Twin Cities
ANSYS® User Meeting
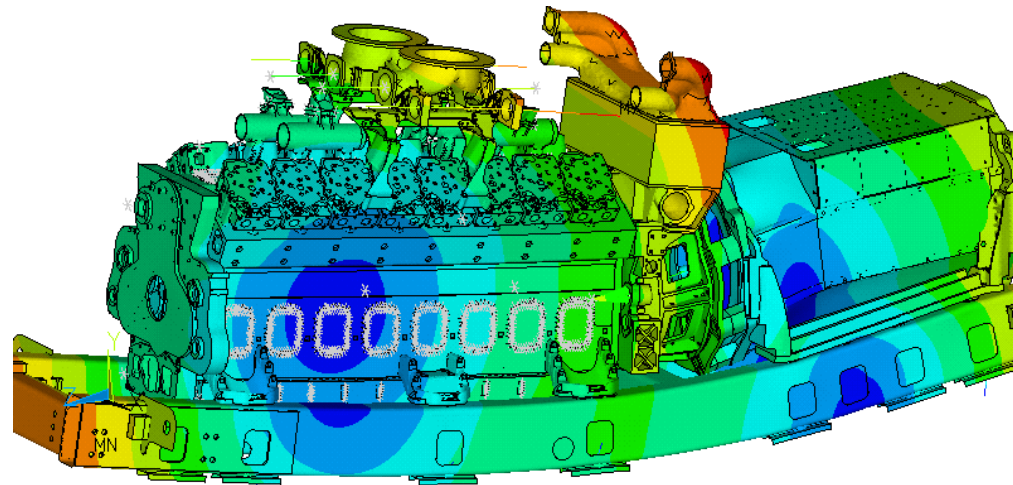
November 2014

Modal Analysis Correlation

… within Epsilon

Modal analysis and more
--- QSK95 Generator set development
--- 11/19/2014

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-- MANY thanks to
Jason Cheah for all the
MATLAB support!!!

Agenda (QSK95 development case study)

- QSK95 background – just released, new generator set from Cummins. With a movie!!!

- Why so much modal analysis? – support of dynamic model (Excite)

- Modal analysis tips and tricks (likely why you came to this)

- MAC analysis basics, tips and tricks – MATLAB vs specialized tools like LMS/Virtual Lab

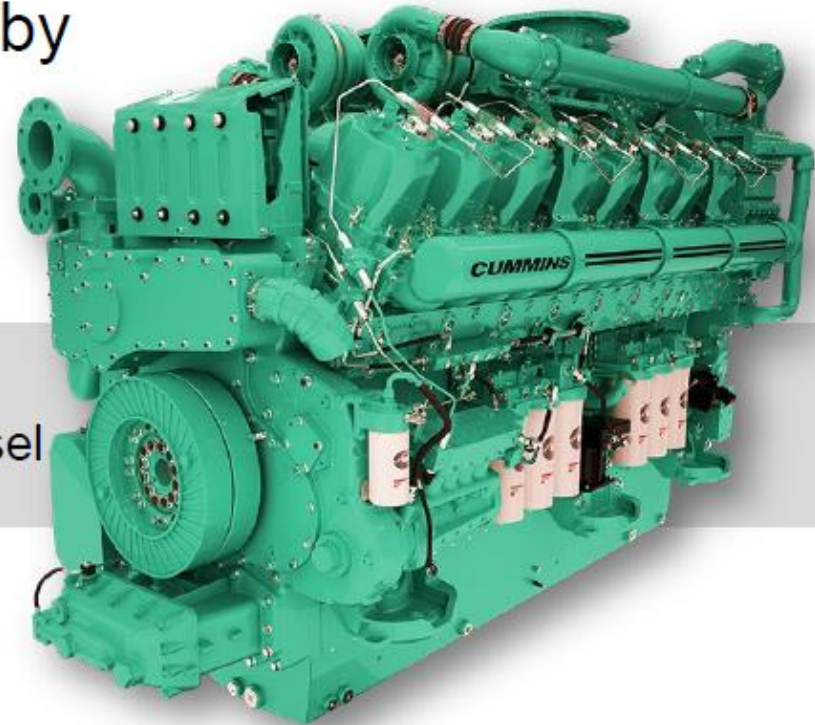- MATLAB optimization, tips and tricks – making the model better
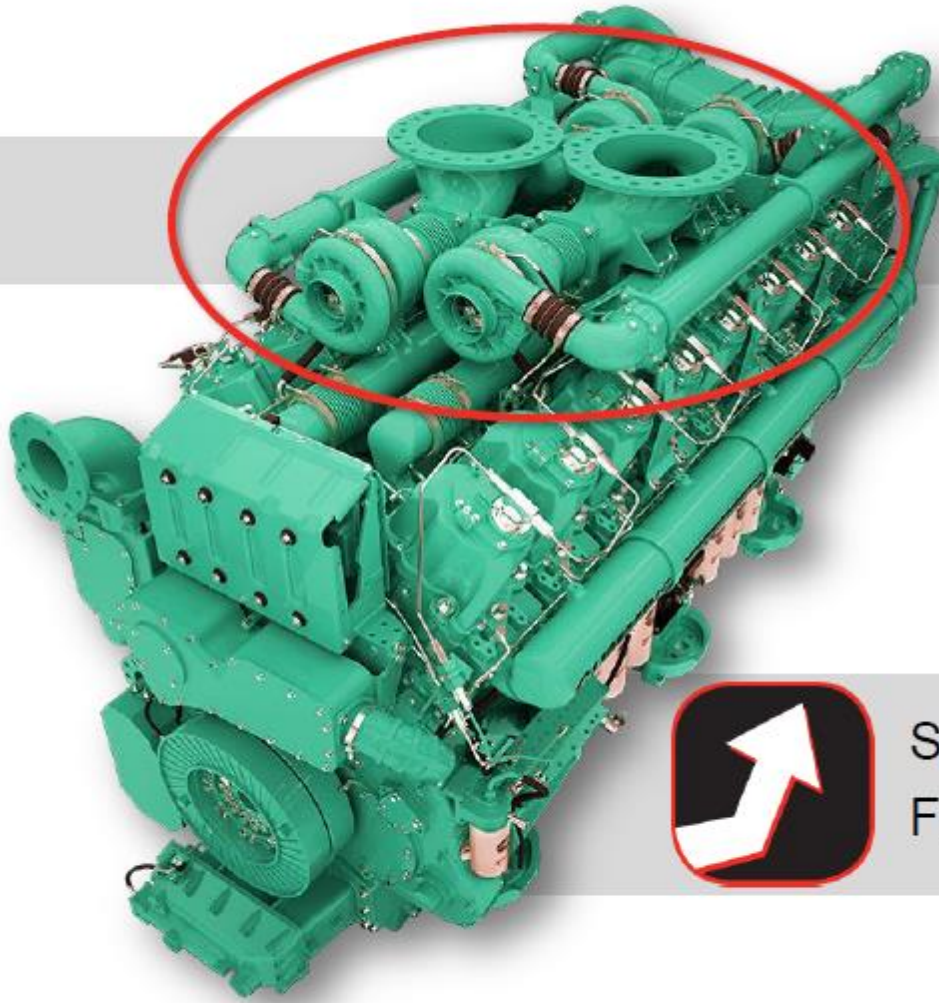
QSK95 Generator Set

More Power

5100 hp standby
4400 hp locomotive
4000 hp continuous

The most powerful ever
16-cylinder high speed diesel

The Power of More™

Cummins Power Generation

QSK95 Generator Set

More Performance

4 x Cummins turbochargers

Single-step **100%** load capability
Full load in just **8.5** seconds

The **Power** of **More**™

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Why so much modal analysis—

- If poorly designed, the product will vibrate excessively and eventually fail.

