Siemens Digital Industries Software

Multi-configuration model updating

Using model update sets to increase finite element modeling realism

Executive summary

As products become more complex, manufacturers are urged to do more simulation earlier in the design cycle. Having realistic finite element (FE) models that can be used in different product configurations and with various boundary conditions are indispensable. By using model update sets in Simcenter™ 3D software, engineers can update FE models while using different mode pairs simultaneously. This makes more physical property information accessible for optimization and reduces the risk of creating a mathematical solution that does not reflect physical reality. By including this functionality, Simcenter 3D correlation analysis and updating fully supports the digital twin development approach. This white paper illustrates how Simcenter 3D can be used to combine mode pairs in sets and achieve a more realistic FE model.

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Introduction

Modeling realism is the foundation of a successful digital twin approach. In the past, structural FE analysis was primarily applied to virtual verification and validation (V&V) in conjunction with physical prototype testing. Now, it needs a prominent role in the design to enable early balancing of performance requirements. The increased focus on virtual prediction demands a close interaction between simulation and testing. Correlating FE models with test data and updating them accordingly must become a continuous process to make sure the most accurate possible results are available at any design stage.

The aim of updating FE models should be to create a wider scope versus evaluating the product or component in a fixed configuration or with defined boundaries. The updated models need to be flexible, as they will be used in parameter studies and design explorations, including configuration variants. They are subject to a significant amount of load cases, including those corresponding to operating points that cannot or will not be tested. Therefore, including more than one FE-test mode pair is recommended during the process.

In this white paper, we explain this with a simple example and illustrate how Simcenter 3D can combine mode pairs in sets and achieve a more realistic updated finite element model. This method is useful for industry workflows such as airframe ground vibration testing (GVT), in which slightly varying tests of the structure are performed. Christopher Pye, mechanical simulation thought leader and Philippe Tremblay, engineering structural applications lead at Maya HTT Ltd, provided the examples stated throughout this white paper.

Simcenter 3D is a part of the Xcelerator™ portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software.

Maya HTT is an industry-leading software development and engineering solutions provider focusing on computer-aided engineering (CAE), computer-aided design (CAD), computer-aided manufacturing (CAM) and product lifecycle management (PLM). They are a longtime partner of Siemens Digital Industries Software providing software and engineering services to global clients across industries.

Considering more parameters better

If multiple modal tests for different boundary conditions are available, it is best to use the majority of that data for model updating. One approach is to set up separate updating processes for each variation. However, this will likely produce different values for common design variables, leading to multiple updated FE models. Going forward, it is then necessary to keep track of and thoroughly select the FE model that most closely matches in boundary conditions or configuration. When using the model update sets, all configurations are included in one updating process, resulting in a single value for each design variable. Using this approach allows the design team to move forward with a single updated FE model fit for all conditions.

Boundary conditions also influence which model parameters can be addressed. Consider the case of a simple beam. Figure 1 displays the modal deformation and unaveraged von Mises stresses in color contour for modes one and three, modeled in free-free conditions. In all modes there are areas of zero translation and zero stress. Changing the mass at a point of zero displacement will have no effect on mode shape or frequency and, vice versa, changing the stiffness at a point of zero stress will have no effect on mode shape or frequency. If changing a parameter has no effect, model updating will be unable to determine an optimal value for that parameter.

Various modes have different points with zero translation. Therefore, performing model updating using multiple modes can address this issue. However, all modes have zero stress at the ends of the beam, so model updating will not be able to determine optimal values for stiffness parameters near the ends.

