SAND2016-6388PE

Sandia National Laboratories

Structural Dynamics Lunchtime Series #1.4
The SMAC Modal Extraction Algorithm for Advanced Users

Randy Mayes

July, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

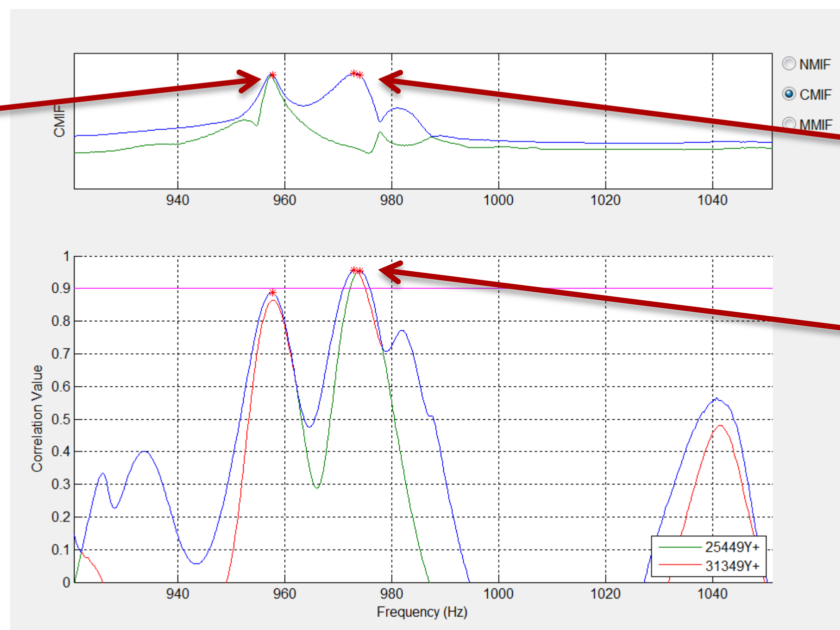
Introduction

- The most important decision: Which modes are you going to extract? and from which references should you extract them?
- When you need to adjust parameters and how to adjust them
- Merging roots from multiple references
- Using Residuals for fitting certain FRFs
- When to fit with Complex Modes

Making the most important decision, which modes to extract and from which references to extract them

- Because most modal tests are on slightly nonlinear structures, I **rarely recommend performing a multi-reference extraction all in one session**. Multi-reference extractions on nonlinear responses can yield multiple false extractions of a single mode or completely miss extractions for some modes.
- Use the imaginary CMIF on FRFs for all references combined to attempt to pick out the pertinent modes. This MIF is not “fooled” as easily by slight frequency shifts of the same mode from one reference to the next.

Two Modes



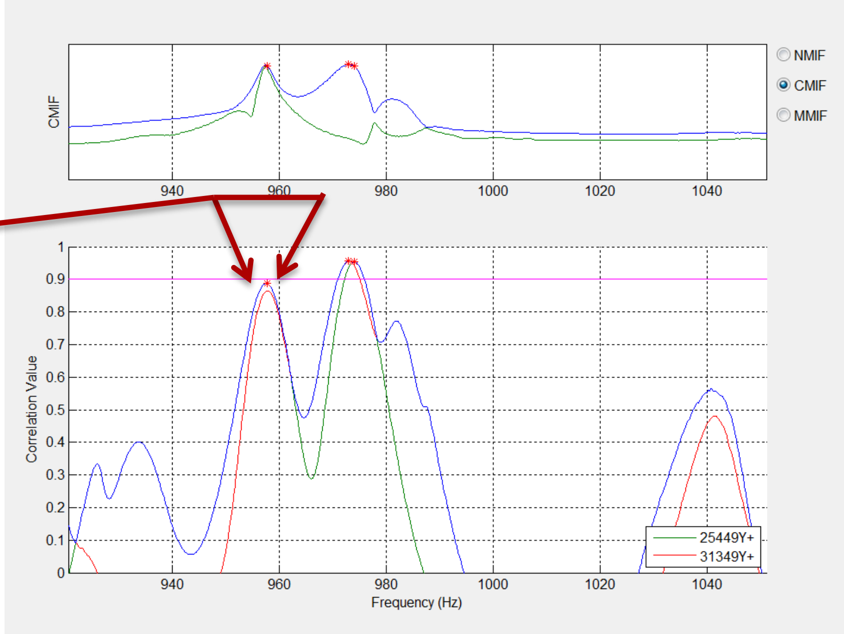
One Mode
Two Roots

CCMIF shows which reference roots come from

Making the most important decision, which modes to extract and from which references to extract them

- The colored CMIF coded up by Rohe gives the indication of which reference excites each mode the most. ***Don't actually SMAC all the data together***, just use the CMIF to locate your modes.
- THEN in separate SMAC runs fit each reference individually as best you can and then pick out the best modes from each reference and consolidate them. This consolidated set should give you an acceptable match to the CMIF of all the data for the bandwidth of interest.