- Structural modes must not interfere with operational orders. This becomes very costly as things get bigger.

- Cost of failure is very high. Sometimes these sets are installed in buildings where removal requires cutting holes in walls, etc.

- So good design requires modal and dynamic analysis. The dynamic part involves multi-body dynamic analysis with explosions (pressure pulses) in cylinders, pistons going up/down etc. AVL Excite is used.

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Dynamic model -- AVL Excite background

- Excite dynamic model includes full crank train, flexible coupling and alternator rotor.

- All bodies are flexible / compliant

- Turbo's ARE included, but not spinning

- Model is driven by pressure pulse applied in cylinders

- Simulation is in the time domain

- Excite is an engine specific modeling tool. It does many things that would be extremely difficult to duplicate in ANSYS. EX - models the engine oil flow along with the dynamics and predicts the bearing oil film pressure which helps predict wear.

Dynamic simulation relies on condensation of the FE bodies by Component Mode Synthesis (Craig-Bampton technique)

For more info:
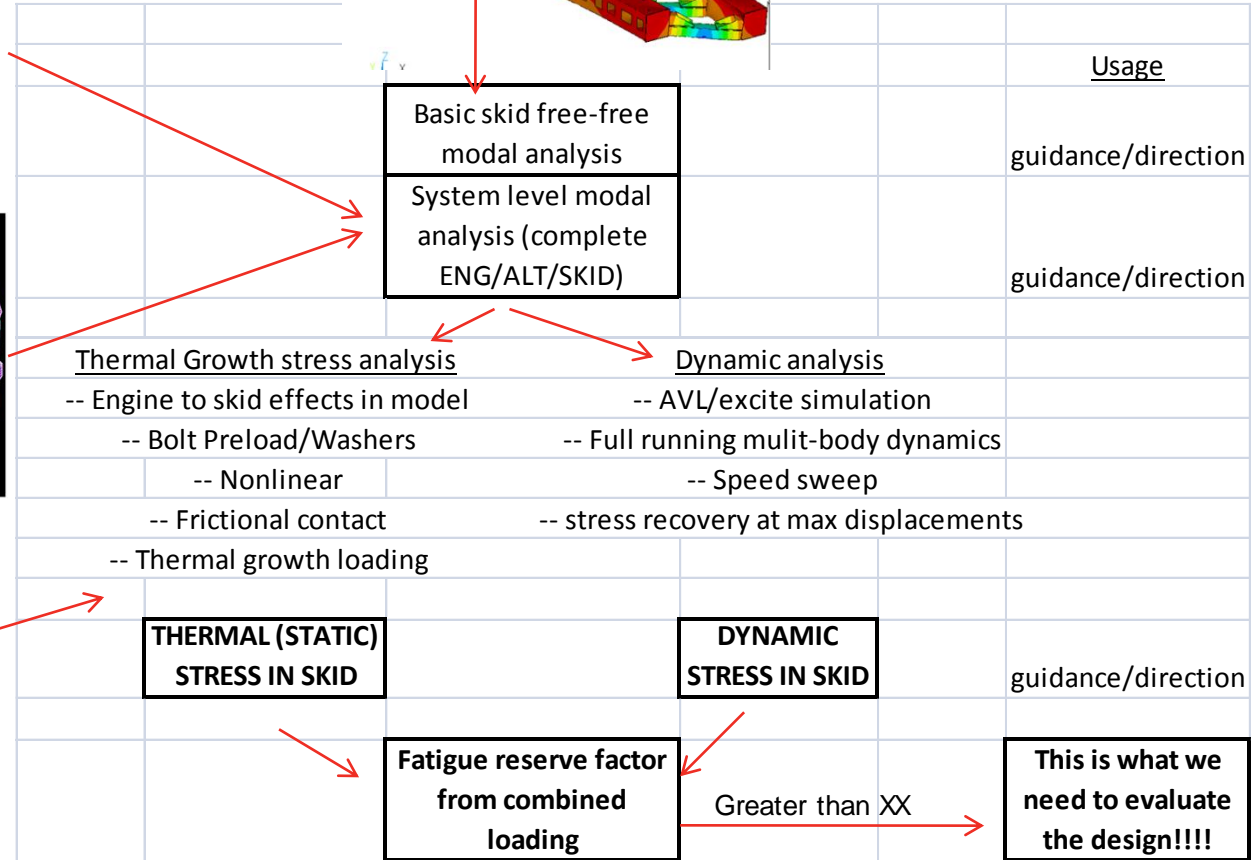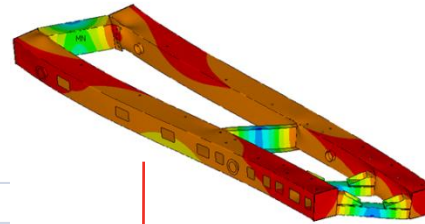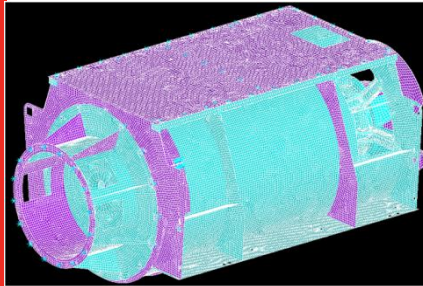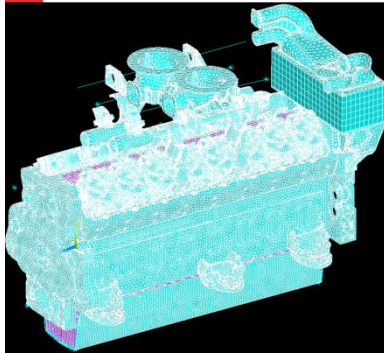https://www.avl.com/excite/

