Dynamics and control of highly flexible structures for aerospace applications

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PhD course: Space Sciences, Technologies and Measurements (STMS)
Curriculum: Sciences and Technologies for Aeronautics and Satellite Applications (STASA)

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Membrane solar panels
- ILC Dover, Teledesic
- Inflatable Solar Array
- DSS's Mega-ROSA
- ESA/EADS Inflatable and Rigidizable Solar Array Breadboard
- L'Garde Inflatable Torus Solar Array

Solar and drag sails
- JAXA's Ikaros
- ESA/DLR solar sail
- NASA's Nanosail-D

Membrane antennas
- L'Garde's LDP inflatable antenna
- L'Garde's Synthetic Aperture Antenna
- L'Garde/NASA's Inflatable Antenna Experiment

GOSSAMER STRUCTURES NOT AVAILABLE
**Introduction - Background and test cases**

**Why gossamer structures?**

- **Advantages:**
  - Lower mass and storage volume
  - Lower launch costs
  - Lower manufacturing costs

- **Drawbacks:**
  - Flexibility
  - Low natural frequencies that can cause instabilities on the central body

**Objectives**

- Study of the dynamics of highly flexible structures
- Study of its vibrations control systems

**Test cases**

1. Oscillations control on the membrane with free edges
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Membrane with external frame structure - Bistable tape springs

Bistable booms:
- are elongated structures made of composite material (e.g. CFRP, GFRP...)
- have low mass per unit length (e.g. 8.6 g/m)
- can be stored in a compact fashion inside the satellite
- present two well-defined stable equilibrium configurations: the deployed (unrolled) and the stowed/coiled one, with the lowest values of stowed strain energy

Plaint weave CFRP:
- 3K HS Carbon Fibers
- epoxy resin
45° wrt the longitudinal axis

Nominal length: 1 m
Nominal thickness: 0.234 mm
Nominal int. radius: 7.5 mm
Mass: 8.6 g
Membrane with external frame structure – Mathematical representation

Dynamics of the booms:
ABD matrix correlates the applied loads to the laminate strains:

\[
\begin{bmatrix}
N_x \\
N_y \\
N_{xy} \\
M_x \\
M_y \\
M_{xy}
\end{bmatrix} =
\begin{bmatrix}
8890.7 & 7525.8 & 0 & 0 & 0 \\
7525.8 & 8890.7 & 0 & 0 & 0 \\
0 & 0 & 7650.6 & 0 & 0 \\
0 & 0 & 0 & 17.8 & 11.6 & 0 \\
0 & 0 & 0 & 11.6 & 17.8 & 0 \\
0 & 0 & 0 & 0 & 0 & 13.7
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy} \\
\kappa_x \\
\kappa_y \\
\kappa_{xy}
\end{bmatrix}
\]

where the units are N and mm.

Stability criterion for shells with no coupling between bending and twisting (the structure is bistable for \( S > 0 \)):

\[
S = 4\hat{D}_{66} + 2\hat{D}_{12} - 2\frac{\hat{D}_{12}}{\hat{D}_{12}} = 1.30 > 0
\]
Membrane with external frame structure – Mathematical representation

Stowed radius: \( R_s = R \frac{D_{11}}{D_{12}} = 11.5 \text{ mm} \)

Approximated torque \( \tau \) just before full deployment:
\[
\tau = \frac{R H \beta}{2R} \left[ D_{22} - \frac{D^2_{12}}{D_{11}} \right] = 24.8 \text{ mNm}
\]

Energy losses due to friction, damping, microcracks and viscoelastic relaxation are not taken into account in theoretical behavior
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Test 1: Elastic and damping properties of the booms

- Experimental evaluation of elastic and damping properties of the boom
- Free length 1 m, fixed on one side
- Sensor: camera with frame rate = 60 frames/s
- Properties calculated with the logarithmic method:
  - Damping ratio: $\zeta = 0.16$
  - Damped frequency: $\omega_d = 4.85$ Hz
  - Natural frequency: $\omega_n = 4.92$ Hz

1 pixel = 0.15 mm
Test 2: Boom torques on a fixed spool

- Measurements with a 100g load cell
- Experimental forces result about 10 times smaller than the theoretical force – compatible with what was observed in other similar experiments by other researchers
- Energy losses due to friction, damping, microcracks and viscoelastic relaxation

![Torque VS deployed length](image)

- Irregular curve because of imperfections in the manufacturing of the boom and/or non perfect verticality during tests.
- Experimental torque results are about ¼ of the theoretical torque.
- The resulting torque values were used to select the motor to drive the spool in later experiments
Test 3: Shock loading at the end of the deployment

- Measurements with two 780g load cells, removing all the static components of the measurements (weight of the structure, boom...)

