Suspension parameter sensitivity analysis

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Outline

- Introduction – suspension design tools
- Important features of suspensions
- Two approaches to sensitivity analysis
  - changes in the transfer functions
  - changes in the system poles

Advanced LIGO suspensions

Quad Noise Prototype

Notes

- Suspensions with N stages have 6N rigid-body degrees of freedom
  - X – in beam direction “longitudinal” with ROLL the angle about that axis
  - Y – the transverse horizontal axis, with PITCH the angle of rotation about it
  - Z – vertical (local frame), with YAW the angle about it.

- Suspensions with N>2 usually have N–1 stages fitted with blade springs to make them relatively soft in Z

History

- 1980s and early 90s – double pendulums at Garching and Glasgow prototypes
- 1990s (Calum Torrie) MATLAB model
  - – assumes left-right and front-back symmetry so that the N-stage by 6 degree of freedom system is represented by 4 separate models of N, N, 2N and 2N dof.
  - – optimisation is relatively straightforward due to the above simplification and also as there were only 2 or 3 stages
- 2000s Advanced LIGO suspensions
  - – the need for large blade springs (mounted at an angle to save space) and complex adjusters (significant off-axis moments of inertia) led to mixing of the 4 separate models
    - – this mixing was initially ignored in modelling

Design tools

- 1990s: MATLAB model for 3 and later 4 stages, for symmetrical suspensions (model is not very flexible)
- 2000s: encapsulate this in Simulink model to include local and global controls (examples in our lab-books)
- 2000s: (Mark Barton) Mathematica model (Toolkit plus instances). Extensible, breaks symmetry if desired, but is complicated and can be slow.
- 2005: MATLAB code adapted to include state-space matrices exported from Mathematica. Generally compatible with original MATLAB approach, but allows cross coupling to be included (for the aLIGO Quads, all 720 TFs have significant magnitude around 1 Hz)

What matters for suspensions

- Isolation and thermal noise
  - our design approach gives comparable isolation in all dofs, so cross coupling does not typically lead to reduced isolation or increased thermal noise in the science band (above 10 Hz for aLIGO).
- Local control
  - easy for GEO, all 6 controllers on the top mass have the same loop, and so cross-coupling does not create any problems and sensitivity to parameter variations is small
  - harder for aLIGO, at least for X, the noise from such a controller is too high (sensor noise transmission at 10 Hz) so another technique, i.e. modal control, which is, however, quite sensitive to parameter variation
  - note that ECD (as for AEI 10m) makes for very robust “control”

What matters for suspensions (2)

- Global control
  - problems were/are seen in GEO with the crossover between intermediate mass and mirror feedback on MCe and MCn, for longitudinal and alignment feedback
    - believed to originate from asymmetry and parameter variation in these suspensions
    - never fully understood, difficult to model accurately due to too many unknowns
  - try to avoid this situation for aLIGO, in particular there are 3 interferometers, lets aim to have the same controllers for all 3.

