GT SMDO : Spacecraft Mass Simulator Project

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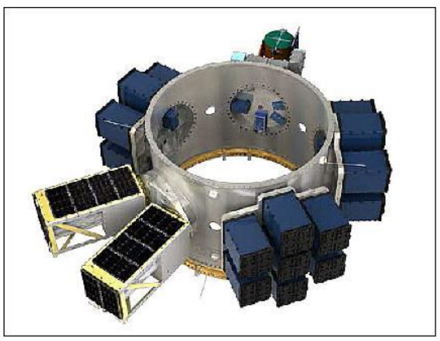
Project Objective:

The space industry often launches small-sat payloads with rideshare structures (see the image below). Structural engineers design their payloads to be 'inertially compatible' with the rest of the structure through coupled loads analyses (CLA). In other words, they ensure that their payload is designed to prevent resonance with other structural components so that other components don't fail (which would cost them a lot of money).



A growing problem in the industry is that contractors often fail to meet the requirements and have to take their payload (say payload A) off the launch. However, engineers from other contractors have spent months designing against payload A. In these situations, there are two solutions : (1) put a big block of steel (very heavy and expensive) to damp out the natural frequencies, (2) put a mass simulator structure in the place of payload A. Our goal is to develop a toolset that can design payload mass simulators for any payload.

Short objective: *Given 6 eigenmodes/frequencies, the payload mass, and the payload CG (center of gravity), design the simplest 'mass simulator' structure that matches the eigenmodes/frequencies, mass, and CG of the original payload*.

The aerospace corporation attempted to solve this problem over the past couple of months, and presented their work at Scitech (please read their paper, [Rapid Design and Analysis of a Payload Mass Simulator Using Digital Tools for Manufacturing Instructions | AIAA SciTech Forum]). However, they were unable to develop a general toolset and asked Dr. Kennedy and I to work on this.

Project Requirements:

- Match the mass m, center of gravity CG and natural frequencies ω_i to the reference structure $m_0, CG_0, \omega_{i,0}$ of original payload
- Ensure positive structural margins (stress constraints) from inertial loading of the launch vehicle, through a linear static analysis
    - Obtain inertial loads through a mass-acceleration curve $a(m)$, [mass-acceleration curve (NASA)](). We'll assume this curve is known/fixed and apply transverse inertial loads of this magnitude to our beam-like structure. Question is which transverse direction to apply it, let's just make an assumption here for now.
- Verify the natural frequencies ω_i do match $\omega_{i,0}$ through finite element modal analysis
    - What we'll do is run modal analyses for each design in a structural optimization to ensure that these match
- The structure needs to be easily manufacturable through additive manufacturing and with tools in the Aerospace Corporation machine shop.
    - This likely rules out traditional topology optimization methods that use artificial or intermediate material strategies to converge on a final structure.
    - They would prefer that we use a parametric CAD tool to design a beam-like structure.
    - Some suggestions from the Aerospace Corporation for having enough shape freedom in parametric CAD to converge on any set of inertial properties are to design tuning-fork or fractal-like structures. They started with simple tapered beam
- We need to maintain a fixed-size attachment part of the structure (see the Scitech paper)

Our Proposed Solution:

- The linear static analysis for structural margins and the modal analysis for natural frequencies ω_i will be performed in TACS, our finite element analysis tool
- Structural optimization for the panel thicknesses and shape variables of the parametric CAD will be handled by a module in TACS called 'caps2tacs'
    - We'll use optimization drivers in FUNtoFEM and the pyoptsparse optimizer
- Mode switching of ω_i which can lead to non-differentiability in the optimization will be handled by a modal assurance criterion (MAC)
    - The MAC computes a permutation map between the original structural modes and the new structural modes
    - I've used machine learning or kernel methods in the past to do the MAC when the finite element mesh between two modes don't match (shape change)
    - I think a cleaner way is to just use MELD in FUNtoFEM to transfer the eigenmodes from one mesh to another (during shape change), then we can do MAC on the same mesh. This can be performed from previous mesh or original mesh during optimization (it's just going to permute our eigenmode indices)
    - We also need to ensure that these matching frequencies are the first two or first 6 modal frequencies, so we may need to use some strategies from Bao Li's publications (we'll see). This part needs some more work

        - Here are two papers on Bao Li's work for topology optimization and adjoint methods for eigenvalue problems
            - Topology optimization using an eigenvector aggregate | Structural and Multidisciplinary Optimization
            - Adjoint methods for computing derivatives of functions of eigenvectors using shift-and-invert preconditioning | Structural and Multidisciplinary Optimization
- For the parametric CAD or shape design of the structure we'll use ESP/CAPS which has an interface called 'caps2tacs' in TACS
    - Aerospace corporation's first approach was a tapered beam structure, and they also suggested extending that using fractal or tuning-fork like structures.
    - My idea is to use a tapered beam with a number of ring-stiffeners. Each ring stiffener will have variable location and variable hole size, with panel thickness variables as well on each separate panel. We may need to add an outer integer optimization to determine the best number of ring stiffeners.
    - If you guys have other ideas for this structure, you are free to explore them. Maybe we could also add longitudinal stiffeners as well. We need to have enough shape and design variables to be able to get pretty close to any reference structure that experiences bending modes (question is how many do we often need?)
    - In 4_sizing_and_shape.py in this folder, I show how to optimize the spar and rib locations of a wing in ESP/CAPS, TACS, etc. We'll do something like this for internal structure position, tacs/examples/caps_wing at master · smdogroup/tacs
- The mass-acceleration curve to inertial load constraint will be enforced by FUNtoFEM

Relevant code links:

1. payload-mass-simulators – this will be the main repo we're going to run the examples and develop the code infrastructure for our problem.
2. TACS – for finite element analysis and gradient-based optimization
3. FUNtoFEM – we'll use this for the outer TACS optimization routines and MELD (for transferring displacements across meshes for modal assurance criterion)
4. ESP/CAPS – the parametric CAD tool that is interfaced with TACS (in the caps2tacs module) to allow shape optimization of a structure
5. pyoptsparse – a tool for nonlinear constrained optimization problems that we use for structural and shape optimization. We may look into some integer-optimization codes as well for changing configuration parameters like number of ring stiffeners, etc.

Starting Structure:

Let's begin by designing a ring-stiffened, tapered beam structure in ESP/CAPS with design parameters (analogous to shape variables) for the ring-stiffener locations and ring-stiffener hole sizes (as a fraction from 0 to 1). You'll want to use a parametric formulation of ring-stiffener locations that prevents stiffeners from crossing over each other during the optimization (they always occur in the same order) – if you want help on this I have some old code to do this. For our starting problem, we'll be designing against the following payload structure:

- Please convert the following from slinches to kg and inches to meters
- Mass of 1.007315 slinches, CG of (0.412529, 0.200275, 16.45522) inches
- First two x and y bending modes of 24.4 and 29.9 Hz
- Second two x and y bending modes of 42.3 and 45.2 Hz (for a total of 4 modes to start with)
- Get the attachment or base structure from the Vinay and Mason's Scitech paper.