

Simcenter 3D FE Model Updating with Multiple Configurations

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1 Introduction

Analytical models are commonly used to simulate product performance at the design stage. Before any prototypes are manufactured, the analytical models can simulate multiple performance domains. One common usage is simulation of the structural performance. This includes static and/or dynamic responses with the major outputs being displacements and stresses.

Once prototype or manufactured products are available, there are still significant uses for the simulation model. These include:

- Simulation of design changes for future updates
- Simulation of new configurations of the product
- Simulation of new operational conditions

To improve the fidelity of these simulations, Simcenter 3D FE Model Update can be used to adjust selected parameters of the simulation model, called Design Variables, to provide a better match to actual product performance. Examples of typical design variables are material properties, such as Young's Modulus and physical properties such as plate thickness.

One of the recent additions to Simcenter 3D 2021.1 FE Model Update is Model Update Sets. This supports industry workflows, such as airframe ground vehicle testing, in which a structure is subjected to multiple dynamic tests, each with slight variations. The user selects a Simulation solution/Test Result pair to be used for the updating process, which define a Model Update Solution. Model Update Sets identify multiple Model Update Solutions that will be optimized simultaneously. Design Variables that are common to multiple Model Update Solutions will be assigned the same value across all solutions during the model updating process.

This paper describes the process of using Simcenter 3D FE Model Update and some of the theory behind it with emphasis on the use of Model Update Sets.

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An important feature of Model Update Sets is that the selected Model Update Solutions do not need to have identical boundary conditions or geometry. In the spacecraft example we will show later, one Model Update Solution uses just the spacecraft bus, and the second uses the full spacecraft including bus and payload. The two are updated simultaneously with common design variables having the same values across both solutions.

2 Why Model Update Sets?

If multiple modal tests have been performed on a structure under different boundary conditions, it makes sense to use as much of that data as possible for the model updating process. One approach would be to perform a separate model update for each configuration, but that would likely produce different values for common design variables, leading to a different updated FEM for each configuration. Going forward, it would be necessary to select the FEM that most closely matches the new configuration. Using the Model Update Sets approach, a single value is obtained for each Design Variable that has been optimized across all configurations used in the Model Update Set. Some design variables can be common to multiple configurations, whereas others may occur in only one configuration. With this approach, the design team can move forward with a single updated FEM that is good for all conditions considered and is physically more appropriate than having multiple FEMs representing one physical reality.

Consider the case of a simple beam. If this is modeled in the free-free condition only, then the first two in-plane mode shapes are as shown in Figure 1 (modes 1 and 3, since mode 2 is out of plane). Figure 1 shows the displaced shapes, and the color contour represents the unaveraged Von-Mises stresses. In all modes there are areas of zero translation and zero stress. Changing the mass at a point with zero displacement will have no effect on mode shape or frequency and, conversely, 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, then model updating will be unable to determine an optimum value for that parameter.