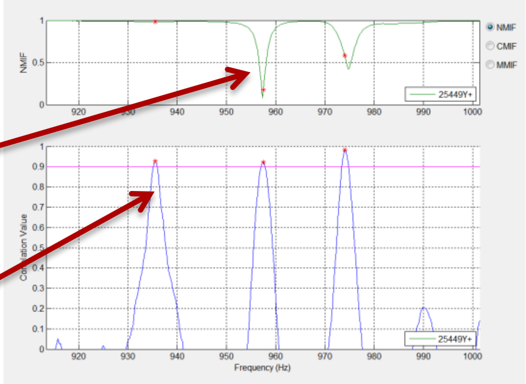
Hint: pick additional starting peaks on either side and see if SMAC finds second root in single data set

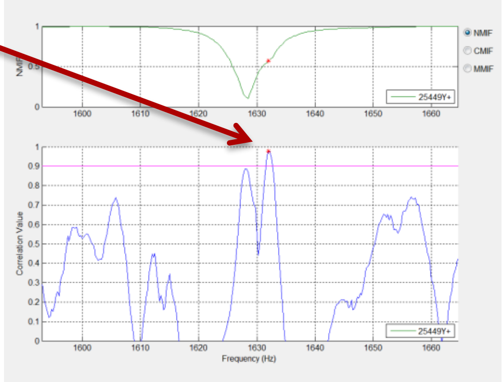


Most important decision - continued

Sandia National Laboratories

- Sometimes the NMIF or the Correlation Coefficient MIF (CCMIF) can help you decide whether to add additional nearby modes.
  - The NMIF usually requires a significant dip (below .7??) to be a mode that is worth extracting the shape.
  - The CCMIF can find modes that are so weak in the data that you will NOT get a good mode shape fit of the weak mode. For a mode you are looking for, this may be a blessing. The fact that you cannot fit it well is the curse.
  - Sometimes you can lower the initial damping estimate and see closely spaced modes in the CCMIF (resolution increases with lower initial damping estimate).
- If you are attempting to fit many dozens of modes, you may need the least-squares multi-reference mode picking algorithm to pick out the best modes from dozens or hundreds you have fit reference by reference. This is probably of use for full experimental based models, but it does not give one much insight into the dynamics. A future talk is planned in the advanced structural dynamics series 2.1.





Starting Damping Estimate 0.001

When and how to adjust parameters

- The default SMAC parameters are pretty robust for a normal modal test where damping is 0.5% or greater. Occasionally you can get better results by adjusting parameters.
- When you run SMAC, the parameters you set are:
  - Full/Partial Frequency Range – Default Full
  - Initial Damping Estimate – Default 0.02
  - Frequency Lines – Default 20
  - Bandwidth of Fit – Default is entire bandwidth of FRFs
  - Minimum Correlation Coefficient Peak to automatically search for a root – Default 0.9 *
  - Auto Search Parameters
    - Frequency Range % - Default 1 *
    - Number of values in each range – Default 11 *
    - Frequency convergence % - Default .05
    - Damping range % - Default 0.25 to 5
    - Number of values in each range – Default 21 *
    - Damping convergence % - Default 2
- The red asterisks above denote parameters I never have found worth changing, so that leaves 7 parameters that one could adjust

Parameter adjustments *

- Initial damping estimate – I adjust this parameter more than any other.
  - It should initially be slightly below the average damping of the system.
  - If your modes have a wide spread in damping, you may need to have one run focused on the lower damping, e.g. 0.1% and another run focused on high damping, e.g. 2 %. If all damping values are within a factor of two, usually the slightly below average damping estimate is adequate for a starting value so that all modes will be extracted.
  - If there are two closely spaced modes you are trying to pull out of the data, using an artificially low damping value may help you see both modes in the correlation coefficient MIF plot and make it possible to obtain both in the automatic extraction.
  - If the initial damping value is very different from the true damping value of a mode, SMAC may completely miss it in the initial correlation coefficient MIF, e.g. initial damping is at 0.1% but true damping is 7%.
- Frequency lines – this was set to 20 lines when (years ago) most of our analyses were for 800 lines of non-aliased data in the FRF.
  - So the ratio of frequency lines to total number of lines should be about 1/40.
  - It is not an extremely sensitive parameter.
  - I increase the number of frequency lines when the total number of lines gets above 3200.
  - In general, more frequency lines gives a more accurate answer for the root, which is slightly counter-intuitive, especially for low damping.

Parameter adjustments **

- Damping range
  - If the true damping is outside of this range, it can cause failure to converge on the mode. SMAC stops after 200 iterations if it fails to converge on a mode. If the damping is within the range, SMAC is always able to converge quickly. Lightly damped structures can be below 0.25% damping. Occasionally we see more than 5% damping.
  - If damping is below 0.25% you will probably also want to change convergence tolerance.
- Frequency convergence % and Damping convergence%
  - These are tolerances that SMAC uses to decide when the answer is good enough. When neither the frequency nor the damping changes from the last iteration by more than the tolerance percentage, SMAC stops iterating and declares it has found the root.
  - If the damping is down at 0.1%, I usually divide both tolerances by 4 to get a more accurate answer.
  - In general, the uncertainty on the final root is within 3 times the tolerances
- Full/Partial Frequency Range
  - SMAC generally gives a more distinct initial correlation coefficient MIF plot if one uses the entire frequency range, i.e. the valleys are lower using the entire range.
  - Occasionally, the number/placement of accelerometers is inadequate for SMAC to detect a particular mode (that may be plainly seen in the CMIF) because the modal filter is inadequate. If one narrows the frequency range so that fewer modes have to be filtered, often that particular mode can then be extracted by SMAC.