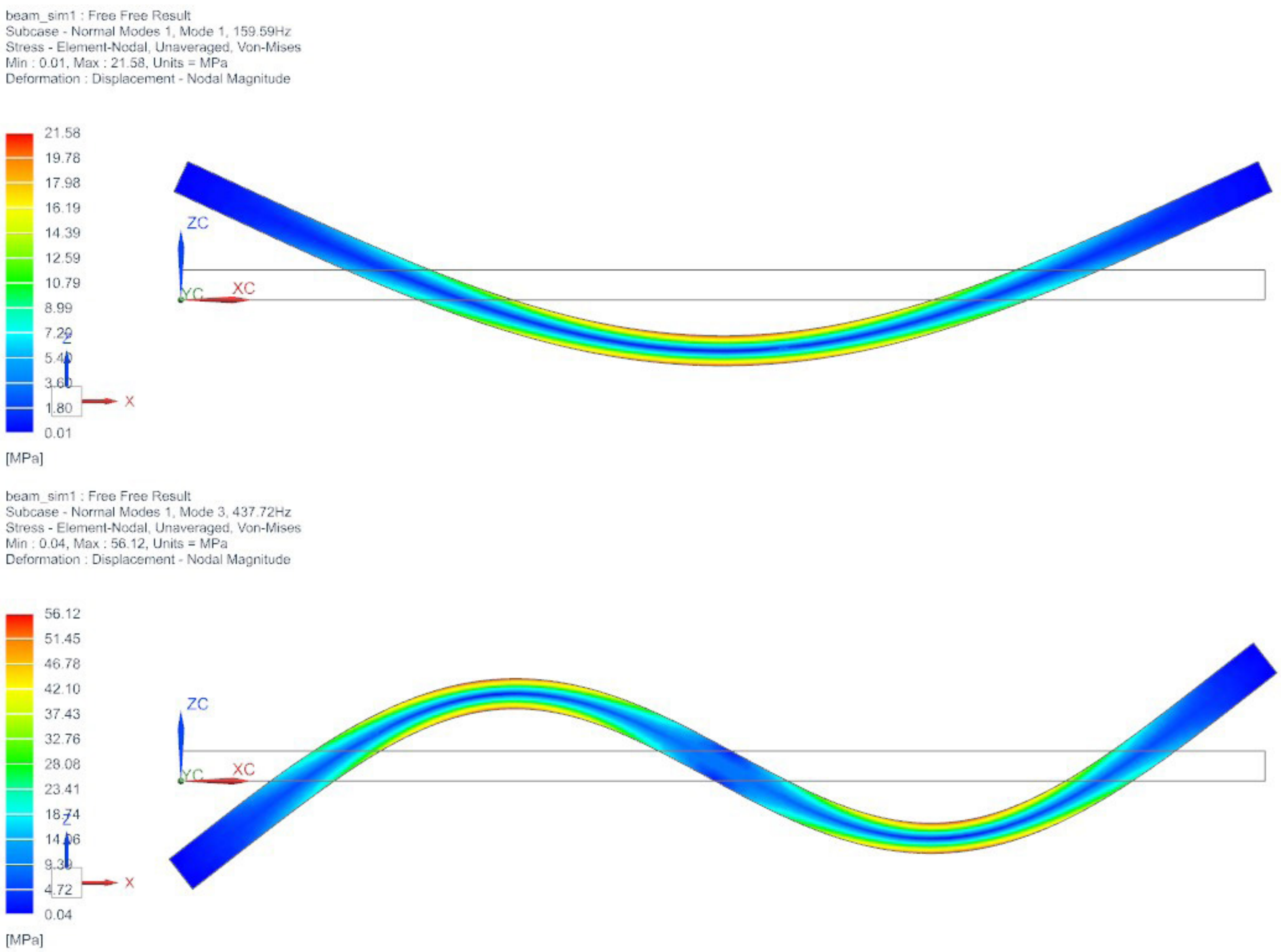

Figure 1. Modes one and three of the beam in free-free conditions.

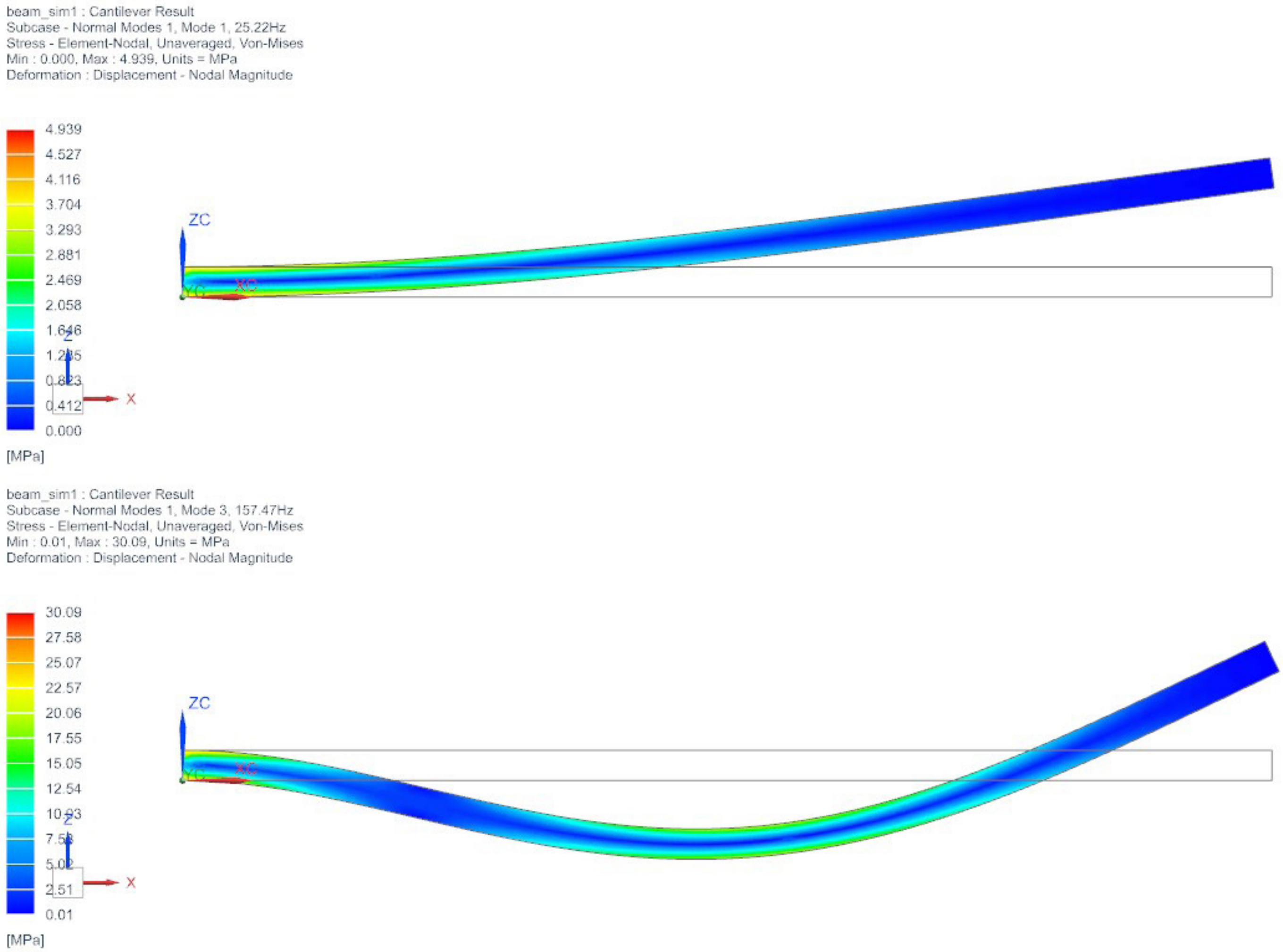

Figure 2. Modes one and three of Cantilever Beam.