Generation
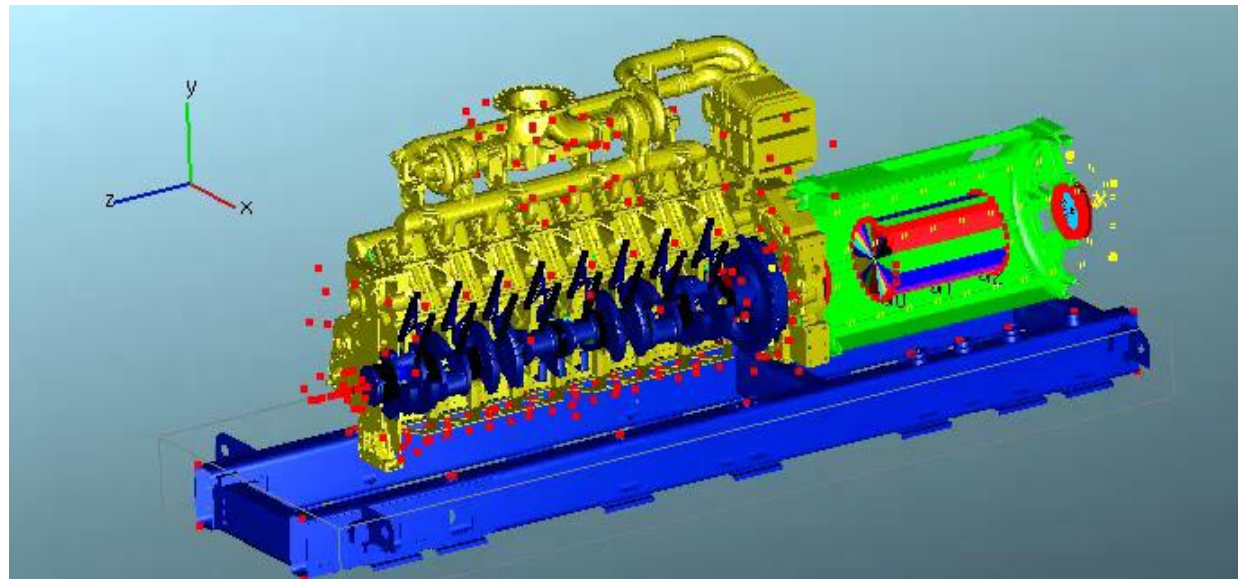
What is Craig-Bampton?

- Method for reducing the size of a finite element model.

- Combines motion of boundary points with modes of the structure assuming the boundary points are held fixed.

- Accounts for both mass and stiffness (unlike Guyan reduction)

- Problem size defined by frequency range

- Allows for different boundary conditions at interface (unlike modal decoupling)

- Need master nodes in ANSYS at all attachment points

- http://femci.gsfc.nasa.gov/craig_bampton/Primer_on_the_Craig-Bampton_Method.pdf

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REVIEW: Large Gen-set durability analysis

Engine FE Model

Usage

Basic skid free-free modal analysis

guidance/direction

System level modal analysis (complete ENG/ALT/SKID)

guidance/direction

Thermal Growth stress analysis
-- Engine to skid effects in model
-- Bolt Preload/Washers
-- Nonlinear
-- Frictional contact
-- Thermal growth loading

Dynamic analysis
-- AVL/excite simulation
-- Full running mulit-body dynamics
-- Speed sweep
-- stress recovery at max displacements

AVL dynamic model

THERMAL (STATIC) STRESS IN SKID

DYNAMIC STRESS IN SKID

guidance/direction

Fatigue reserve factor from combined loading

Greater than XX

This is what we need to evaluate the design!!!!

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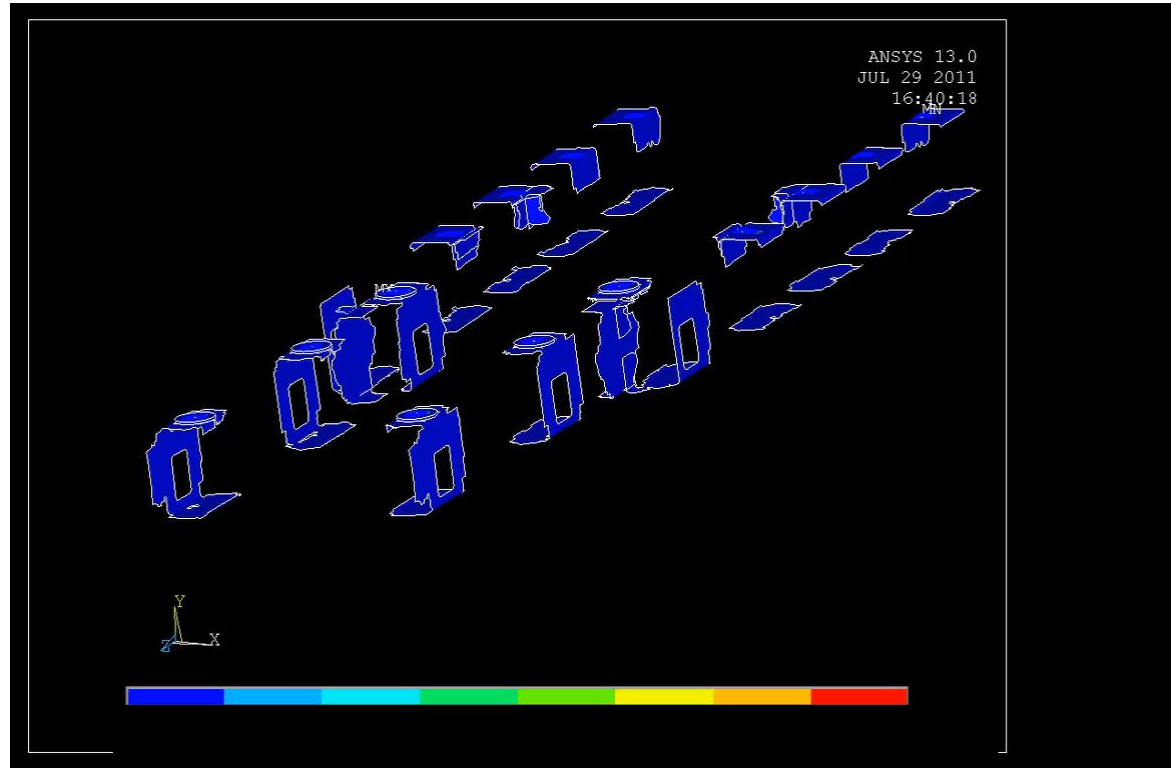Cummins

Stresses in the skid at a certain engine speed

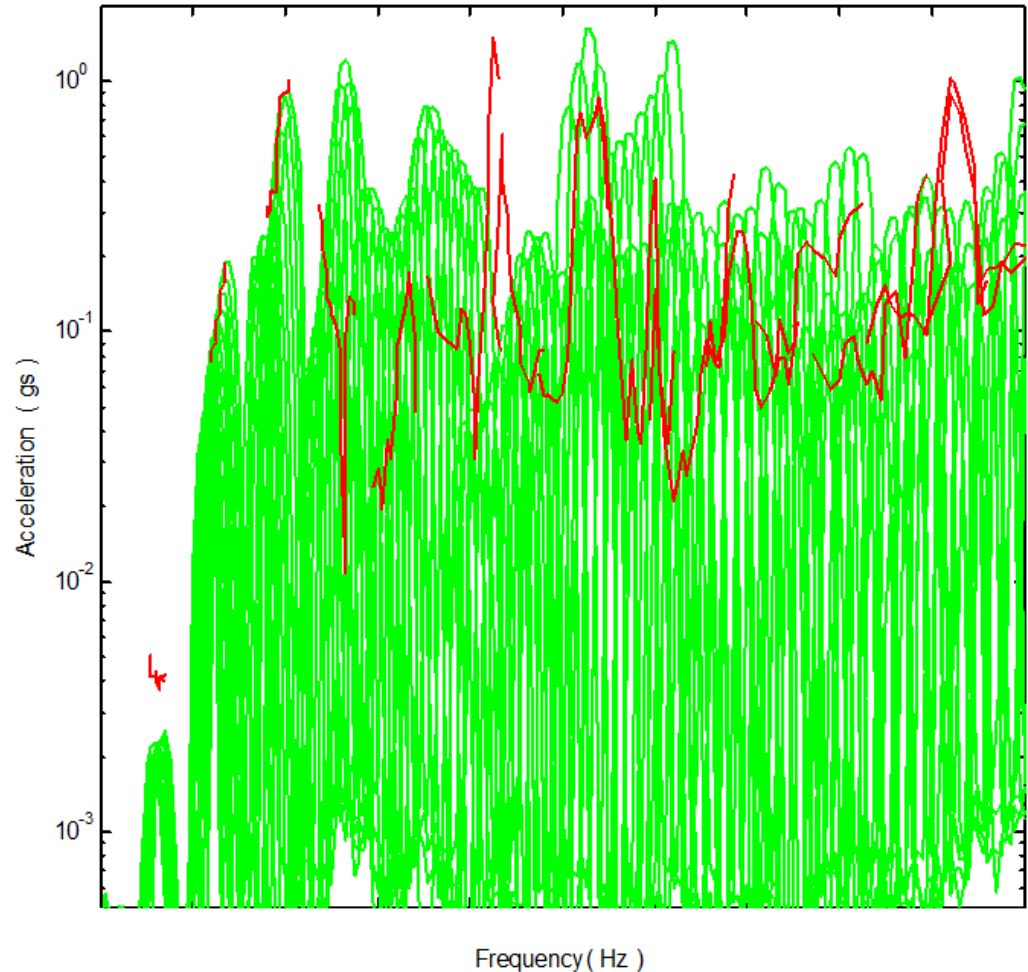Stress is compared to the endurance limit