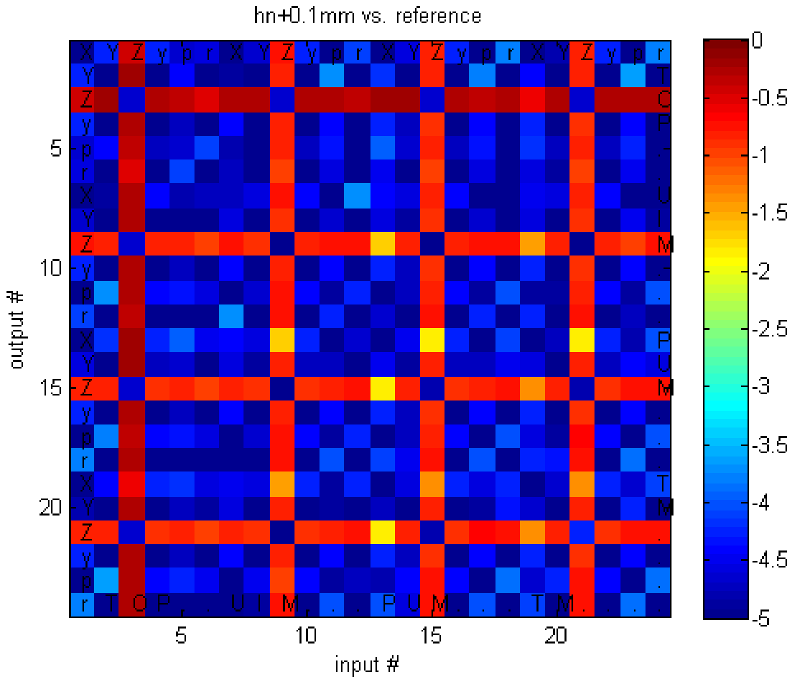
Parameters

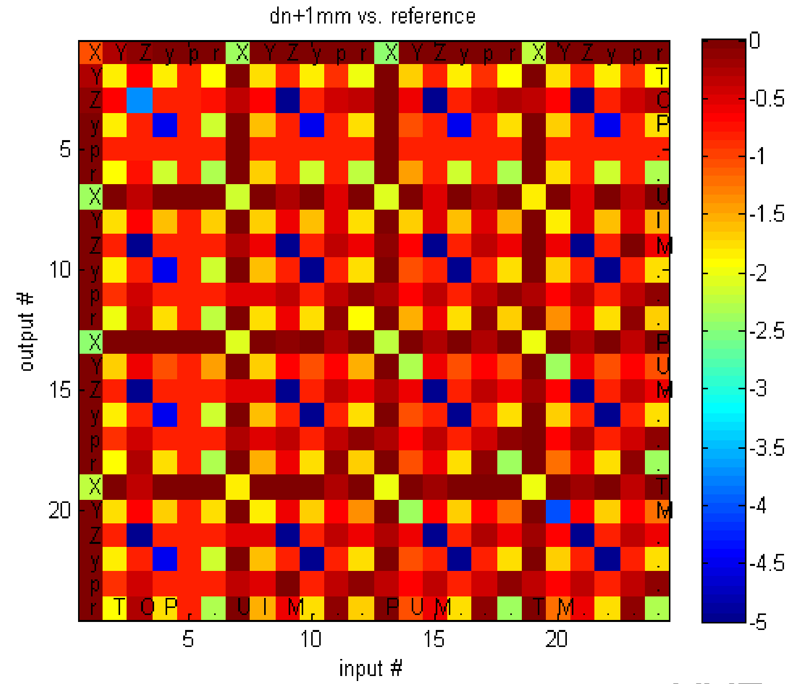
- The suspension is specified by
  - N masses, and the associated moments of inertia.
  - the blade springs
  - the wires (usually 4 per stage except 2 at top)
  - the attachment points among the above (referred to the centre of mass at each stage)
- These parameters predict system poles of varying frequency and Q
- Another description is the transfer functions from the 6(N+1) possible inputs to the 4N possible outputs
  - not all of these are available/used in the real system
  - strictly N+1 to include the suspension point as an input, note only 6N shown in following plots as the first and second 6 sets of TFs differ only by a scale factor.

Transfer function approach

- MATLAB based, using Mathematica-generated quad model with all cross-coupling included
  - calculate the (24x24) TFs for the reference and perturbed suspensions (one parameter at a time, takes a few s)
  - find the ratio of the magnitudes of these TFs over the frequencies occupied by the modes: 0.2 to 6 Hz for aLIGO, with 1013 (= enough) log-spaced sample points
  - sum the ratio to obtain a single number for each TF
    - works quite well because most features are "reasonably symmetrical" in frequency (peaks or troughs)
  - compare this number to that for no change (1013 here)
    - take log10 of that difference
  - plot a log image of the result (examples follow), with Jet colorbar and [-5,0] colour scale
    - blue/green colours mean almost no change
    - yellow suggests a small change, probably not important unless the controller is very sensitive to changes
    - red indicates a change that needs investigation

