost
- Swing angle rate estimate accuracy
  - Necessary to determine the direction to issue translational commands
- Swing plane estimate accuracy
  - The assumption is made that pendulum swing is highly elliptical and that the swing plane angle moves slowly
  - Inaccuracy results in control force occurring out-of-plane reducing efficiency

Pendulum Damping Control Strategy. When the vehicle is properly aligned ($|\psi_{Pend}| \le \psi_{Db}$) with the pendulum plane, the control strategy is to fire RCS thrusters opposing the pendulum velocity (V_{Pend}). This control methodology is illustrated in Figure 10.

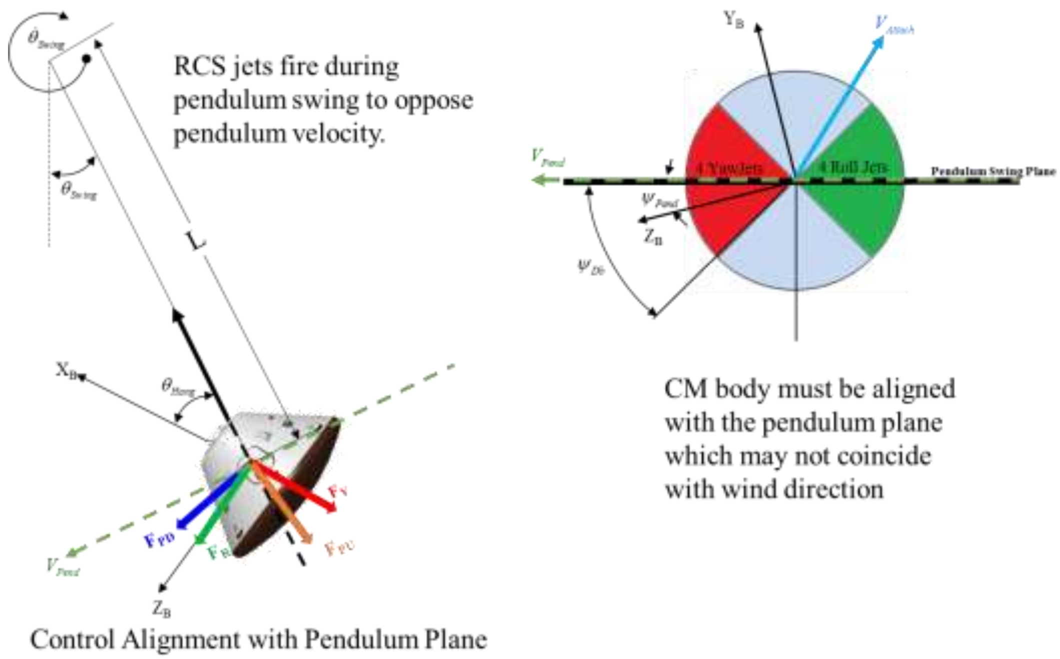

Figure 10. Damping Pendulum Motion

To protect the system from exhausting propellant the following steps were taken:

- Only attempt to damp when the pendulum energy is above a parameterized threshold
  - Prevents action from being taken during nominal three-main chute descent
  - Only activates when pendulum induced effects become the driver to landing loads
- Perform pendulum damping only when the remaining propellant is above a minimum reserve parameter
  - A propellant reserve guarantees that propellant is available to maneuver the CM to final alignment prior to touchdown impact
  - Requires an estimate of the remaining propellant

Two methods for CM body alignment to the pendulum swing plane were tested:

- Active maneuvering of the CM to the swing plane using the heading control system
  - Active control to the pendulum swing plane results in the largest reduction of peak pendulum swing amplitude at the highest cost to propellant
- Allow alignment to occur passively during descent
  - This method is opportunistic with minimal propellant cost
  - Does little to reduce pendulum motion

A swing angle rate dead band was used to prevent firings from occurring in the improper direction due to estimation error.

Pendulum Damping Conclusions. Pendulum damping control was able to successfully reduce peak pendulum swing amplitudes in some scenarios. Pendulum damping is severely limited by control authority, propellant loading, and flight time. Due to algorithm complexity and marginal reduction in touchdown impact loading, this approach was abandoned.