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

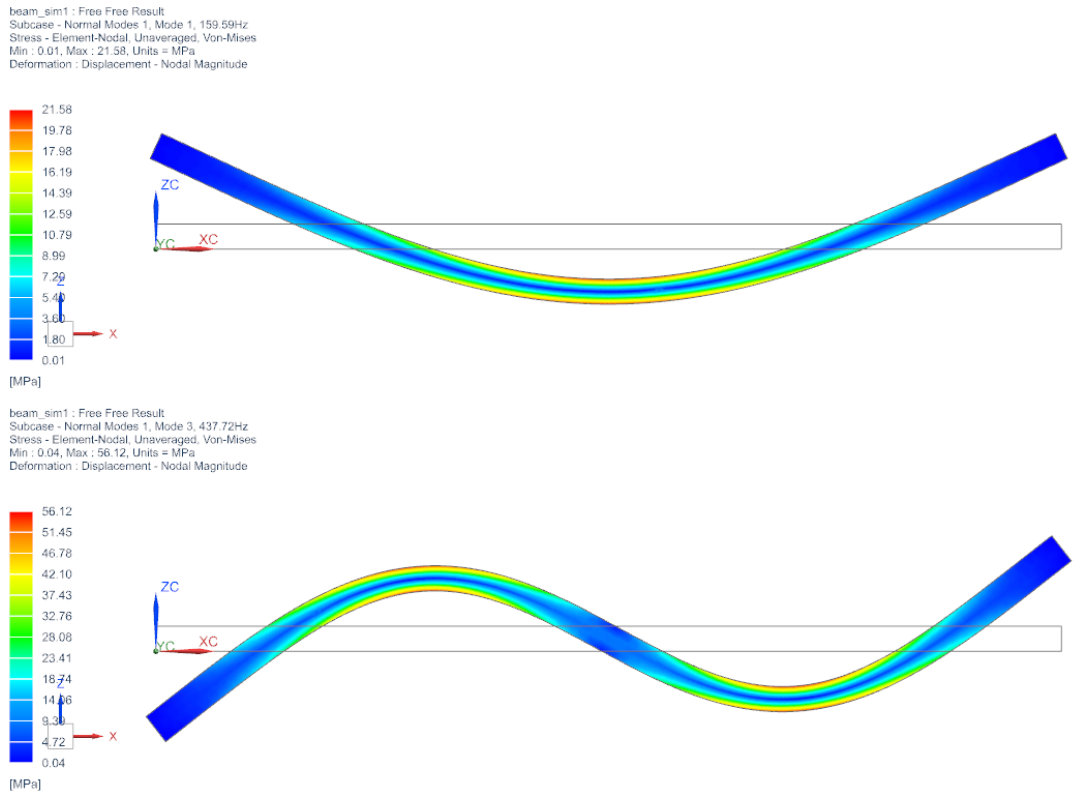


Figure 1: Modes 1 and 3 of Free-Free Beam

Figure 2 shows the same beam with one end fixed. There are now stresses at the fixed end of the beam and so model updating will be able to optimize the stiffness in that region. However, the lack of translation in all modes at that point means that 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 that is appropriate.

Performing a model update using the two configurations allows a wider range of beam parameters to be optimized in a single pass. Performing a model update using just one configuration will always have some mass or stiffness parameters that have very small or no influence on mode shapes and frequencies. Combining multiple configurations into a single model update can overcome these limitations.

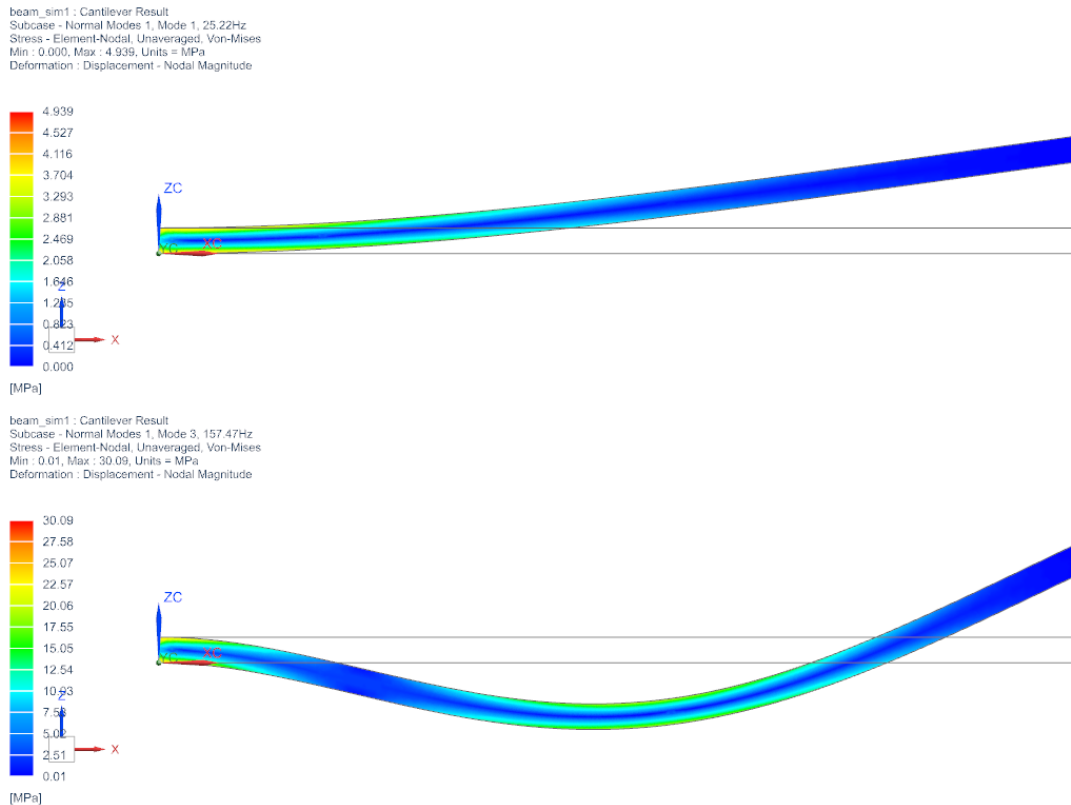


Figure 2: Modes 1 and 3 of Cantilever Beam

3 Simcenter 3D FE Model Update Overview

Simcenter 3D FE Model Update requires the following inputs:

- Modal test data of the structure under defined boundary conditions. The data typically includes:
 - Natural Frequencies
 - Mode Shapes
 - Frequency Response Functions (FRFs)
- An FE simulation model that represents the test structure including boundary conditions, for example, an airframe with the same fuel and or passenger loading. The model should include the following items:
 - Design Variables defined and the model solved with a Simcenter or MSC Nastran SOL 200 – Model Update solution type. This is a special solution that performs a partial SOL 200 solution (SOL 200 license is not required) to determine Design Variable and reduced matrix sensitivities.
 - A set of Degrees of Freedom (DOFs) that will be used to define a reduced model used in the model updating process. This set should include the DOFs used for the modal test.

The test results are loaded into the Simcenter 3D simulation file containing the simulation model. The user then sets up the Model Updating process by identifying the following:

- The set of test results to be used as a reference for the model updating process.
- Simulation model solutions that correspond to the test conditions.
- Targets – These are the test results that the model updating process will try to match by varying Design Variables. Targets can be natural frequencies and mode shapes.
- Design Variables – The updating is typically performed using all the Design Variables defined in the FEM but there is an option to deactivate some of the Design Variables.

An overview of making these selections is covered in the following sections and details are presented in Appendix A. The theory behind the updating process is presented in Appendix B.

4 Defining and Solving a Model Update Set

The model being used to illustrate the process consists of a Spacecraft. It has been simulated and tested in two configurations: Bus Only and Spacecraft (Bus + Payload). These are shown in Figure 3.

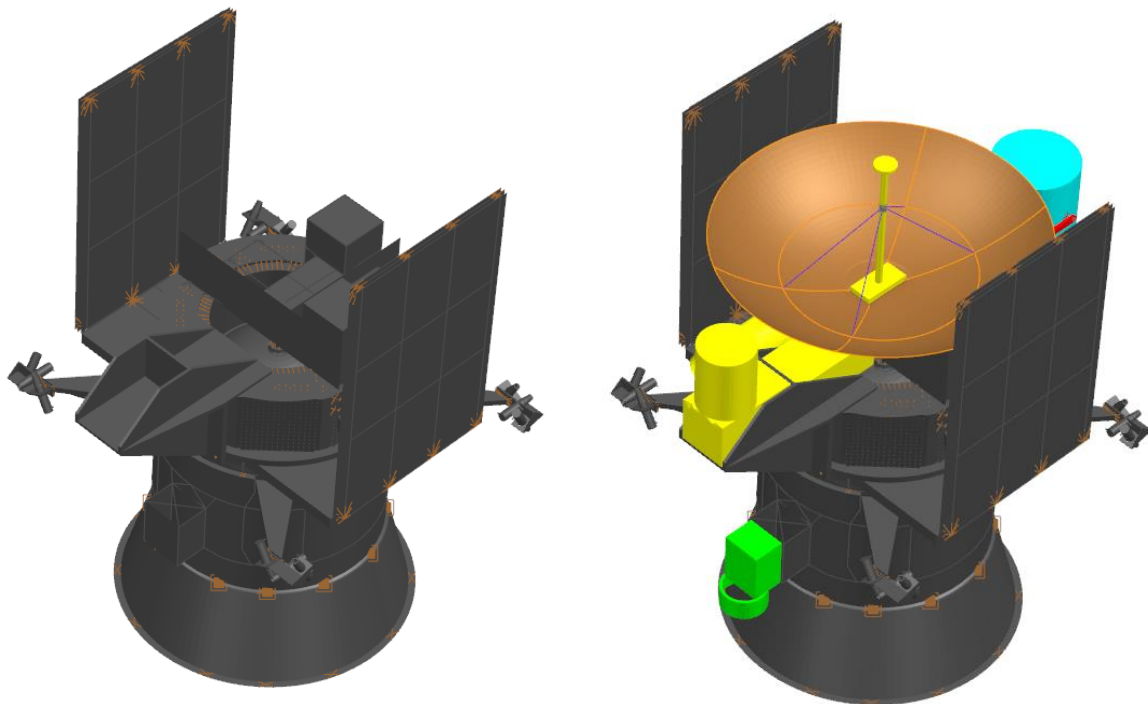


Figure 3: Spacecraft Configurations - Bus Only and Bus + Payload

4.1 Defining Model Update Solutions for the Bus and the Spacecraft

A Model Update Solution is required for the Spacecraft as well as for the Bus Only. Achieving this involves defining a new Model Update Solution, selecting the Bus Only test results and the Bus Only SOL 200 Model Update Solution, and then defining the targets. The detailed steps are given in Appendix A.