Example results: TF method





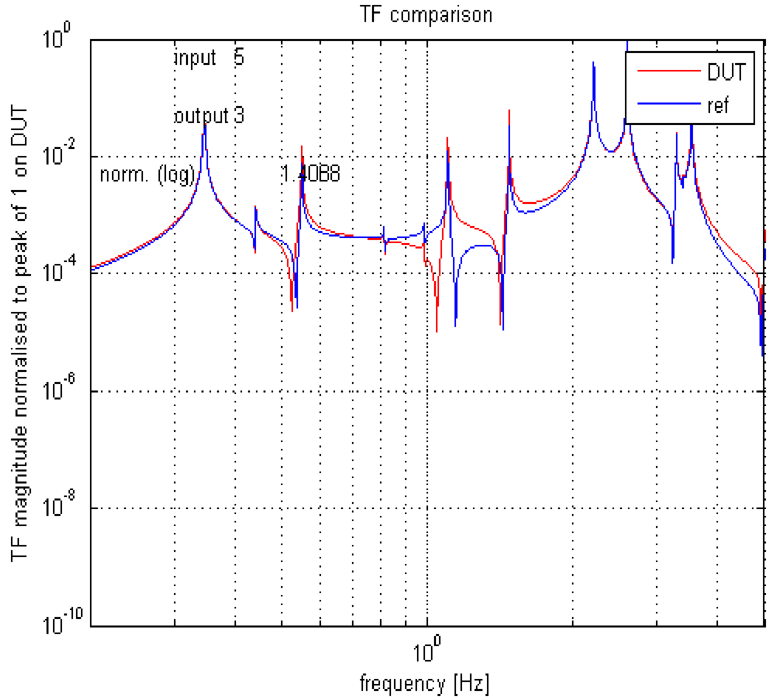
XYZypr

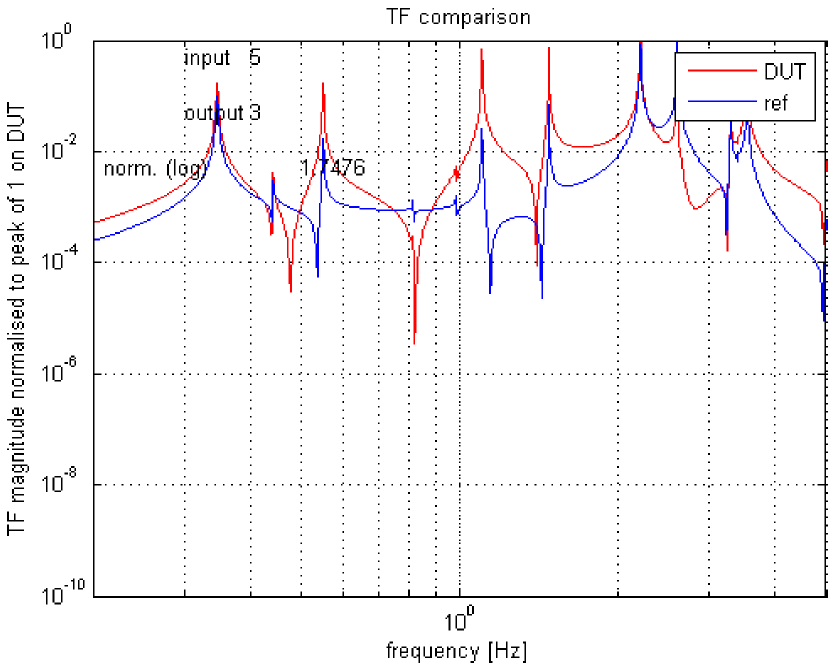
- 100 micron change in front-back position of top mass centre of mass
- z–non-z TFs affected, little else, some controllers will tolerate this

10x larger change (1mm) causes moderate alteration of in many TFs

likely to cause problems unless the controller is quite robust

Examples: TF method





- the (5,3) TFs from the small change (pitch–z)
- this could affect modal control, (i.e. poorer performance but still stable)