CONTROL STEERING MODIFICATIONS

An alternative to removing pendulum motion is to reorient the CM and reduce the probability of a low angle impact at touchdown. Impact angle (ϑ) varies during a single cycle of pendulum swing and can be shifted because the CM is at a hang angle with respect to vertical. Bounding impact angle scenarios are shown in Figure 11.

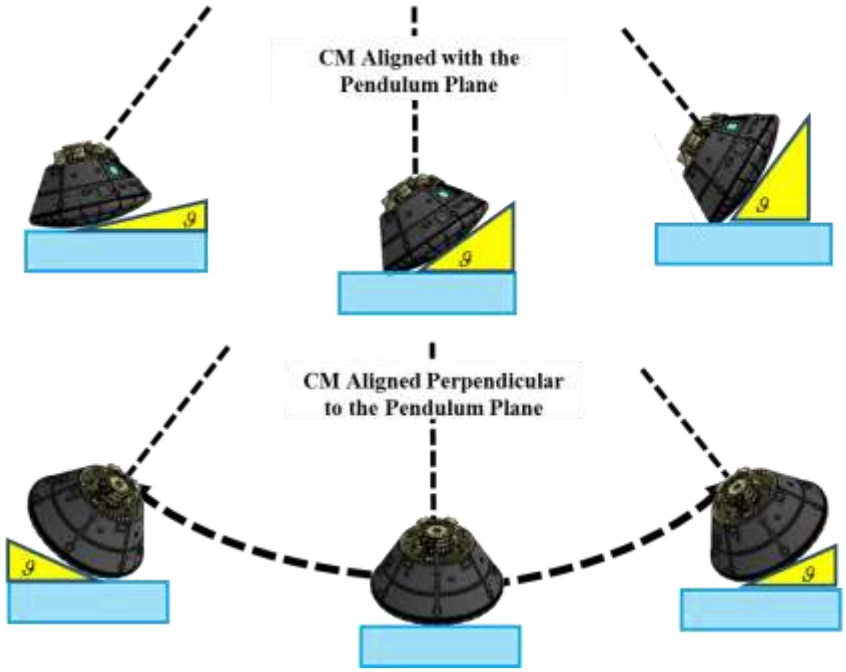

Figure 11. Impact Angle Relation to Pendulum Swing

The range of impact angles is largest when the CM is aligned with the pendulum swing plane and has the highest probability of impact at the center of the heat shield. Alternatively, when the CM is aligned perpendicular to the swing plane the range of impact angles is reduced and has the lowest probability of impact at the heat shield center.

Pendulum Pointing Method. When GN&C detects large pendulum energy, and a horizontal velocity magnitude $|V_{Attach}|$ that is below a parameterized threshold, the CM is pointed perpendicular to the swing plane. This reduces the likelihood of impact in the center of the heat shield in conditions where impact attitude is the primary driver to landing loads.

The rationale for aligning perpendicular-to-pendulum only in cases below a particular horizontal velocity threshold are twofold:

1. The geometric change in heading angle becomes smaller as steady-state wind velocity increases regardless of orientation of the pendulum swing plane with respect to the wind direction.
2. Wind alignment becomes the driver at higher velocities in terms of load failures given the expected maximum limit cycle growth of pendulum velocity.

A sensitivity study was performed by varying the velocity threshold and examining load failures to determine the best switching point from perpendicular-to-pendulum, to wind alignment. The cross-over velocity point is illustrated in Figure 12.