Figure 2 shows the same beam with one end fixed. There are now stresses at the fixed end of the beam. As a result, model updating can optimize the stiffness in that region. However, the lack of translation in all modes at that point means its mass parameters cannot be optimized. The stiffness related parameters at the other end of the beam can be determined by a third simulation/test combination with the other end fixed or by assuming the beam is symmetric, if this is the case.

Performing an FE model update using these two configurations allows a wider range of beam parameters to be optimized in a single pass. When FE model updating uses only one configuration, some mass or stiffness parameters have minimal or no influence on mode shapes and frequencies. Combining multiple configurations in a single model update can overcome these limitations.

Model updating with Simcenter 3D

Simcenter 3D includes a dedicated functionality for this purpose. The software features model update sets for optimizing multiple configurations simultaneously. Common design variables between configurations are assigned the same value across all solutions during the model updating process. There is no need to have identical boundary conditions between the different mode pairs. In the spacecraft example we will show in section 4, one FE model update solution uses just the spacecraft bus, and the second has the full spacecraft including bus and payload. The two are updated simultaneously with common design variables having the same values across both solutions.

Simcenter 3D requires these elements as an input:

- Modal test data of the structure under defined boundary conditions:
  - Natural frequencies
  - Mode shapes
  - Frequency response functions (FRFs)
- An FE simulation model that represents the test structure with boundary conditions:
  - Define design variables and solves the model with a Nastran SOL 200 – model update solution type that performs a partial SOL 200 solution to determine design variables and reduced matrix sensitivities
  - Define a set of degrees of freedom (DOFs) that correspond to the measurement locations. These are used to define a reduced model used in the model updating process

The test results are loaded into the Simcenter 3D simulation file, and the user can set up the model updating process by providing the following input:

- The set of test results that must be used as a reference for the model updating process
- Simulation model solutions that correspond to the test conditions
- Targets, which are test results the model updating process tries to match by varying design variables. These can be natural frequencies and mode shapes
- Design variables that are either defined in the FE model or from a more targeted selection

The theory behind the updating process is described in the Appendix.

Model updating of a spacecraft

This section focusses on a spacecraft example that has been measured in two configurations: bus only and full spacecraft (bus plus payload). See figure 3.

Defining the model update solutions for bus and spacecraft

It is necessary to define a model update solution for both the full spacecraft and bus only configurations. This involves selecting the test results and their corresponding SOL 200 model update solution, and then defining the targets.