Problem: We would like better correlation between test and analysis

Linear Vibrations – Generator End of Skid Base - Transverse

Sample of linear vib correlation – not bad up to ~50 Hz…
-- this is best of best

Green – Excite
Red – Test

Problem: We would like better correlation between test and analysis

The green lines are the EXCITE results: 30 rpm steps. The black lines are the average spectrums of the measured data: order by order: 15 rpm steps. The dotted blue line is the measured peak hold spectrum of a speed sweep. The red lines are the TVSIM2 results.
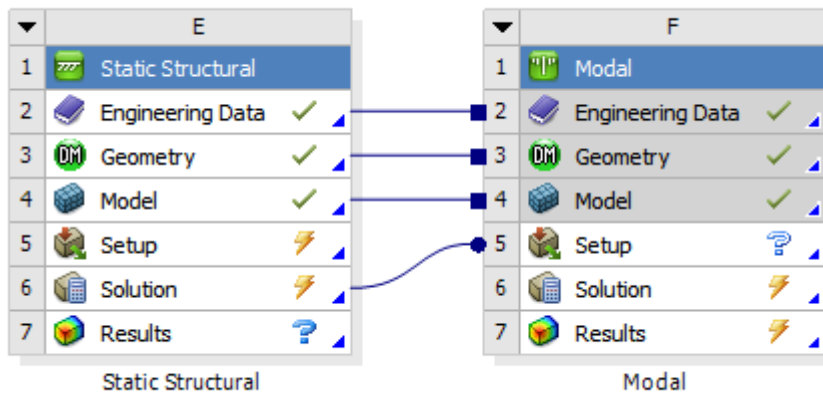
Of course torsional correlation is much better/simpler…
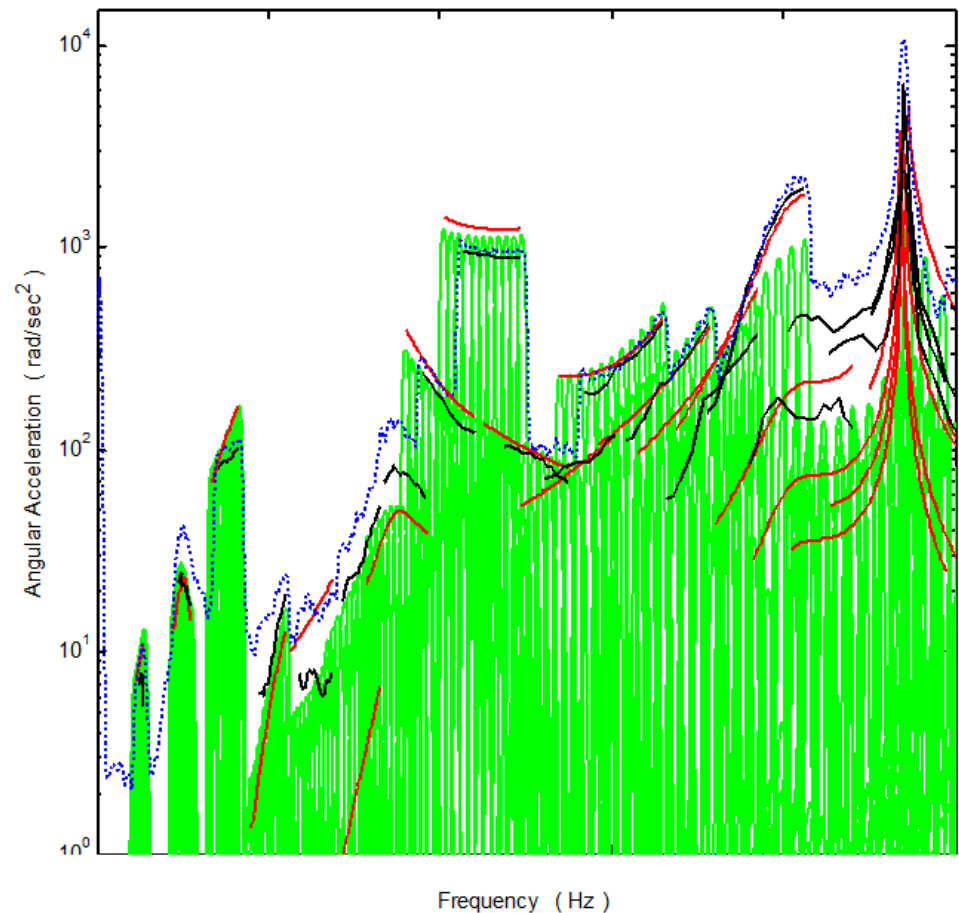
So to improve the correlation, we need to get the modes of the structure properly represented. This is why we do so much modal analysis… Fortunately we have some modal testing to correlate against. Here are a few tips and tricks:

- Typically using the block lanczos solver… Any comments on that?

- Recommendations:
  - Always run a free-free modal and make sure your rigid body modes are zero. If not, debug. Don't block these out with a frequency range.
  - Never rotate CERIG's!
  - For mass elements --- don't ignore the rotational inertia's
  - Minimize contact. Even with the MPC option, issues have been seen. This is currently under further scrutiny.

- There is nothing in the world that is infinitely stiff. So use constraints in a modal analysis with caution. Hopefully the test/real system is isolated with isolation modes well separated from structural modes. If not, there may be participation with the foundation. (simulations with constraints on the structure of interest is rarely correct)

- For shaker table correlation the test article modes frequently interact with the fixture, so its not uncommon to have to include the fixture for correlation.

- Don't ignore pre-stress effects (think of the guitar string)

- Isolation can effect structural modes, especially if the structure is tall. Its wise to include isolator springs in the model (after checking the free-free modes as mentioned above)

- When using Classic, switch to win32 mode to save AVI movies

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Modal tip and tricks—at least a little here on ANSYS…

Pre-stressed modal in WB

To reduce modal solution time
- extract the LANB solutions in chunks over ranges (and combine the .rst's if necessary)…
- large ranges harm solution speed… especially empty regions.

