LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-
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Springs For A Metric Ton Of Payload

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This is an internal working note
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Springs for a Metric Ton of Payload
Brian Lantz
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It was recently suggested that the payload for Advanced LIGO be increased to 1000 kg. We should try to avoid this, as added weight results in larger springs and/ or decreased range/ and or additional power dissipation for the isolation system. However, it seems possible to make a system which will work for a one metric ton payload.

Given the following design parameters:
material: Maraging 300,
E = 1.86e11 pascal,
yield = 2e9 pascal,
working point = 25% of yield
3 springs per stage
max length 50cm – to fit in the system
max width = ½ of length – helps things fit, also otherwise the stress gets weird
max thickness = ??. Wire EDM can cut any thickness
2 cm seems pretty thick, though, so let's use that for now.

max force of inner actuators = ?? 10 lbs (44 N)
desired max range of inner stage = 100 microns
max stiffness of inner stage spring = 44 N/1e-4 m = 4.4e5 N/m

max force of outer actuator = ?? 50 lbs (222 N)
desired max range of outer actuator = 300 microns
max stiffness of outer stage springs = 7.4e5 N/m

For a system with a 700 kg first stage and a 750 kg second stage, it is possible to meet the various requirements with a 1000 kg payload. It is not easy or pretty, and the design space is getting cramped, but it is not impossible.

This calculation was done using a design tool that Dan DeBra wrote and I modified. Some output from that code is included below. The units are all SI, except the actuator force, which is in pounds (since that's how they are spec'd). Output from the design tool is included below – a possible solution is:

inner stage spring (set of 3) 35 cm long, 10.4 cm wide, and 15.1 mm thick
combined vertical stiffness is 7.9e5 N/m
each vertical actuator need 5.9 lbs to push 100 microns

outer stage spring (set of 3) 35 cm long, 12.3 cm base, 16.6 mm thick
combined vertical stiffness is 1.21e6 N/m
each vertical actuator need 27 lbs to push 300 microns

The coupled vertical frequencies are 3.0 and 8.9 Hz
These springs are big, but acceptable

Included are excerpts from the design tool output. There is text and there are some diagrams. The text includes some user input and should be self explanatory. The two diagrams show the available design space for the two springs.

The given parameters are

1) the number of springs,
2) the material properties,
3) the spring's working point as a fraction of the yield stress, and
4) the masses of the stages.

Then, given a length and a stiffness (or frequency), the tool solves for the base width and the spring thickness.

The blue and magenta diagonal lines are the solution sets for particular stiffness values. Various limits are shown in the graphs. The 'x' marks show the design point generated in the text.

```
           inner stage HAM

SupportedMass =
        1750
inner_dist =
  1.0000e-004

freq of inner stage? 4
finlbs =
  5.9191e+000
the total vertical inner stage stiffness is 7.90e+005 N/m
to push 100 microns, each inner stage vertical actuator needs 5.91908 pounds
choose the blade length (m): .35
inner_base =
  1.0446e-001
inner_thick =
  1.5161e-002

           outer stage HAM
freq of outer stage? 8.5
foutlbs =
  2.7146e+001
the total vertical outer stage stiffness is 1.21e+006 N/m
to push 300 microns, each outer stage vertical actuator needs 27.1464 pounds
choose the outer blade length (m): .35
outer_base =
  1.2265e-001
outer_thick =
  1.6555e-002
The coupled resonant frequencies are (final design):
ans =
  8.9137e+000
  2.9658e+000
   >>
```