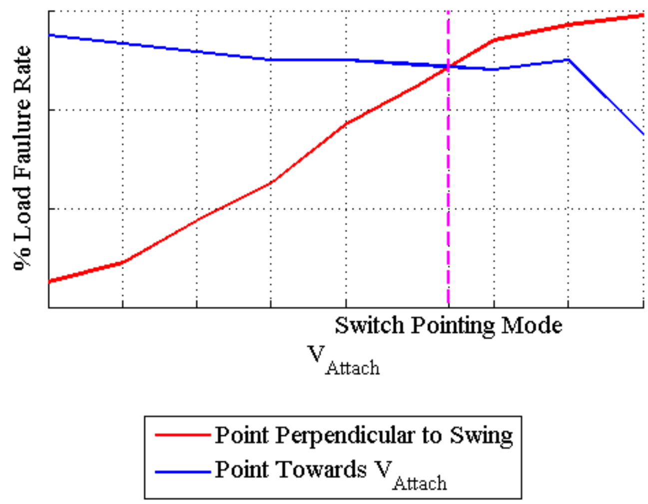

Figure 12. Velocity Switching Threshold

The swing plane has two sides and is not necessarily coincident with the wind velocity direction. The side of the swing plane is chosen to minimize the angle with respect to the wind velocity direction as shown in Figure 13.

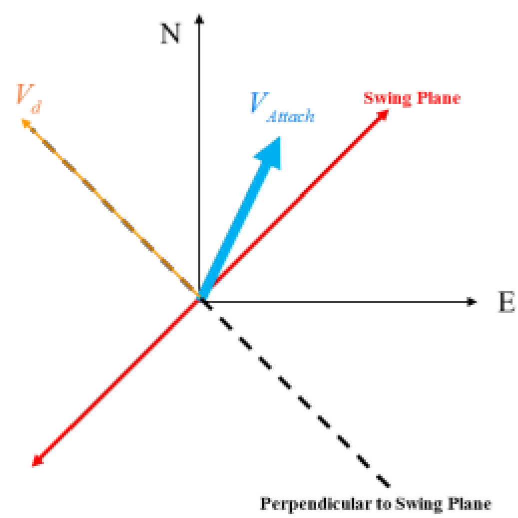

Figure 13. Pendulum Pointing Method

STABILITY ANALYSIS

The closed-loop system for heading control is depicted in the block diagram shown below. Heading errors formed from sensed velocity, attitude and body rates are driven to zero by phase-plane control with a Schmitt trigger. Rate limit (RL) and attitude dead band (DB) parameters specify the attitude control bandwidth.

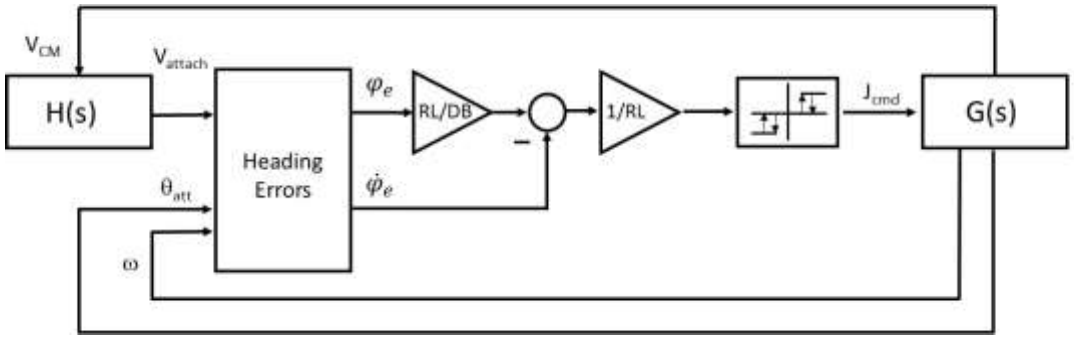

Figure 14. Close-Loop Heading Control

The Observer transfer function H(s) can be developed from Equation (1) where the input *u* is assumed zero. This has been shown to be valid when translational RCS firings (opposing jets) are not used. The poles of the Observer can be arbitrarily placed by solving Equation (18) for gain G. Poles are placed at frequencies which are 3 and 5 times faster than the pendulum frequency.

$$|sI - A + GC| = 0 \tag{18}$$

The resultant transfer function is shown below for the two-dimensional case.

$$H(s) = \frac{V_{attach}(s)}{V_{CM}(s)} = \frac{75\omega\left(s^2+\omega^2\right)}{(s+3\omega)(s+5\omega)^2} \tag{19}$$

We note that in this instance the transfer function resembles a typical notch filter. The system exhibits oscillatory modes due to pendulum, riser twist torque and riser force (wrist attitude) which can be excited by RCS firings. The below Nichols chart shows open-loop characteristics broken at the attitude error and rate command locations. The pendulum mode disappears when the Observer is turned on. Neither loops show any significant change to stability margins with Observer.