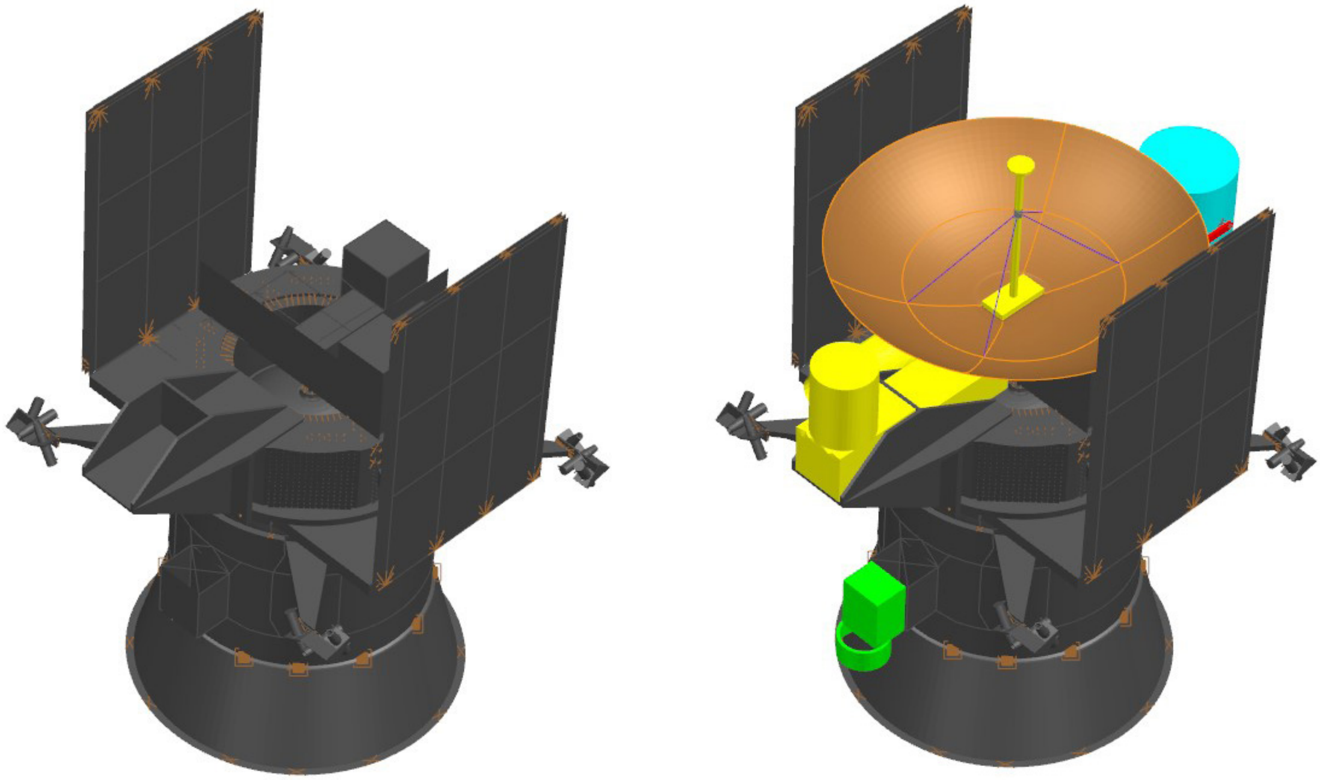

Figure 3. Spacecraft configurations - bus only and bus plus payload.

Creating a model update set

Once the model update solutions have been created, a model update set combining both is defined and they are solved simultaneously. In figure 4, the model update set definition dialog box lists all model update solutions, which the user can select from.

Mode pairing

The master model update solution defines the mode pairing method by default. If no master is selected, the user has the option to define it as modal assurance criterion (MAC), cross orthogonality (X-Ortho) or manual. MAC and X-Ortho pairing methods also determine the correlation metric used to optimize shape errors. Once the set is defined, the next step is to calculate the errors for the combined solutions. These are the union of the errors for the selected solutions.

Table 1 shows the error percentages calculated for modal frequencies for the full spacecraft solution. Since model updating has not been performed at this stage, the current errors are the same as the initial errors. The maximum error in the frequency targets for the spacecraft solution is 89 percent.

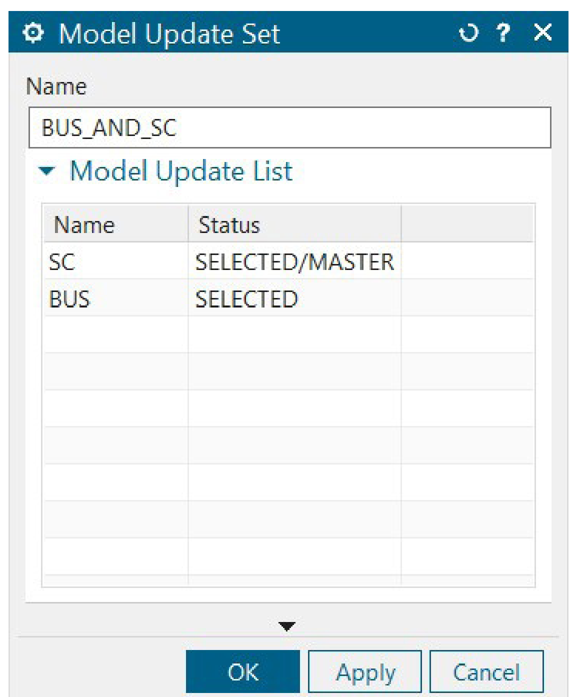

Figure 4. Defining model update set.

Table 1 - Initial error percentages for spacecraft frequencies.

Id	Current Error	Initial Error	Ref Mode Id	Ref Freq	Work Mode ...	Current ...	Initial Value
Frequencies	27.749	27.749					
1	-7.985	-7.985	1	25.251	1	23.235	23.235
2	-11.083	-11.083	2	27.600	2	24.541	24.541
3	-9.828	-9.828	3	28.669	3	25.851	25.851
4	-6.329	-6.329	4	29.856	5	27.967	27.967
5	-13.906	-13.906	5	31.088	4	26.765	26.765
6	-11.266	-11.266	6	35.225	6	31.257	31.257
7	89.446	89.446	7	36.116	15	68.419	68.419
8	-14.615	-14.615	8	38.594	7	32.954	32.954
9	1.222	1.222	9	45.145	11	45.697	45.697
10	-13.981	-13.981	10	49.382	9	42.478	42.478
11	-14.258	-14.258	11	49.803	10	42.702	42.702
12	-31.255	-31.255	12	53.418	8	36.722	36.722
13	-16.340	-16.340	13	58.584	13	49.012	49.012
14	23.984	23.984	14	59.644	18	73.949	73.949
15	21.749	21.749	15	63.647	20	77.490	77.490

The errors are combined with the errors for all other targets, as well as with the bus errors, to give overall errors. In this case, the overall error is 29.6 percent, as shown in table 2.

Id	Current Error	Initial Error
All Errors	29.590	29.590
SC_MU Errors	32.408	32.408
Frequencies	27.749	27.749
Mode Sha...	36.476	36.476
BUS_MU Errors	26.475	26.475
Frequencies	13.173	13.173
Mode Sha...	35.047	35.047

Optimization

Once the model update set is defined, it is possible to decrease the errors with optimization. During the complete process, the reduced model is used for calculation, which means the model can be rapidly solved with many design variables.

Throughout this process, the original solutions remain untouched. Therefore, all changes are fully reversible at any time. This allows users to try different optimization strategies and parameters in multiple runs of the optimizer. The design variables can be reset to their initial values at any stage. This allows optimization to begin from their initial values. Alternately, multiple optimizations can be performed in sequence using different methods, parameters, design variables and active targets.