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So what the heck is MAC analysis?

- A modal analysis will be correlated with a test when the frequency and the mode shape is correlated. The tool used to compare shapes is the MAC (modal assurance criterion) table. It's nothing more than a vector dot product that is scaled such that the values will range between 0 and 1. Zero is no correlation and 1 is perfect correlation.

- There are commercial codes to calculate the MAC table such as LMS/Virtual Lab correlation. However, Jason the "MATLAB wiz" has coded this into MATLAB. This might be of interest for those who want to dabble in this with minimal investment. The only significant thing missing is the side-by-side movies:
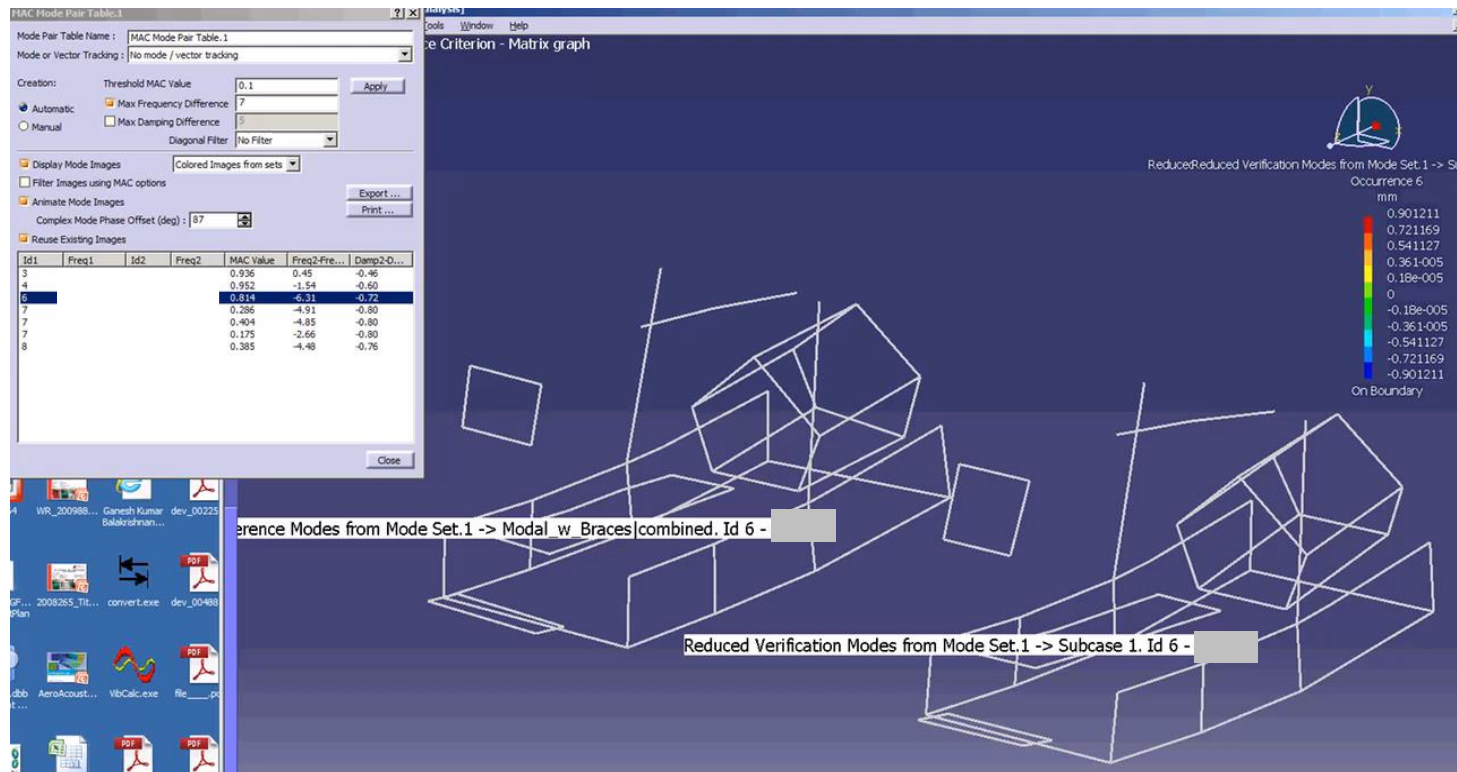
MAC details…

- Comparing simple vectors of numbers from the test and analysis
- I used Classic/APDL to automate the post processing, to get the results at nodes rear the test locations
- Recommend using RSYS for cases where the acels are in a different coordinate system than the model

The modal assurance criteria (MAC) was first presented in 1980 [1] by Allemang and Brown. In general it measures the degree of proportion between two modal vectors in the form of a correlation coefficient. MAC is defined in equation 1.

$$MAC(\{\psi\}_r, \{\psi\}_s) = \frac{\left|\{\psi\}_r^{*t} \{\psi\}_s\right|^2}{\left(\{\psi\}_r^{*t} \{\psi\}_r\right)\left(\{\psi\}_s^{*t} \{\psi\}_s\right)} \quad (1)$$

NOMENCLATURE

$\{\psi\}_r$	r^{th} mode shape/ eigenvector
$\{\psi\}^{ext}$	extended mode shape/ eigenvector
$\{\psi\}^{*t}$	complex conjugate and transponate
ψ_{ij}	i^{th} mode shape, j:th coordinate location
$[\Psi]$	mode shape/ eigenvector matrix

More info:
http://sdrl.uc.edu/sdrl-info/doc/Papers/IMAC2002-MAC20Years.pdf
http://sem-proceedings.com/16i/sem.org-IMAC-XVI-16th-Int-163801-Modal-Assurance-Criteria-Value-Two-Orthogonal-Modal-Vectors.pdf
http://www.plm.automation.siemens.com/en_us/products/lms/virtual-lab/correlation/