4.2 Creating a Model Update Set

Once the Model Update Solutions have been created, a Model Update Set that combines both can be defined, so that they are solved simultaneously. The Model Update Set definition dialog simply lists all existing Model Update Solutions, and the user selects the solutions to be included using a contextual menu, Figure 4.

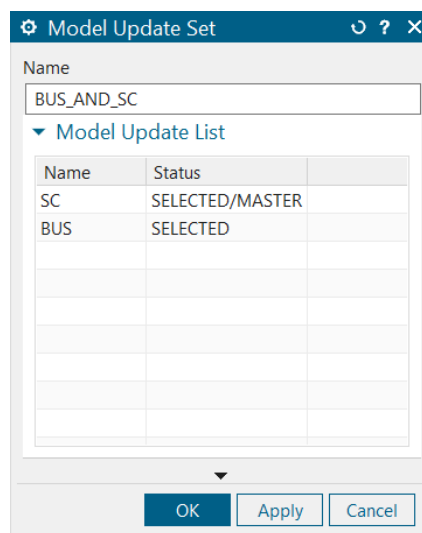


Figure 4: Defining Model Update Set

4.3 Mode Pairing

By default, the master Model Update Solution defines the mode pairing method. If no master is selected, the user has the option to define the mode pairing method: Modal Assurance Criterion (MAC), Cross-Orthogonality (X-Ortho), or Manual. MAC and X-Ortho pairing methods also determine the correlation metric used to optimize the 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 errors (expressed as %) calculated for modal frequencies for the full spacecraft solution. Since no model updating has 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%.

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

Table 1: Initial Errors for Frequencies from Spacecraft Solution (Errors expressed as %)

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%, 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

Table 2: Initial Error Summaries.

4.4 Optimization

With the Model Update Set defined, it is now possible to perform optimization to decrease the errors. All optimization is performed using the reduced model, which means that the model can be solved very quickly, allowing for optimization with many design variables.

During optimization, the original solutions are untouched. Therefore, all changes are fully reversible. This allows different optimization methods and parameters to be tried using multiple runs of the optimizer. The design variables can be reset to their initial values at any stage, allowing optimization to start from the initial values. Alternately, multiple optimizations can be performed in sequence using different methods, parameters, Design Variables, and active targets. No optimization strategy will work for all models. In this particular case, just running the Least Squares Optimizer with frequency and mode shape targets for the first 15 modes active improves the overall error from 29.6% to 14.77%.

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

1. Deactivate all mode shape targets. This gives an initial overall error of 21.7%. It changes because mode shape errors are not included in the overall error calculation.
2. Optimize solution using parameters shown in
3. Figure 5. Overall error is reduced to 0.16%.
4. Reactivate targets for mode shapes 1 through 15 for both solutions in set. The overall error is now 4.1%.
5. Optimize again with the same settings. The overall error is now 1.57%.

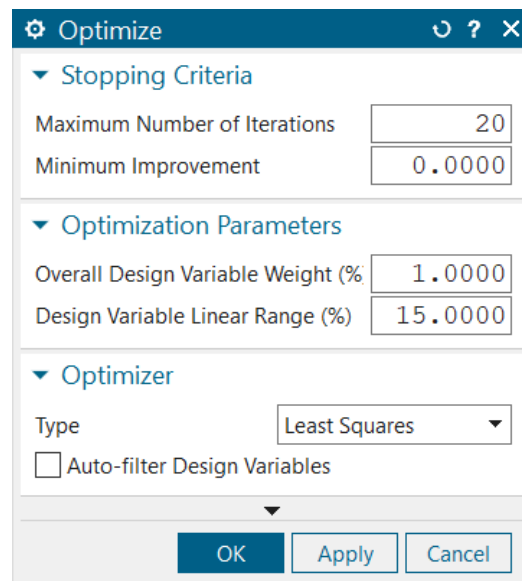


Figure 5: Model Update Optimize Form

4.5 Updating Design Variables and FEM

The FE Model was then updated using the Design Variable values determined by the optimizer. The Design Variable changes applied to the FEM after the first optimization are shown in Table 3.