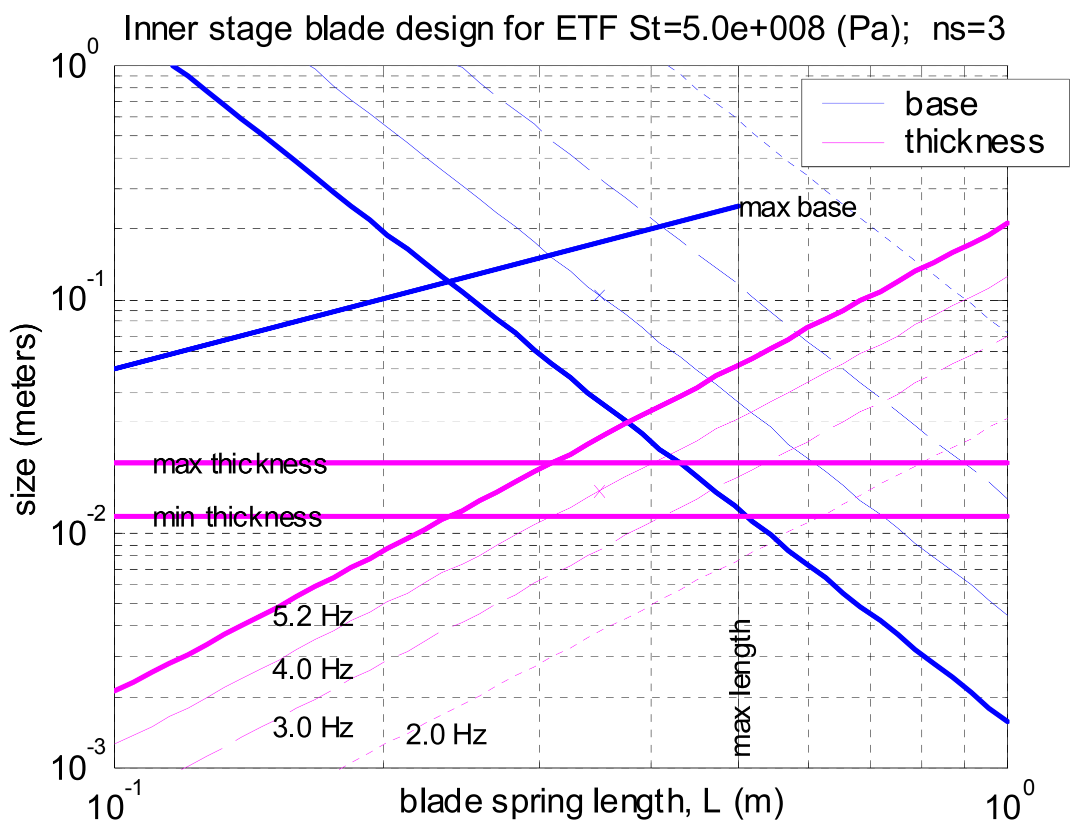

Figure 1. Possible design for the inner stage blade springs of an isolation system similar to the ETF Technology Demonstrator. The stage masses are: stg 1 = 700 kg, stg 2 = 750 kg, static payload = 500 kg, dynamic payload = 500 kg. The diagonal magenta lines show the relationship between length and thickness given a particular stiffness. The diagonal blue lines show the relationship between length and base width for the same set of 4 stiffness values. For example, a 4 Hz spring 30 cm long will be about 11 mm thick and 17 cm wide at the base, while a 4 Hz spring 35 cm long (the two x marks) will be 15.1 mm thick and 10.4 cm wide. The heavy diagonal lines correspond to the maximum stiffness that a 10 lb actuator can displace by the current distance req (100 microns). The line called 'max base' shows springs that are half as wide as they are long. Our springs should probably not be wider than this. The 'max base' requirement implies a minimum thickness which is also shown. The maximum thickness and maximum length requirements are arbitrary. The frequencies correspond to the mass of the inner stage plus static payload suspended from the inner stage springs. (The outer stage is fixed, the dynamic payload springs and masses are ignored.)