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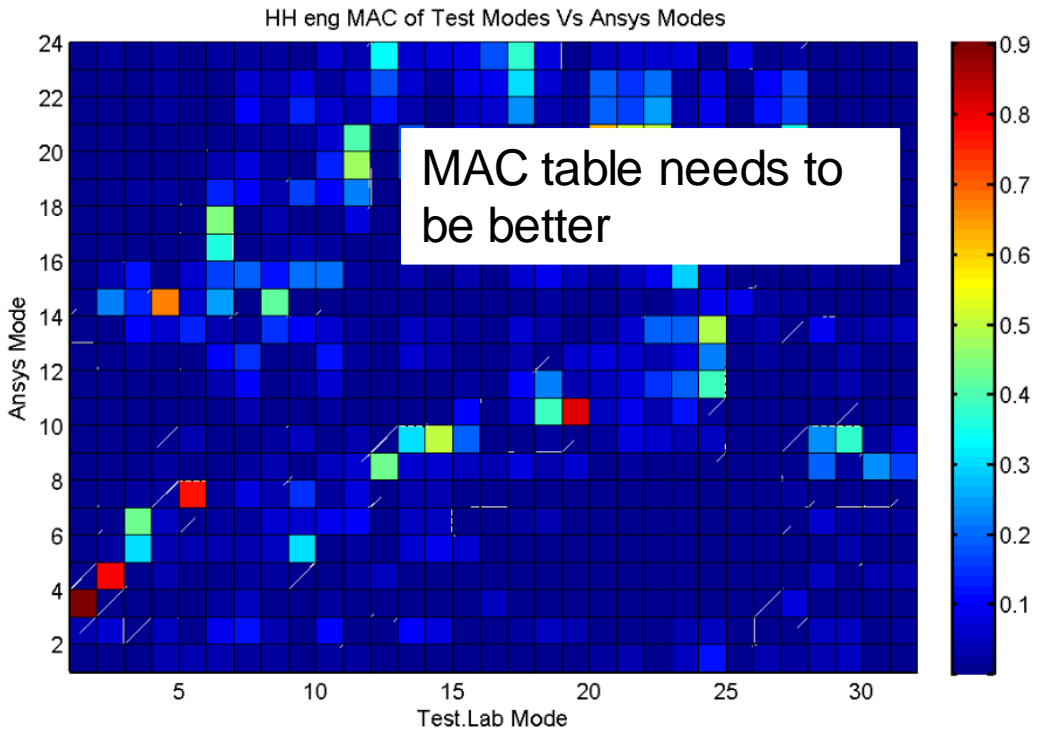Cummins

Model correlation

- Lesson learned – before building up Excite model, get the modes right to a certain frequency (exact number is TBD)

- Start with the pieces and build up from there
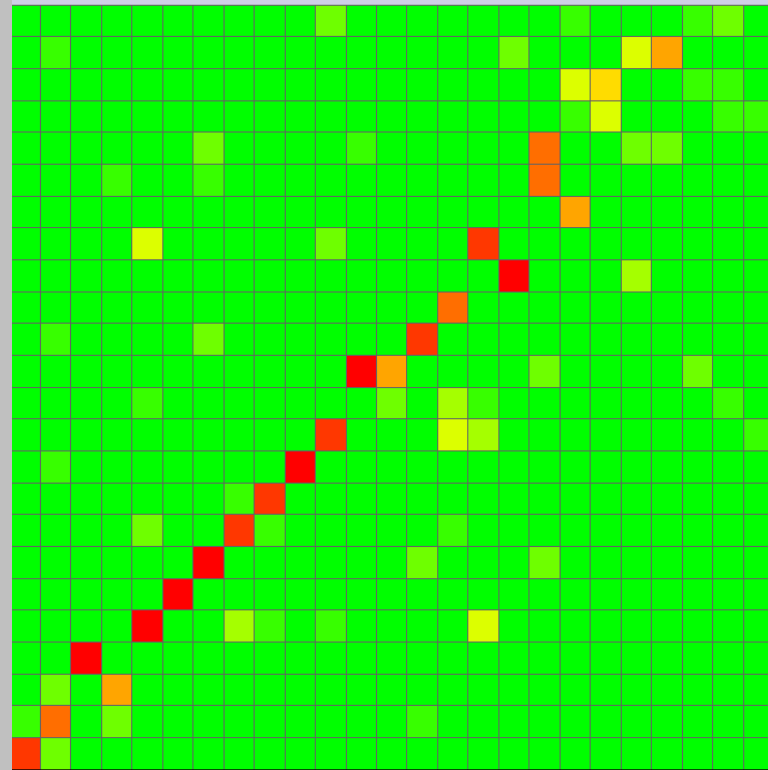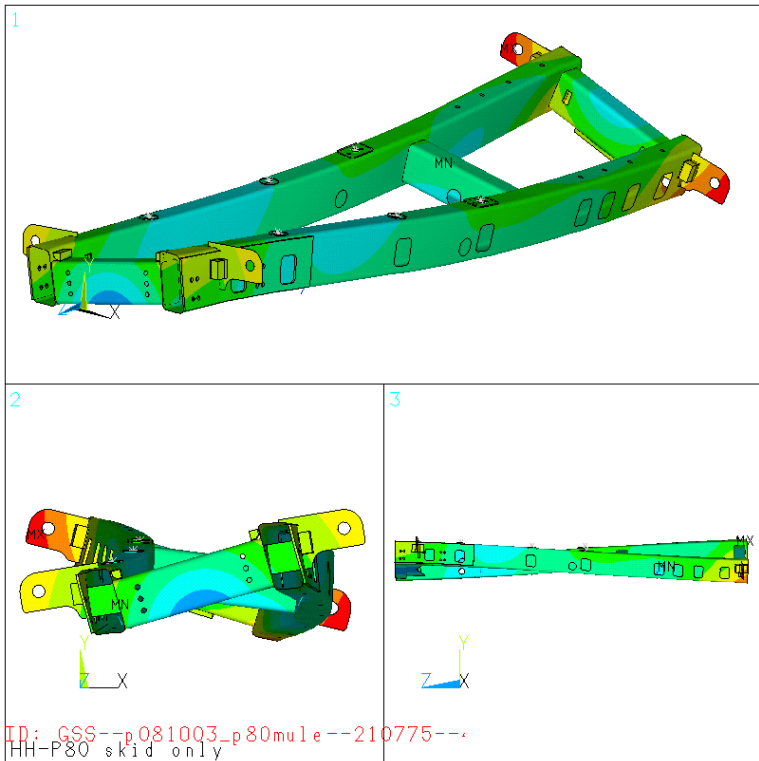
- IE: QSK95 engine:
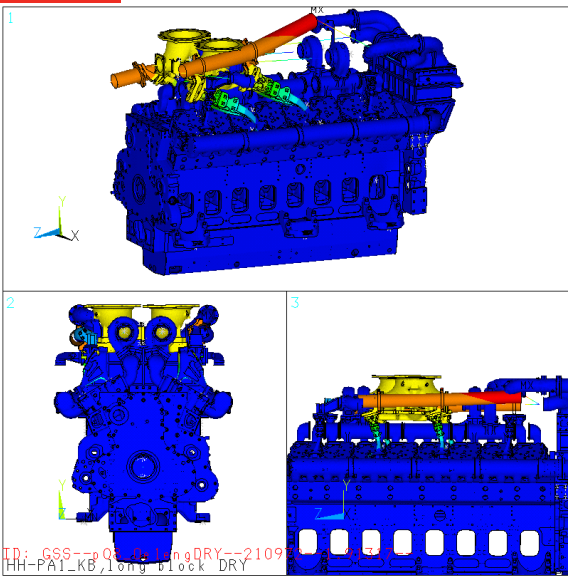
# Skid correlation is much better, but of course a simpler part!