No optimization strategy works for all models. In this particular case, running the least squares optimizer with frequency and mode shape targets for the first 15 modes improves the overall error from 29.6 percent to 14.77 percent.

After experimenting with different strategies, the best method found for optimizing this particular model is:

- Deactivating all mode shape targets - This gives an initial, overall error of 21.7 percent. It changes because mode shape errors are not included in the overall error calculation
- Optimizing solutions using parameters shown in figure 5 – The overall error is reduced to 0.16 percent
- Reactivating targets for mode shapes one through 15 for both solutions in set - The overall error is now 4.1 percent
- Optimizing with the same settings - The overall error is now 1.57 percent

Updating design variables and FE model

The FE Model is updated using the design variable values determined by the optimizer. Table 3 displays the design variable changes applied to the FE model after the first optimization.

Solving the bus and spacecraft solutions from the updated FE model and recalculating the errors, gives an overall error of 9.4 percent. This is slightly different from the final error resulting from optimization. This is because all steps in the optimization process take the sensitivity values that are calculated on the initial FE model. In reality these change in every loop. Repeating the full optimization cycle further reduces the overall error to 3.3 percent. A final cycle is performed with the first 15 shapes and frequency targets active, and the overall error is reduced to 0.05 percent.

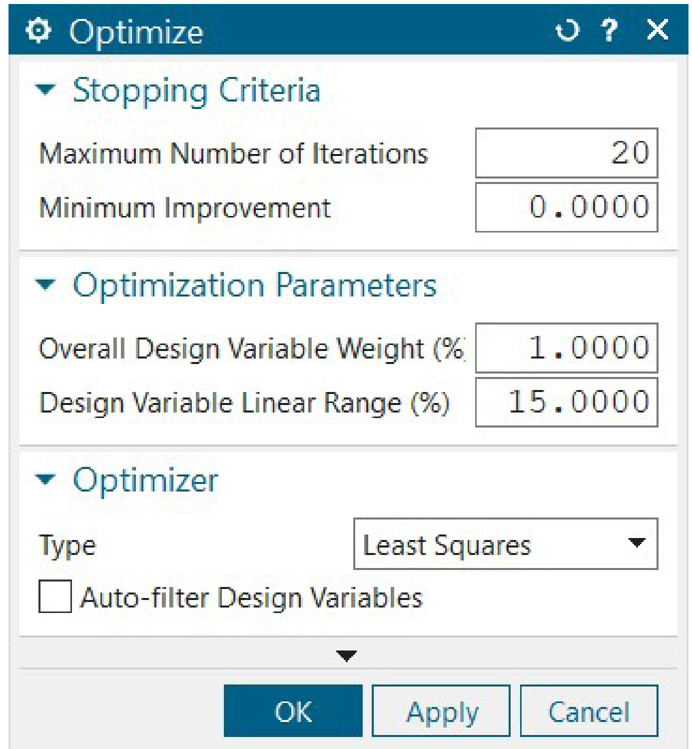

Figure 5. Model update optimize form.

Entity	Label	File	Property Name	Old Value	New Value
Physical Property	120	FEM	Z Rotation per Radian	2.000000E+11	3.034589E+11
Physical Property	1329	FEM	Z Rotation per Radian	5.000000E+12	3.653098E+12
Physical Property	1405	FEM	Z Rotation per Radian	3.000000E+14	3.000000E+14
Physical Property	1000347	FEM	Translational Stiffness	1.000000E+09	1.000000E+09
Physical Property	1000347	FEM	Rotational St..ss per Radian	1.000000E+09	1.000000E+09
Physical Property	1000356	FEM	Rotational St..ss per Radian	1.000000E+09	1.000000E+09
Physical Property	1000356	FEM	Translational Stiffness	1.000000E+09	1.000000E+09
Physical Property	1000357	FEM	Rotational St..ss per Radian	1.000000E+10	1.000000E+10
Physical Property	1000357	FEM	Translational Stiffness	1.000000E+10	1.000000E+10
Material	1	FEM	Young's Modulus (E)	1.160000E+08	6.666133E+07
Material	10	FEM	Young's Modulus (E)	7.000000E+07	9.763955E+07
Material	11	FEM	Young's Modulus (E)	1.160000E+08	1.428661E+08
Material	12	FEM	Young's Modulus (E)	7.000000E+07	1.026137E+08
Material	13	FEM	Young's Modulus (E)	7.000000E+07	9.873616E+07
Material	14	FEM	Young's Modulus (E)	1.200000E+08	1.158012E+08
Material	17	FEM	Young's Modulus (E)	7.000000E+07	6.998998E+07
Material	20	FEM	Young's Modulus (E)	3.000000E+07	2.193412E+07
Material	21	FEM	Young's Modulus (E)	7.000000E+07	4.127031E+07
Material	22	FEM	Young's Modulus (E)	7.000000E+07	1.030159E+08
Material	23	FEM	Young's Modulus (E)	7.000000E+07	9.669467E+07
Material	24	FEM	Young's Modulus (E)	1.160000E+08	5.800000E+07
Material	25	FEM	Young's Modulus (E)	1.160000E+08	1.123605E+08
Material	26	FEM	Young's Modulus (E)	1.160000E+08	1.354491E+08
Material	27	FEM	Young's Modulus (E)	1.160000E+08	1.170178E+08
Material	28	FEM	Young's Modulus (E)	7.000000E+07	9.480480E+07
Material	29	FEM	Young's Modulus (E)	7.000000E+07	6.999196E+07
Material	30	FEM	Young's Modulus (E)	7.000000E+07	8.277614E+07
Material	31	FEM	Young's Modulus (E)	1.200000E+08	8.124003E+07
Material	32	FEM	Young's Modulus (E)	1.200000E+08	6.000000E+07
Material	33	FEM	Young's Modulus (E)	1.200000E+08	1.925519E+08
Material	34	FEM	Young's Modulus (E)	7.000000E+07	9.308418E+07