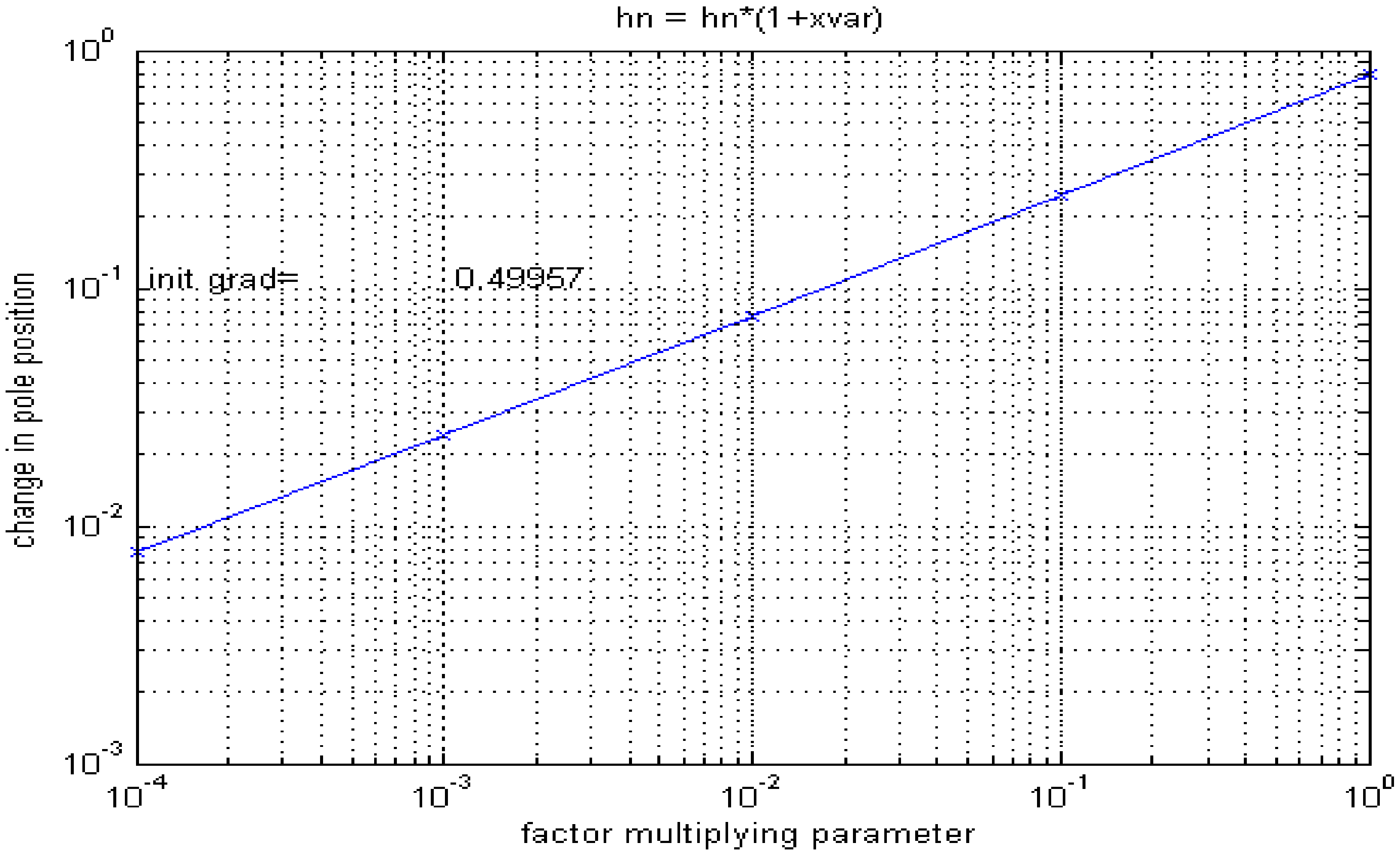
same TF for the larger shift

easy to see why modal control could have trouble (look at ~1 Hz)

Pole method

- Uses the same MATLAB model
  - obtain poles for reference and perturbed suspension (one parameter at a time), for 5 logarithmically-spaced variations of the parameter (from 10^{-4} to 1 times a nominal value: 1mm in the example)
  - calculate the distance between the two sets of poles on the complex plane (assume that the ordering of poles over frequency does not change, see below)
  - loglog plot the total distance against the parameter change
  - use the smallest changes to estimate the gradient and either the largest value or an extrapolation to estimate the sensitivity (human intervention copes with the re-ordering of poles if the perturbation is too big, normally for >>1mm in a stable design with well-spaced modes as for aLIGO)

Pole example, same parameter up to ~1mm shift of c.o.m.



Conclusion

- Even with ~10x tighter production tolerance on aLIGO suspensions (100 microns for many of the key parameters for a person-sized structure), care will be needed to assemble the suspensions very well to avoid having to trim the controllers to match each suspension
- These tools provide a quick guide about which parameters have the biggest effect
  - versions that run directly in Mathematica are planned to allow assessment of parameters that are not normally included in the MATLAB version
- Of course the right way to do this is to model plant and potential controllers together, but for that we need to know the control topology (not quite decided yet).

References

MATLAB models

- Thesis, C.I. Torrie, Glasgow.
- Examples on GEO Logbook e.g. original logbook p 2688, also others in the 2000+ page range (e.g. on SR loop design)

Mathematica Models

- Mark Barton's pages on the LIGO wiki

https://awiki.ligo- a.caltech.edu/aLIGO/Suspensions

/MathematicaModels

("albert.einstein"   LSC login needed)

My recent work

- T1100175-v3 on the LIGO DCC.