Looking to improve the correlation via optimization…

- An effort to improve the MAC correlation:
  - To date, have tried /opt, Matlab and ModeFrontier for the optimization process (mostly Matlab fgoalattain)
  - Parameterize certain features
  - Setup the ANSYS model so that it can run with assigned parameters
  - MATLAB does the MAC table
  - MATLAB outputs some correlation variables (MAC of some mode pairs)
  - Looping process

- With main block of eng in CMS form, can do 128 modal runs per night

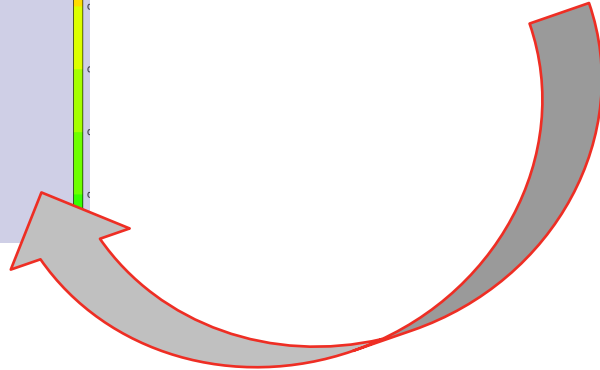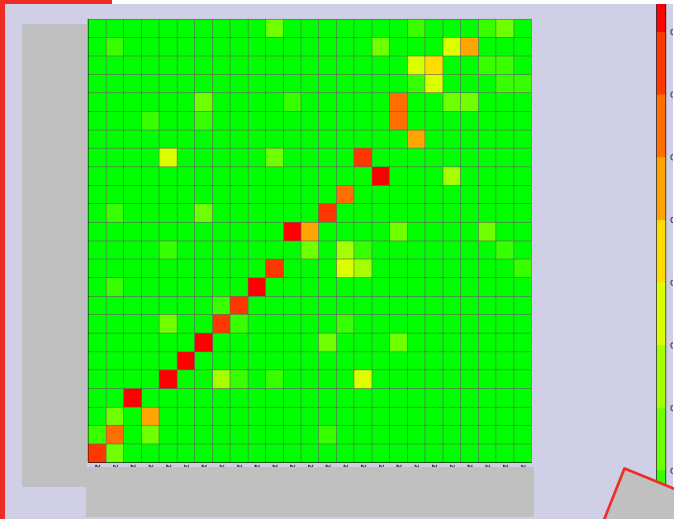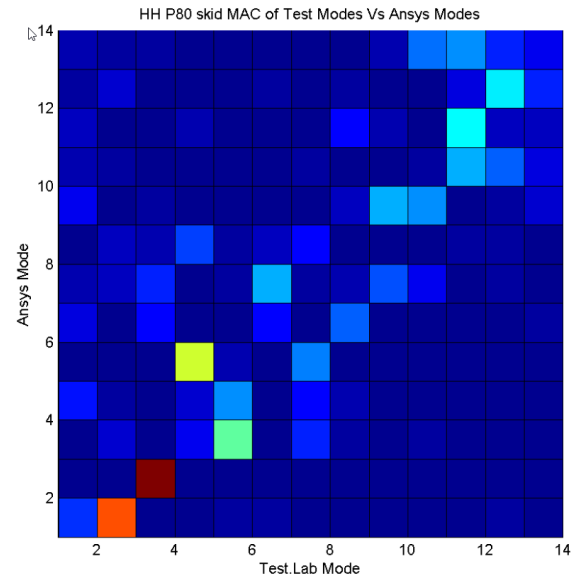- Gave up on doing this in LMS/correlation they focus on NASTRAN
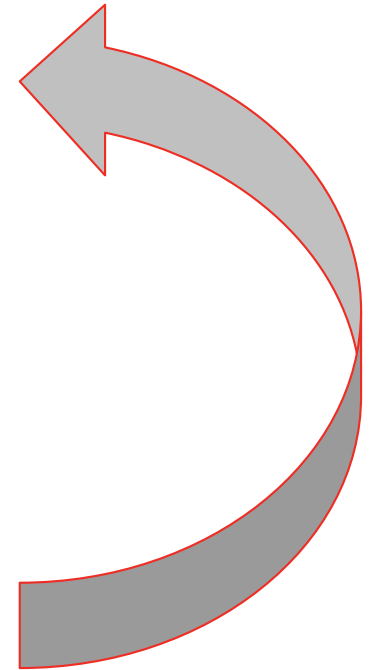
Looking to improve the correlation via optimization… An optimization exercise … Can this be done?

Started with the 95 skid – good MAC table:
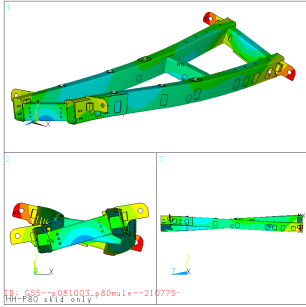
Then added parameters to "mess up" the MAC table:


HH P80 skid MAC of Test Modes Vs Ansys Modes

Now we have an optimization problem with a known answer to experiment on….
-- 12 parameters to adjust

Notes/lessons learned… (MATLAB opt)

- Initially was blindly using fgoalattain, but that didn't work well at all…

- After further review—better solution is the "Global Opt Toolbox" with genetic algorithm and pattern search solvers as this problem is nonsmooth… (likely complex in several ways—the gradient is only obtained by perturbation)

- After ~10 tests with this class of solvers the best method seems to be:

  - gamultiobj solver with heuristic crossover (genetic algorithm with multiple objectives)

  - Selected 2 goals:

    - Mean MAC of modes 2-8 (ignore the first as that automatically gets better with the higher modes)

    - Mean delta frequency of those same 7 modes

  - Interesting that the 2 goal method is better than 14, or 1 – although 14 was second best

 - Have also had success with pattern searching

Results:

- At run 64 got mean_diag7 = .9048 and deltaF = 3.23

- This optimized model is actually better than the original…

- Not totally sure if this is the absolute best optimization method but it does work!

HH P80 skid MAC of Test Modes Vs Ansys Modes

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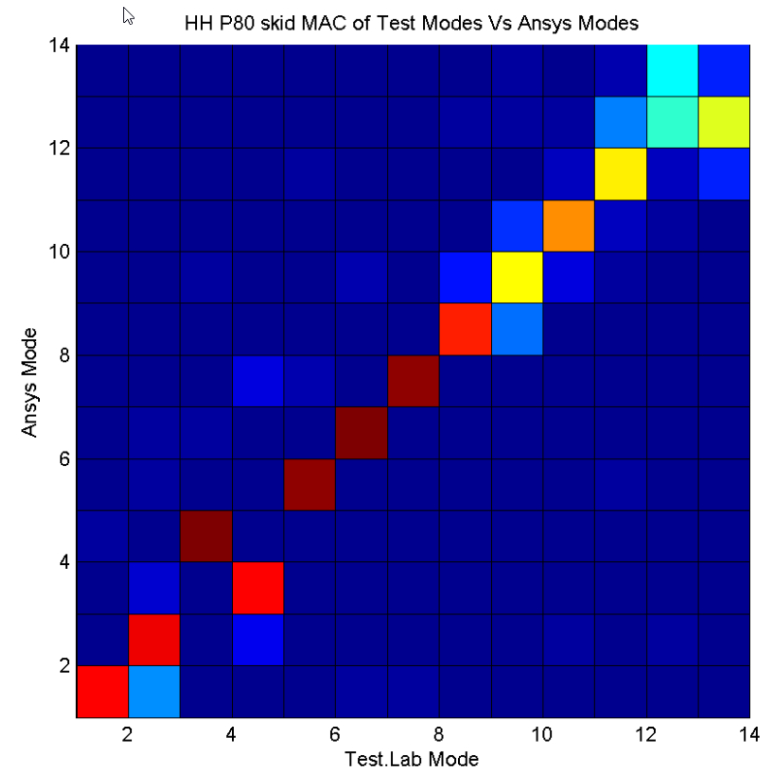
Important to pick the proper parameters…

- This sort of optimization requires manual as was as automatic "playing" with the model.