The progress in error values through the updating process is shown in table 4 and figure 6. The optimizer computes design variable values expected to give small errors. However, after updating and solving the FE models, the reduction in errors is not as significant as predicted. This is because their initial value is considered throughout the process rather than recalculating the first order sensitivities at each loop. The major advantage of using the reduced model is that optimization is rapidly performed. For the model presented here, optimization loops take, on average, less than 10 seconds. The cycle of deactivating shape targets, optimizing, reactivating shape targets and optimizing a second time, takes about one minute. Therefore, this is a practical and easy way to try a number of different strategies to reach the most effective optimization. A second advantage is the ability to optimize for many design variables. For this particular model, 28 design variables were used. Other projects have been successful with hundreds of design variables.

Table 4 - Progress of error values in updating process.

		Error (%)						
		Initial	First Optimization	First Update	Second Optimization	Second Update	Third Optimization	Third Update
Overall		29.59	1.57	9.41	0.07	3.31	0.05	0.05
Spacecraft	Overall	32.41	1.52	3.61	0.08	0.39	0.05	0.05
	Frequencies	27.75	0.63	2.67	0.04	0.42	0.03	0.03
	Shapes	36.48	2.06	4.35	0.11	0.35	0.07	0.07
Bus	Overall	26.48	1.62	12.81	0.05	4.67	0.05	0.05
	Frequencies	13.17	1.01	4.32	0.02	0.54	0.02	0.03
	Shapes	35.05	2.05	17.60	0.07	6.58	0.07	0.07

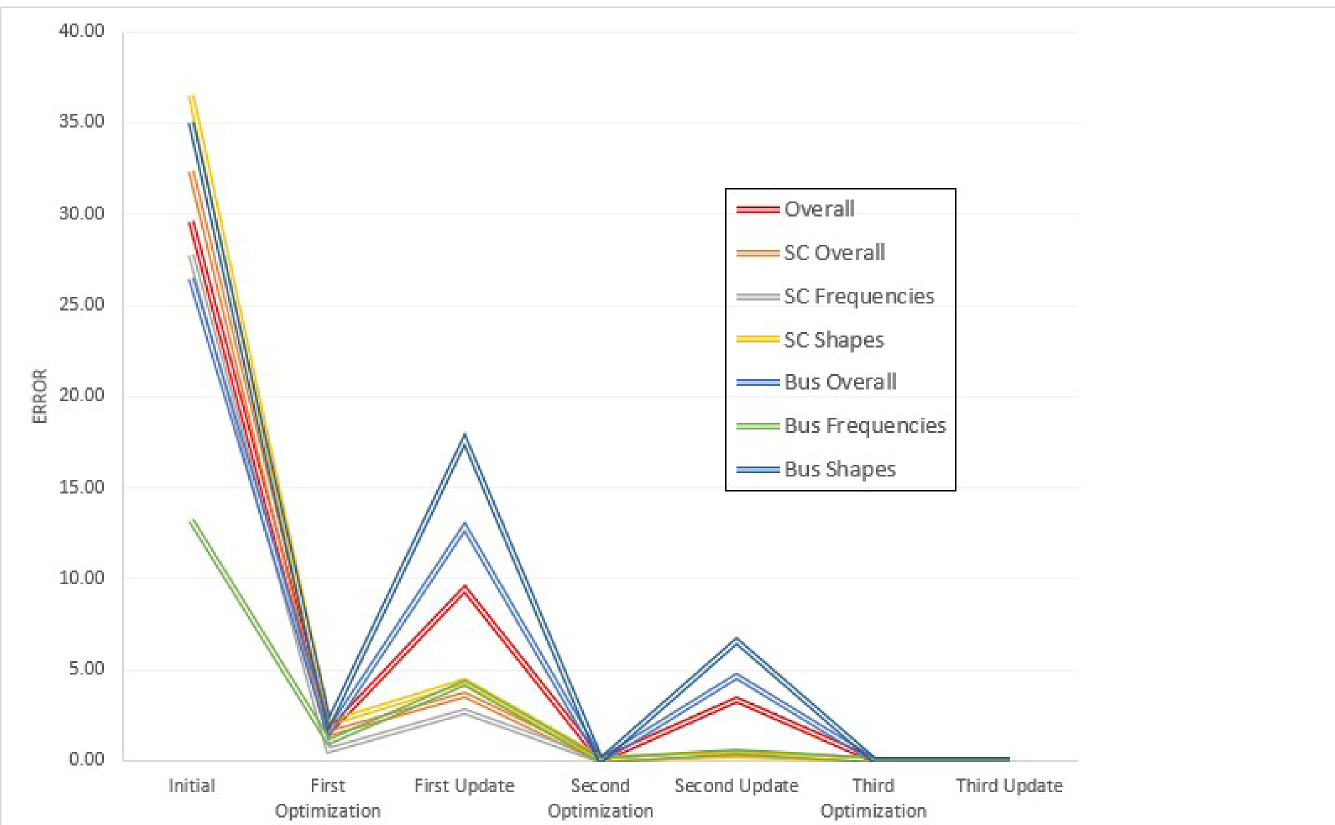

Figure 6. Progression of error values in updating process.