- Partial deployment of the boom (the last 21.5 cm in this case), with the tip suspended by a cord.

- The results are compatible with other similar experiments by other researchers on different woven materials (GFRP)

![Image of measurement setup]

![Graph showing shock torque on the two load cells]

20/10/2017
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Numerical simulations with PID control system acting on the boom

- Simple model where the boom is simulated as a series of masses, springs and dampers, fixed on one side, free on the other.
- With the elasticity and damping coefficients applied it showed a very similar behavior to results of preliminary test 1.
- Applying a control force with a PID controller on the boom it damps out the oscillations quickly.

Different values for the Kp, Ki, Kd coefficients.
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Experimental tests – Gravity Offloading System

- Used to simulate absence of gravity
- The vertical component of the tension vector of the cords is equal to the $F_g = m \cdot g$ of the masses
- Length of the cables: 4.94 m
- Deployer mass ($m_A$) >> tip mass ($m_B$), $\beta_A << \beta_B$
Experimental tests – Components (electronics and software)

- **SENSOR MPU 6050 #1**
- **Arduino Uno #1**
  - Program #1
    - Arduino Software IDE controls sensor #1 and motor
  - Serial communication
- **MOTOR SHIELD**
  - Booms deployment and retraction
- **SENSOR MPU 6050 #2**
- **Arduino Uno #2**
  - Program #2
    - Arduino Software IDE controls sensor #2
  - Serial communication
- **STEPPER MOTOR**
  - Only during controlled deployment

Sensor attached to the deployer

Sensor attached to the external structure
Experimental tests – Components (mechanical and structural)

Deployer:
• aluminum structure
• 3D printed spool

External structure:
• Steel plates and screws
• EPDM rubber dampers

MASS:
• Deployer (including structure, motor, gearwheels) = 495 g
• 2x booms = 16 g (94 cm)
• External structure = 721 g
• Tip mass = 38 g

TOTAL = 1270 g

NOT AVAILABLE
Experimental tests – Results
Non controlled deployment

• Booms are kept in coiled configuration with a cable circled around the assembly to avoid self-deployment
• Cable is cut at t=0
• Booms deploy, shock load at the end of the deployment
• In some cases they would not deploy until the end (especially when they were coiled and released after some time – like in the photo sequence)

NOT AVAILABLE
Experimental tests – Results
Non controlled deployment

- From the accelerations chart:
  - Clear shock load at the end of the deployment
  - The spool oscillates around the equilibrium angle at the end of the deployment because of the shock load, i.e. the boom is in axial oscillation

- From the FFT chart:
  - Very noisy signal
  - Clearly possible to recognize the frequency of oscillation of the spool at the end of the deployment

NOT AVAILABLE
Experimental tests – Results
Controlled deployment/retraction

Oscillations are mainly due to:
• imperfections in the booms (they are not perfectly straight)
• they have some microcracks in the borders that generate a «non fluid» deployment and retraction

16x speed NOT AVAILABLE
Experimental tests – Results
Controlled deployment/retraction

Example from a deployment test (the results of the retraction would be similar)

• From the accelerations chart:
  • The dampers damp out the peaks of the oscillations, keeping the accelerations between -0.2 and 0.2 m/s^2
  • Some of the peaks of the accelerations (in blue) are due to friction between the spool and the booms during deployment
  • Clearly possible to see the end of the deployment at t = 420 s

• From the FFT chart:
  • The dominant frequency is due to the motor
  • The dampers damp out almost completely the peak due to the motor on the external structure.

Motor frequency:
23.74 Hz

NOT AVAILABLE
Experimental tests – Results comparison

In the non-controlled case (in red) the disturbances provoked by the quick deployment of the booms generate high accelerations with very broad frequency range.

In the controlled case (in blue), there is only one dominant peak that is damped out efficiently by the dampers.

Frequency (Hz)
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• What was done:
  • Numerical simulations on a free membrane (not presented here)
  • Numerical simulations and experimental tests on a deployable structure (deployer + booms)
  • Additional numerical simulations that were not presented here

• Summary of the results:
  • Benefits of a controlled deployment:
    • Lower accelerations imparted to the central body (but for longer time)
    • Vibrations can be damped out with simple passive dampers
  • More reliable deployment (after long time of stowage, the booms can lose their self-deployment capacity)
  • No shock torques, that are a concern when deploying membranes
  • Possibility to retract the panel whenever necessary

• Disadvantages:
  • Increased mass and volume
  • Increased complexity
THANKS FOR YOUR ATTENTION!