Kennedy Engineering Academy
Accelerated Training Program Showcase

"Design of the Core Stage Inter-Tank Umbilical (CSITU) Compliance Mechanism"

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NE-M2 Structures & Mechanisms Design
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Background

- Born in Daytona Beach, FL
- Raised in Knoxville, TN
- Graduated from Powell High School

College

- Tennessee Technological University
- Graduated May 2012
- Bachelor of Science: Mechanical Engineering

Previous NASA Experience

*Internship, Marshall Space Flight Center, Fall 2009*
- Undergraduate Student Research Program (USRP)

*Co-op, Kennedy Space Center, Spring 2010, Summer 2012*
- Co-op Program
ATP Overview

Supervisor: Joe Porta
Mentor: Patrick Maloney
Branch: NE-M2, Structures & Mechanisms Design Branch

Topics Covered:
I. Required Reading
II. Diverse Work Assignments
III. Targeted Work Assignments
IV. Final Project
Design of the Core Stage Inter-Tank Umbilical (CSITU) Compliance Mechanism

Project Goals

- Design the compliance mechanism for the CSITU system to a 30% level
  - 3D models completed in Pro/Engineer
  - Relevant design analysis
- Must meet all system requirements and establish basis for proceeding with detailed design

Tasks to be completed

- A design that meets requirements for the 30% design review, 01/16/2013
Umbilical arms provide commodities to the launch vehicle prior to T-0. Commodities can range anywhere from hydraulics, pneumatics, cryogenic, electrical, ECS, etc...

- Umbilicals commonly employ truss structures to deliver commodities to vehicle
- Common configurations include:
  - Tilt-up
  - Swing Arm
  - Hose Drape
  - Drop Arm
- Umbilical arms will be mounted to Mobile Launch Platform
- SLS currently has 9 T-0 umbilical arms
The compliance refers to the ability of the umbilical to adjust to minor changes in vehicle location. The compliance mechanism refers to the mechanism on the ground support equipment (GSE) that compensates for these changes. For the CSITU, these minor changes, or vehicle excursions, can be up to ±4 in.

- Excursions refer to movements of the vehicle caused by wind loads and thermal expansion
- It is ideal to have significant vertical compliance so a passive secondary release mechanism may be implemented

Example of compliance for Tilt-Up Umbilical Arm (TUUA)
Project Approach

- Brainstorm design concepts
  - Create sketches, simple dynamic models, hand calcs
- Review trade study documents and new technologies
  - Review TUUA, TSM, Apollo swing arm designs
- Create a comparative analysis
  - List Pros/Cons
- Gain Feedback
  - Mentor, Engineers, Chief Engineers, etc...
- Choose concept and develop
General & CSITU Specific Requirements

1,500 lb and 36” wide x 48” long ground plate
+/- 4.0” in Z-axis (orthogonal to tower face)
+/- 2.0” in Y-axis (parallel to tower face)
+0.5”/-2.0” in X-axis (vertical)
10,000 lb maximum loads in to vehicle
Blast Load: 8 psi vertical, 4 psi horizontal.

Design Criteria
Mechanism must allow ground plate to rotate 10°
At least 12” of retract distance at closest point to vehicle
Design shall include provisions to prevent binding, jamming, or seizing
Capability for easy ground plate manipulation when mating to vehicle
Repeatable retract position at launch
Design Considerations

• How compliant is it
• Primary/Secondary disconnect
• Primary/Secondary retract method
• Retract distance
• Commodity line routing
  - Mechanism must leave room for commodities
  - What kinds of bends will the lines be making?
• Stiffness of commodity lines
  - Changes center of gravity of plate
  - Effects passive secondary disconnect system
• Rotating vs. Translating surfaces
  - Translating surfaces more susceptible to binding
  - Prefer redundant rotating surfaces over redundant translating
Tilt Up Umbilical Arm (TUUA) Prototype

LH2 Tilt Up Umbilical Arm is shown below. The compliance mechanism includes 4 struts, a translating truss, and a rotating truss.

**PROS**
- Testing in progress
- Achieves excursion requirements
- Struts are already designed for smaller TUUA plate

**CONS**
- Translating surfaces susceptible to binding
- Complex strut design with tight tolerances
- TUUA configuration different from CSITU (swing arm)
- Struts not designed for vertical compliance

**SPRING RATES**
- Springs in diagonal struts calculated to be 1414 lbf for CSITU

Example of compliance for Tilt-Up Umbilical Arm (TUUA)
Concept Development

Draped Configuration
Drape is a common configuration (OSMU, ICPSU)

PROS
Compliant in all directions

CONS
GSE for mating operation
CSITU has 1500 lb ground plate at retract

Tail Service Mast (TSM)
Have been used for Apollo and Shuttle

PROS
Long record of reliability
Plates for Shuttle ≈1600 lb

CONS
TSM tilt-up vs. CSITU swing arm
Scissor Link with Translating Mechanism at Plate

- Scissor link accommodates excursions in the y and z
- Translating mechanism achieves x excursions

**PROS**
Achieves excursions requirements
Rotating surfaces

**CONS**
Translating surfaces susceptible to binding
Limited vertical compliance
Large moment load on pins at truss

**SPRING RATES**
Springs at ground plate calculated to be 500 lbf

**MOMENTS**
Moment at truss is 48,000 in·lbf
Concept #2

Scissor Link with Struts
- Scissor Mechanism has universal joints at truss
- Spring loaded struts provide nominal plate location

PROS
Achieves excursions requirements
Rotating surfaces

CONS
Translating surfaces susceptible to binding

DYNAMICS
Model created in Pro/E Mechanism to simulate mechanism movement through worse case vehicle excursions (right). This is useful for characterizing mechanism behavior.