After three optimization cycles, the overall error can be reduced from 29.6 percent to 0.05 percent.

The improvement from the initial to final MAC matrices for both models is shown in Figure 7 and 8.

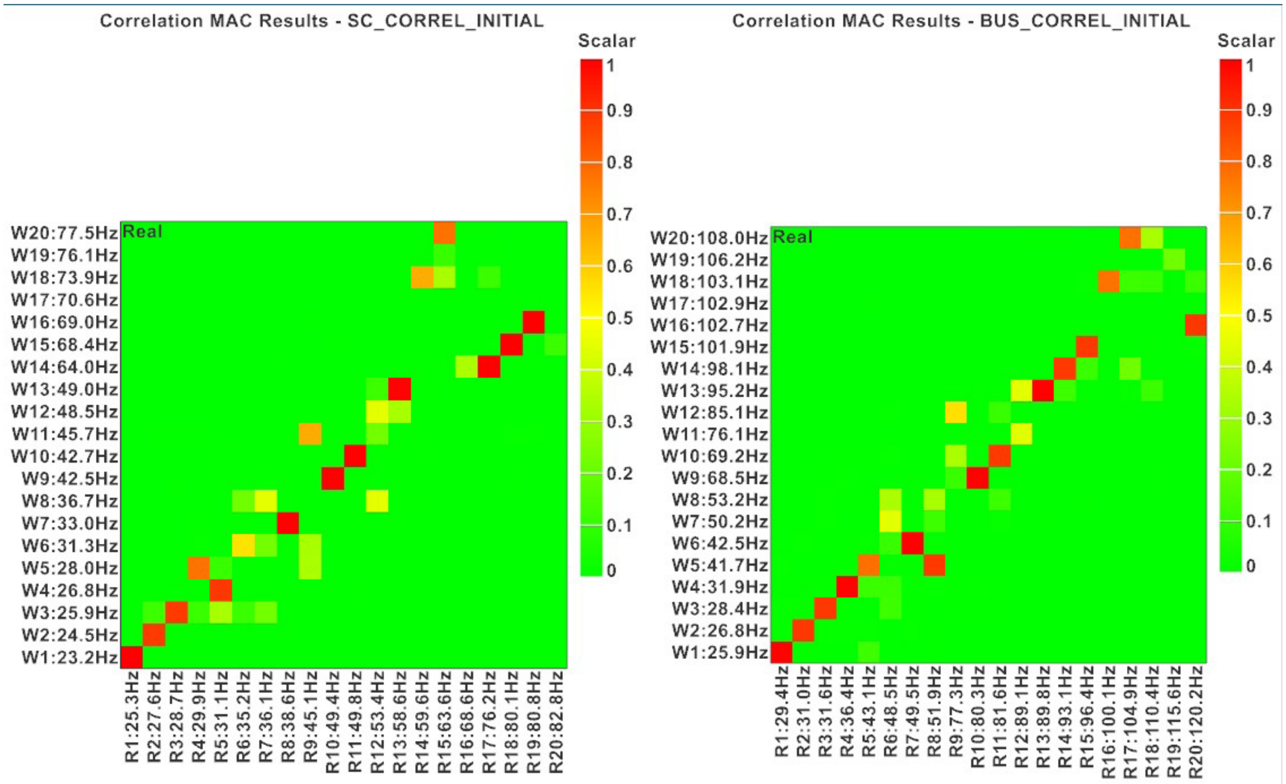

Figure 7. Initial MAC matrices for both models.