- Jason made this simple test model and messed up the 3 springs. Then used optimization to improve the MAC by only adjusting K1 and K2. He got an improvement in MAC, but this would clearly NOT be a better dynamic model.

- I don't *think* this is the case with the skid but I don't know how to prove it other than running it in the time domain (Excite) and check correlation there…

- Thoughts?
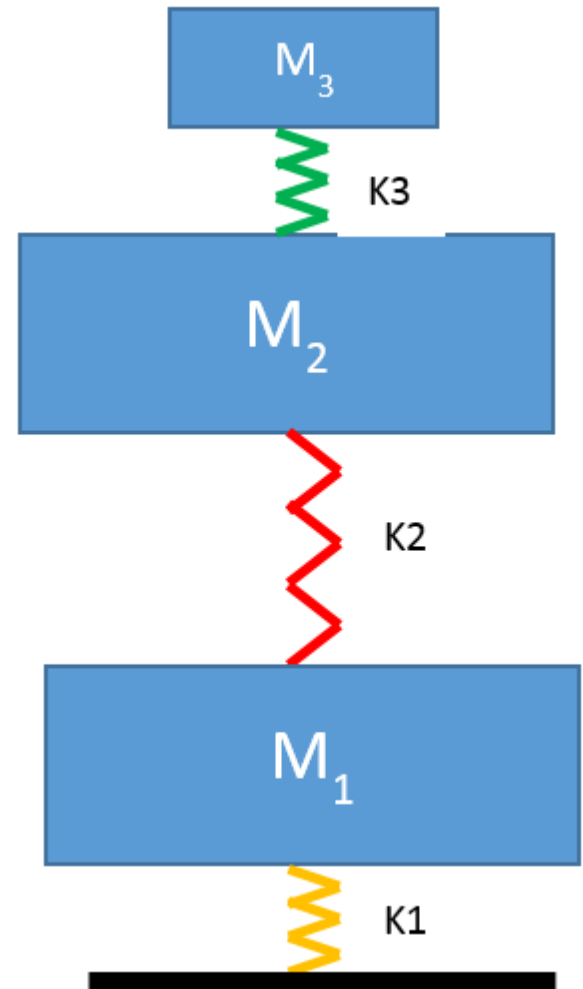
Now - the QSK95 – complex models can be difficult to correlate:

- This is getting much better… Currently trying to figure out why that 7th structural test mode is so hard to duplicate. Contact is suspect…

HH eng MAC of Test Modes Vs Ansys Modes
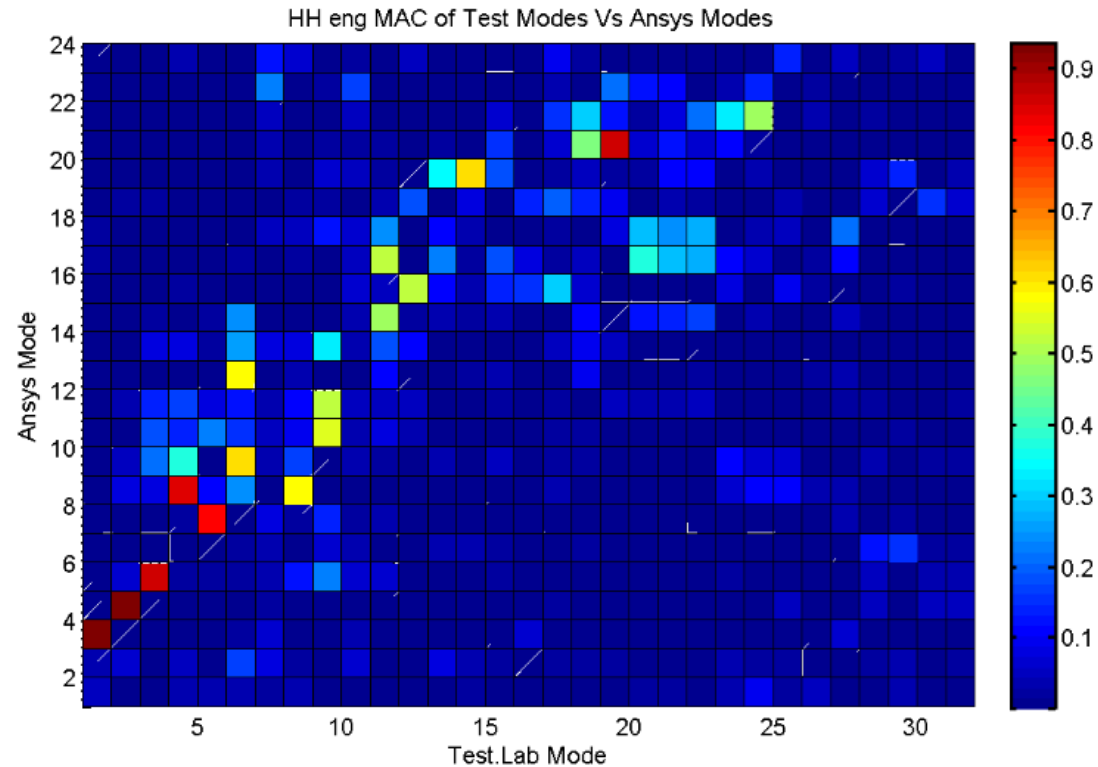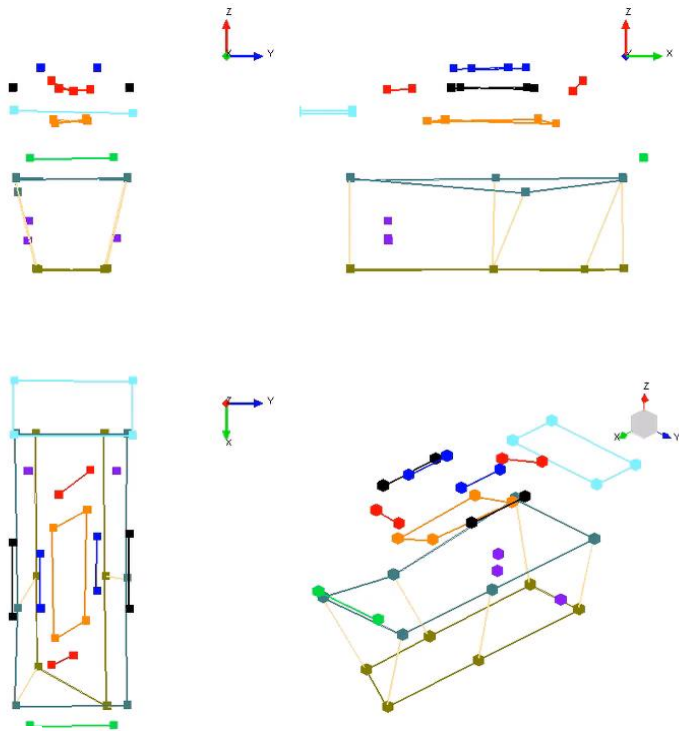
- As you can see this is work in progress… Models can always be made better, so there is really no "end" to this! Higher modes would be of interest for acoustic prediction.

- Thanks for listening…
  - Thoughts, comments, suggestions are welcome!!!

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