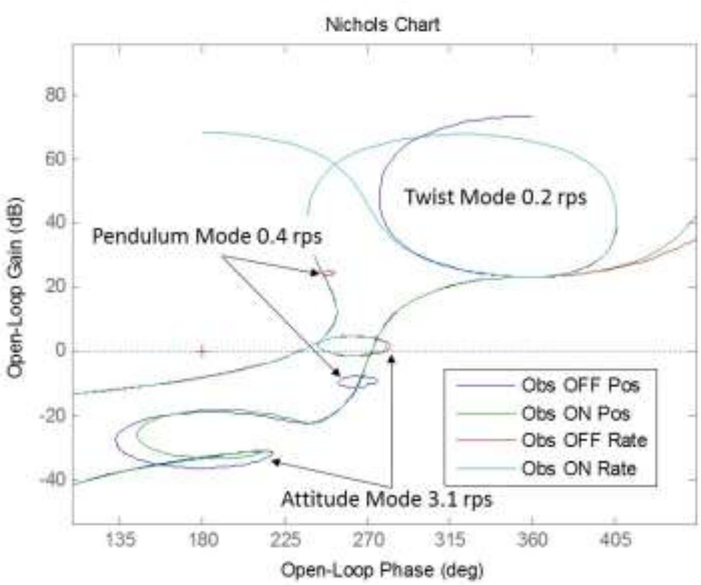

Figure 15. Open-Loop Nichols

OBSERVER PERFORMANCE

The pendulum Observer has been compared to CPAS flight test data where detailed photogrammetric data was used to reconstruct the motion of the main parachute cluster and relative motion to the drop test article (PTV). In 2-main chute drop test CDT 3-11 pendulum motion developed and grew to limit cycle. In Figure 16 and Figure 17 CDT 3-11 reconstruction data is shown as compared to the Observer estimations for swing angle, swing plane angle and horizontal wind velocity produced using sensor data from PTV.