SPRING RATES
Springs in struts calculated to be 708 lbf
Concept #3A

Controlled Manipulator Arms
- Derived from industrial manipulators, common in production
- Uses pneumatic/hydraulic cylinders to offload weight
- Allows for easy handling of object
- Rotating pedestal is optional

PROS
Achieves excursions requirements
Rotating surfaces
Easy operator manipulation

CONS
Complex control system for cylinders
Potential for mechanism to lock up (failure of control system or cylinder binding)

PNEUMATIC/HYDRAULIC SIZING
Aft cylinder estimated to be 3215 lbf
Forward cylinder estimated to be 2500 lbf

Passive Manipulator Arms, from Tariq Rahman, Ph.D in document "A Simple Technique to Passively Gravity-Balance Articulated Mechanisms"

- Uses springs to passively balance four bar linkages
- Linkage is balanced in all positions

PROS
Achieves excursions requirements
All Rotating Surfaces
Easy operator manipulation
Reduces retract actuator size
No actuators used for linkage control

CONS
Change in plate mass will change spring rates

SPRING RATES
Initial calculations estimated springs to be about 300 lbf

Credit: Tariq Rahman, Ph.D

Desktop Prototype
Concept Decision

Concept #3B, Passively Gravity Balanced Linkage
After completing the comparative analysis, this design was chosen.

- Use of rotating surfaces
  - Increased reliability
- Allows for operator manipulation
  - Require no extra GSE for mating
- Repeatable retract position after launch
- Meets vehicle excursion requirements
- Allows sufficient compliance to accommodate a secondary release actuated by vehicle rise

Credit: Tariq Rahman, Ph.D
Using the conservation of energy method, springs rates can be calculated to achieve a balanced system.

For a static analysis, kinetic energy = 0 and potential energy is constant.

*Assume supporting links are massless and free length of spring is zero \((x_0=0)\). This is accomplished by moving the spring and adding a pulley and wire at these locations.

\[
\frac{\partial}{\partial \theta_n} (PE) = 0
\]

\[
PE_n = -m_n g l_n \cos \theta_n + \left(\frac{K_n}{2}\right)(x_n - x_0)^2 - 2Mg l_n \sin \theta_n
\]

Using law of cosines and setting \(x_0=0\),

\[
x_n^2 = a_n^2 + b_n^2 + 2a_n b_n \cos \theta_n
\]
Substitute into potential energy equation,

\[ PE_n = -m_n gl_n \cos \theta_n + \left( \frac{K_n}{2} \right) (a_n^2 + b_n^2 + 2a_n b_n \cos \theta_n)^2 - 2Mgl_n \sin \theta_n \]

Take partial derivative of potential energy equation,

\[ \frac{\partial}{\partial \theta_n} (PE) = m_n gl_n \sin \theta_n - K_n a_n b_n \sin \theta_n + 2mgl_n \sin \theta_n = 0 \]

Solve for \( K_n \),

\[ K_n = \frac{gl_2}{a_2 b_2} (m_2 + 2M) \]

The same method can be used to find \( K_{n-1} \)

The resulting spring rates are:

\[ K_2 = \frac{gl_2}{a_2 b_2} (m_2 + 2M) \quad K_1 = \frac{gl_1}{a_1 b_1} (l_1 m_1 + 2l_2 m_2 + 2l_2 M) \]
A study was done to determine the sensitivity of the spring rates to the ground plate mass (M).

From the results, a change of 40 lbf saw 2.6% change in required spring rates.
Dynamic Analysis

A Dynamic model was created in Adams to simulate the compliance dynamics. This is useful for determining spring rates, joint loads, expected mechanism behavior, etc...

- Arrows represent spring force direction vector
Dynamic model created (Adams) to verify hand calculations for the spring rates
The results in Adams verifies calculations are accurate and shows passive balance is obtained
Force Analysis

Quantification of mechanism behavior can be easier understood using the Adams post processing feature.
When simulating maximum vehicle excursions, this is useful for determining link angles with respect to time. This feature is also very useful for dynamic force analysis.
Primary Retract Mechanism
The primary release mechanism will employ either a pneumatic or hydraulic cylinder to achieve the 10° plate rotation and 12” retraction

- Mechanism can accommodate this system
Design Development

Passive Secondary Release Mechanism

- Static wire rope attached to bottom of truss
- Wire rope pulls lever arm to create a separation force between plate and vehicle
- The maximum vehicle rise before actuation is 12.5”

➢ Compliance mechanism can accommodate all aspects of the secondary release mechanism
Design Development

Primary Release Dynamics
The sequence below depicts the primary release mode for the compliance

Note, springs have not yet been placed

MATED  10° of Rotation  12” of Retract

- Mechanism can achieve design goal for 10° plate rotation and 12” retract
ATP Final Project

Vehicle Integration and Launch (VIL) CSITU 30% Design Review, 1/16/2013
Future Work

Mature design to 60% level

- **Detailed Design**
  - Member shapes/size
  - Spring configuration/pulley configuration
  - Spring deflection distances
  - Determine where to place side-to-side reaction forces

- **Analysis**
  - Factor in stiffness of hoses
  - Redo hand calculations to include supporting members
  - Spring rates
  - Determine required force to react side-to-side loading
  - Stress Analysis
ATP Project Takeaways

Increased proficiency in Pro/Engineer, Pro/E Mechanism, Adams

Increase in umbilical knowledge
- Functionality
- Varying configurations
- Design considerations

Better understanding of the work going on at KSC

Contacts from many organizations around center
Questions?
Project as of Today