Parameter adjustments ***

- Bandwidth of Fit
  - If one discovers the bandwidth of interest is smaller than the entire bandwidth, the bandwidth can be limited so that SMAC does not attempt to extract any roots outside the bandwidth of fit.
  - This parameter does not affect the accuracy of roots in any way.

The Merge Roots Option

- Sometimes one has to perform multiple SMAC runs on the same FRF set to extract all the roots. The merge roots option can be used to pull in roots extracted from another SMAC run, and then all shapes can be fit with all the proper roots in the final SMAC run to give the most accurate mode shape extraction. Merge roots just pulls in the shape file ending in .ash that was saved from the previous fitting session and only uses the frequency and damping from that file to include with the current roots.

Using Residuals in Mode Shape Fitting

- For real mode shapes, the imaginary part is the only part that needs to be fit with all shapes simultaneously, because the real part is dependent on the imaginary part.
- Sometimes people wish to show the match to the amplitude of the FRF which has significant effects from the real portion. In general most of the residual effects are in the real part of the FRFs.
- The rigid body modes have a flat line real part in the FRFs which may not have been extracted, but can be easily fit with the general inertance residual.
- The high frequency out of band modes have a significant real part that is proportional to omega squared. This is the general compliance residual.
- Once these two residuals are included in the fit, the FRF amplitude looks better throughout the band. Particularly the antiresonances are much more accurate in frequency. But they really don't help the real mode shape fits at all.
- With complex modes, one has to fit the residuals, or the complex mode shapes are polluted by the out of band modes, both rigid body and high frequency. Many codes do not account for the residuals and so the mode shapes are polluted.
- SMAC actually saves residual terms when you save the shapes for complex modes.
- Residual terms are only applicable for the reference from which they were obtained. THEY WILL NOT WORK FOR FRF SYNTHESIS FROM ANY OTHER REFERENCE.

Using Real Vs Complex Modes

- Complex mode shapes are usually caused by geometry localized damping, and have the appearance of moving nodes.
- I always begin with real modes and far more than 90 percent of the time this is adequate because:
  - FE model validation is based on real modes.
  - Often complex modes are only very slightly complex, and real modes are an adequate estimate.
  - Complex mode fits may actually give a worse estimate because they may be polluting the fit with residuals from other modes that are not fit in the bandwidth. The animations will indicate the mode is complex (since the nodes move) and in reality they may not be complex at all. I have seen dozens of complex mode animations at IMAC that I am almost positive could have and should have been simulated with real modes.
  - Some complex modes (for structures that have very low damping) are caused by instrumentation distortions.
    - False imaginary estimate from distortions on hammer force
    - 90 degree shift of FRF in accelerometers due to cross axis sensitivity
  - What are you going to do with complex mode shapes?
- If accuracy and localized damping require complex mode fits, always use inertance (rigid body modes) and compliance (high frequency out of band mode) residuals so that the complex mode shapes are not falsely fitting the residual effects of other modes. Since complex modes give you twice as many parameters to fit FRFs, the local frequency fit may look better, but may actually be worse if residuals were not considered.

References

- Mayes, Randall L. and Johansen, David D., “A Modal Parameter Extraction Algorithm Using Best-Fit Reciprocal Vectors”, Proceedings of the 16th International Modal Analysis Conference, pp517-521, February 1998
- Mayes, Randall L., and Klenke, Scott E., “The SMAC Modal Parameter Extraction Package”, Proceedings of the 17th International Modal Analysis Conference, pp 812-818, February 1999
- Mayes, Randall L., and Klenke, Scott E., “Automation and Other Extensions of the SMAC Modal Parameter Extraction Package”, Proceedings of the 18th International Modal Analysis Conference, pp 779-785, February 2000
- Mayes, Randall L., Dorrell, L.R., and Klenke, Scott E., “Applications of the Automated SMAC Modal Parameter Extraction Package”, Proceedings of the 18th International Modal Analysis Conference, pp 772-778, February 2000
- Hensley, Daniel P., Mayes, Randy L., “Extending SMAC to Multiple References”, Proceedings of the 24th International Modal Analysis Conference, pp 220-230, January 2006
- Simmermacher, Todd, Mayes, Randy, “Estimating the Uncertainty in Modal Parameters Using SMAC”, Proceedings of the 27th International Modal Analysis Conference, paper 262, February 2009
- Mayes, Randall L., "A Multi-Degree-of-Freedom Mode Shape Estimation Algorithm Using Quadrature Response", Proceedings of the 11th International Modal Analysis Conference, pp 1026-1034, February, 1993