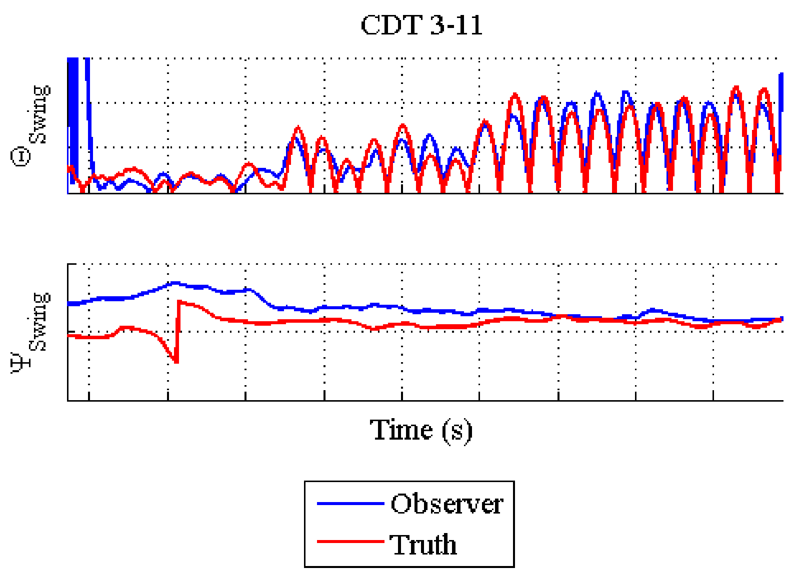

Figure 16. Observer Swing Angle and Swing Plane Angle CDT 3-11

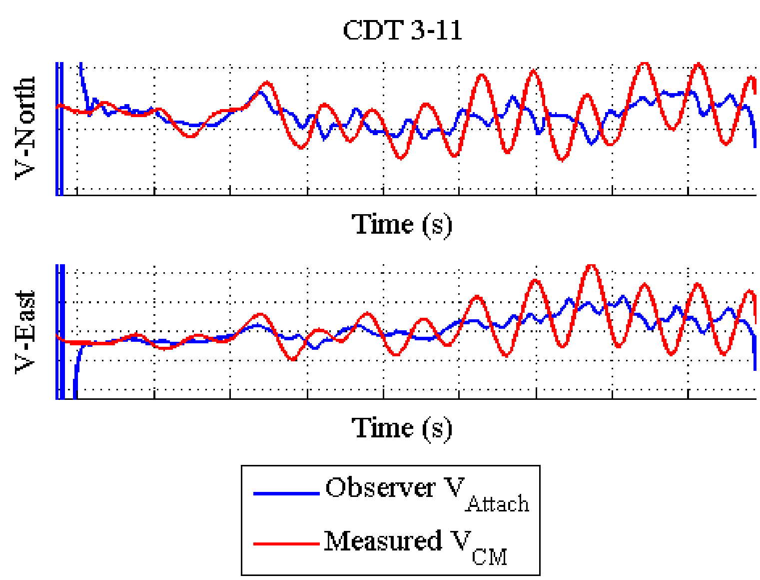

Figure 17. Observer Attach Point Velocity CDT 3-11

The Observer quickly converges upon true main cluster parachute state. It accurately estimates the swing phasing and amplitude. The true swing plane is difficult to define because composite parachute motion is ellipsoidal with a very high eccentricity. The semi-major axis can only be approximated. With uncertainty and expected lag due to filters, the swing plane estimation is well within expectation and suitable for alternate heading strategies. Estimates of the attach point (wind) velocity in the local horizontal plane are centered within the CM total velocity as expected.

LANDING IMPACT PERFORMANCE

Figure 18 illustrates the change in landing impact angle dispersions on the CM due to different control strategies when large pendulum motion is present. Control strategies shown are:

- No Observer – Wind alignment
    - This was the baseline controller and only attempts to maneuver the vehicle such that it points in the direction of horizontal travel
    - Has no knowledge of the pendulous state
- Observer – Wind Alignment
    - Maneuvers the vehicle to align with the direction of the estimated horizontal wind velocity with pendulous states removed
- Observer – Perpendicular to Pendulum (Alternate)
    - Maneuvers the vehicle to align perpendicular to the estimated swing plane on the side nearest the wind direction when horizontal is low and pendulum energy high

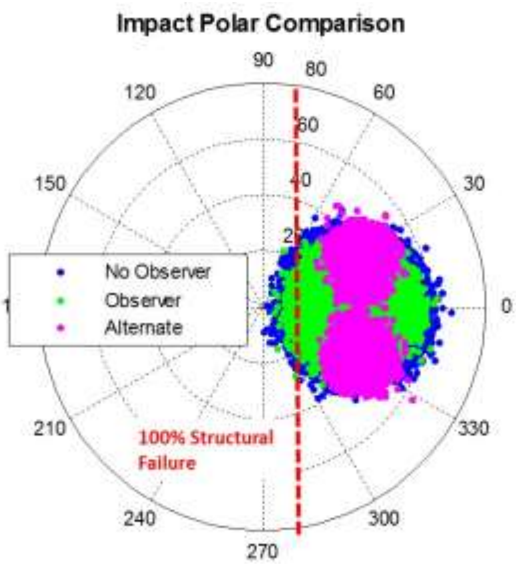

Figure 18. Landing Impact Location

High-fidelity GN&C simulations have demonstrated 35% improvement in load success probability when the pendulum Observer and alternate heading strategy is employed on the Orion vehicle. It should be noted that additional measures were taken to reduce the effect of pendulosity on EM-1 beyond the pendulum Observer.

- Altitude of main parachute deployment was reduced
    - Allows less time for pendulum motion to develop and reach a limit cycle
- The hang angle was increased (through CG constraints)
    - Shifts the impact points outward helping avoid shallow impact angles

CONCLUSION

GN&C has successfully developed an algorithm to mitigate the effects of pendulosity for the Orion spacecraft. This flight software solution avoids costly parachute or vehicle structure design changes. Extensive Monte Carlo analyses with high-fidelity parachute models have demonstrated the robustness of the system and contributed to higher vehicle reliability for Orion missions of the future.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical contributions of the entire Orion GN&C team at NASA, Lockheed Martin, and respective contractors.