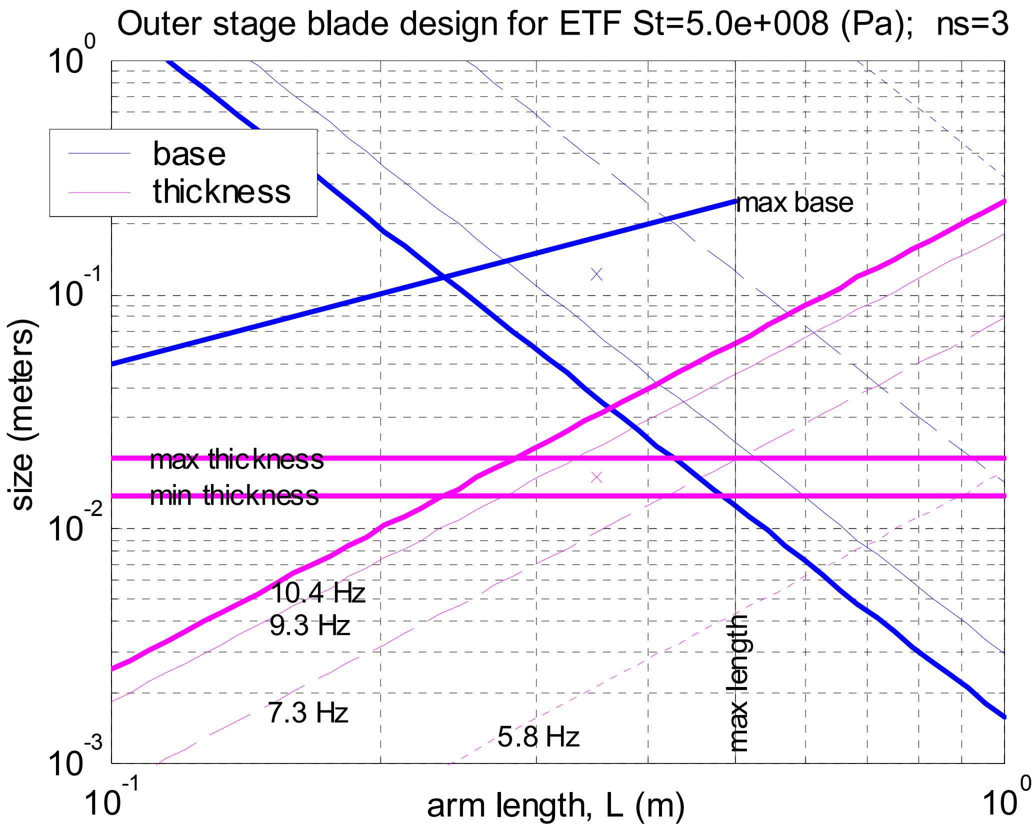

Figure 2. Design figure for the outer stage springs. The figure is similar to that in figure 1. The design point shown is for 3 springs with combined vertical stiffness of 1.21e6 N/m = 8.5 Hz 'frequency', and 35 cm long, which results in a 12.3 cm base and 16.6 mm thickness. The frequency calculated is for the outer stage mass (700 kg) suspended by the outer stage springs to a fixed foundation **and** by the inner stage springs to an inertially fixed inner stage. This is sort of what the open loop plant for the outer stage will be like if the inner stage control is on. The maximum stiffness is calculated for 50 lb force actuators generating 300 microns of displacement.

The code used to generate these calculation is included. It is called LIGO_stage_designer2.m. The formulas for the base width and thickness are:

```
function B=Base(ElasticMod,StatForce,Length,StressLevel,kspring)
E=ElasticMod;
F=StatForce;
L=Length;
St=StressLevel;
kv=kspring;
B=(6 * E^2 * F^3)./(L.^3 * St^3 * kv^2 );

function h=thickness(ElasticMod,StatForce,Length,StressLevel,kspring)
E=ElasticMod;
F=StatForce;
L=Length;
St=StressLevel;
kv=kspring;
h=(L.^2 * kv * St)/(E * F);
```

If one sets the ratio of the base divided by length to be fixed (let B/L = width_ratio = .5), then one can combine these equations to solve for the minimum blade thickness. This works out to be

```
min_thickness = sqrt(6/width_ratio) * sqrt(Load/allowed_stress);
```

One can then plot the minimum blade thickness as a function of the payload, as shown in figure 3.

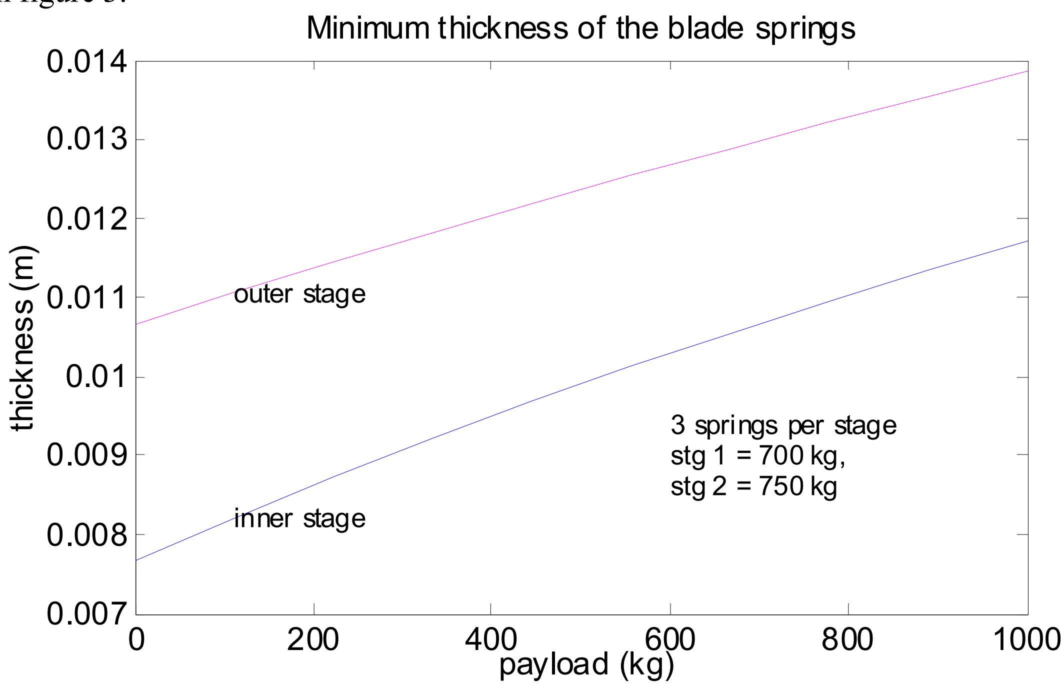

Figure 3. Minimum blade thickness as a function of different payloads.

This figure was generated by min_thickness.m