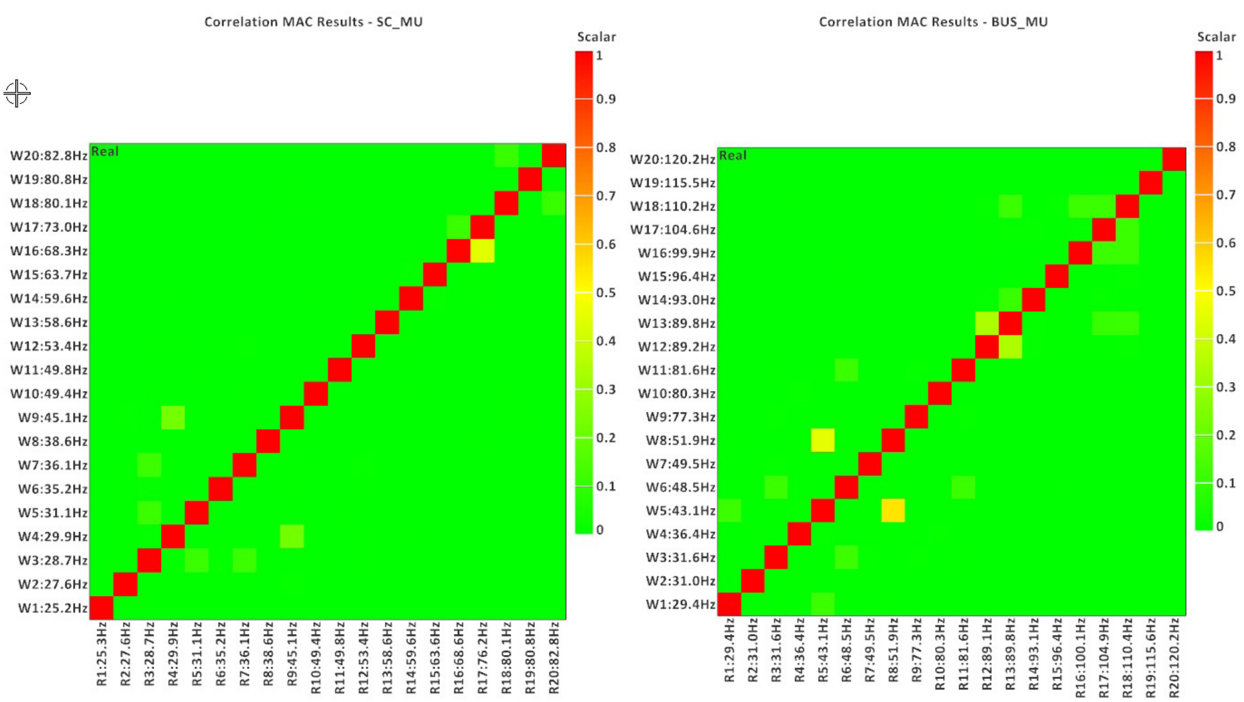

Figure 8. Final MAC matrices for both models.

Conclusion

Model update sets are a valuable functionality of Simcenter 3D correlation and updating analysis. They are used to optimize model parameters across multiple FE models/test configurations. The outcome is a single FE model that has been validated across all test configurations. The model can be confidently used for further product development and various use-case scenarios.

The optimization process tends to predict smaller errors than what is achieved when the design variables are optimized and the updated FE models are solved. For the best model improvement, multiple optimization, updating and solving FE model loops can be performed. The practical limit is likely determined by the solution time of the FE model, which in the case of the spacecraft was two to three minutes.

The use of a reduced model for optimization allows many strategies to be rapidly tested. There is no individual strategy that works for all models. The method used here reduced the overall errors from 29.6 percent to 0.05 percent in three optimization cycles.

This model updating process can dramatically increase the realism of FE models used in a digital twin development approach.

Appendix: model updating theory

Error calculations
The errors are calculated as shown in equation 1 and 2, where f_{ana} is the frequency from the analysis (work) model, f_{tgt} is the frequency from the test (reference) and Corr is the value of the mode shape correlation metric, either MAC or X-Ortho.

$$\varepsilon_{freq}(\%) = 100 * \left(\frac{f_{ana}}{f_{tgt}} - 1\right) \quad \text{Equation 1}$$

$$\varepsilon_{shape}(\%) = 100 * (1 - Corr) \quad \text{Equation 2}$$

Objective function and weights
Weights are a part of the optimization objective function shown in equation 3, where T_{errors} are the errors in the active targets and $DV_{changes}$ are the normalized changes in a design variable. A and B are user-defined weights.

$$\min\left(\sum A\,(T_{errors}) + O \sum B\,(DV_{changes})\right) \quad \text{Equation 3}$$

Weight A is the individual weight assigned to each target. A larger value will favor that target in the optimization process, generally resulting in a smaller error.

Weight B is the product of the individual weight assigned to each design variable and the overall design variable weight entered on the optimization dialog. A large weight will reduce the value variation for the associated design variable. A weight of zero allows for complete freedom. A weight value can be thought of as the inertia of the design variable.

Least squares algorithm

The Simcenter 3D model update least squares algorithm implementation uses an unconstrained, convex and quadratic minimization solution that uses QR factorization or singular value decomposition (SVD) methods.

Since the current optimizer implementation is unconstrained, the minimum found might not be a global minimum. This is more likely when there are many targets, such as in FRF optimization. However, since the least squares algorithm rapidly converges in comparison to the other two algorithms, it is the default optimizer for the Simcenter 3D model update.

Steepest descent

The steepest descent algorithm minimizes the objective function based on the absolute value of the target errors and design variable changes. This algorithm performs several descent steps (inner iterations) where it changes the design variable with the highest sensitivity.

Genetic algorithm

The Simcenter 3D model update genetic optimization algorithm is a global, fully constrained optimizer. Global optimization techniques are known to be computationally expensive. However, genetic algorithms have a higher probability than a random search within the optimization space. Heuristic search techniques based on Charles Darwin's theory of natural selection can be used to correlate modal test data and finite element models.

The main genetic algorithm implementation takes care of the scaling attributes, encoding and decoding schemes, mutation operators, cross-over operators, and the probability associated to cross-over. The elitism flag is turned on in some specific cases. The methodology employed in the Simcenter 3D model update involves two reproduction plans: the steady-state reproduction with or without elitism.

The optimization is initiated using a random seed value. Therefore, even if design variables are reset to 1.0, the optimizer will give different results.

Siemens Digital Industries Software

Headquarters
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 972 987 3000

Americas
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 314 264 8499

Europe
Stephenson House
Sir William Siemens Square
Frimley, Camberley
Surrey, GU16 8QD
+44 (0) 1276 413200

Asia-Pacific
Unit 901-902, 9/F
Tower B, Manulife Financial Centre
223-231 Wai Yip Street, Kwun Tong
Kowloon, Hong Kong
+852 2230 3333

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