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

Table 3: Design Variable Changes Applied After First Optimization

Solving the Bus and Spacecraft Solutions from the updated FEM and recalculating the errors gave an overall error of 9.4%. This is slightly different from the final error that resulted from the optimization. That's because the optimization is performed on a reduced model that behaves slightly differently than the full model. Repeating the optimization cycle (Optimize/Update FEM/Solve) further reduced the overall error to 3.3%. A final cycle was performed, this time with the first 15 shape and frequency targets always active, and the overall error was reduced to 0.05%.

The progression in error values through the updating process is shown in

Table 4 and

Figure 6. These show that the optimizer computes Design Variable values that are predicted to give very small errors, which are slightly different from the errors computed from the full model. The major advantage of using the reduced model is that optimization is performed very quickly. For the model presented here, a typical optimization solve took less than 10s. The cycle of deactivating shape targets, optimizing, then reactivating shape targets and optimizing a second time, takes about one minute. It is, therefore, very practical and easy to try a number of different strategies to get 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 successfully used hundreds of Design Variables.

		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

Table 4: Progression of Error Values through Updating Process

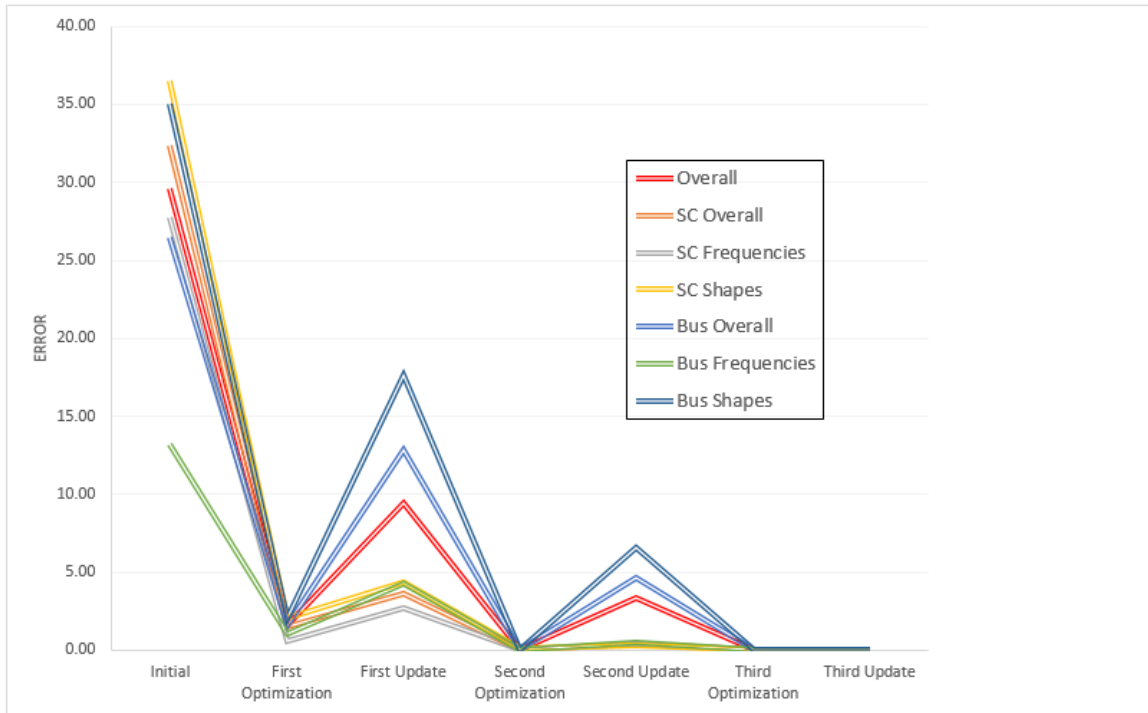


Figure 6: Progression of Error Values through Updating Process

After three full optimization cycles, the overall error has been reduced from 29.6% to 0.05%.

The initial and final MAC matrices for both model are shown in Figure 7, Figure 1 and Figure 8, respectively. The dramatic improvements achieved through the model updating process are clearly apparent.

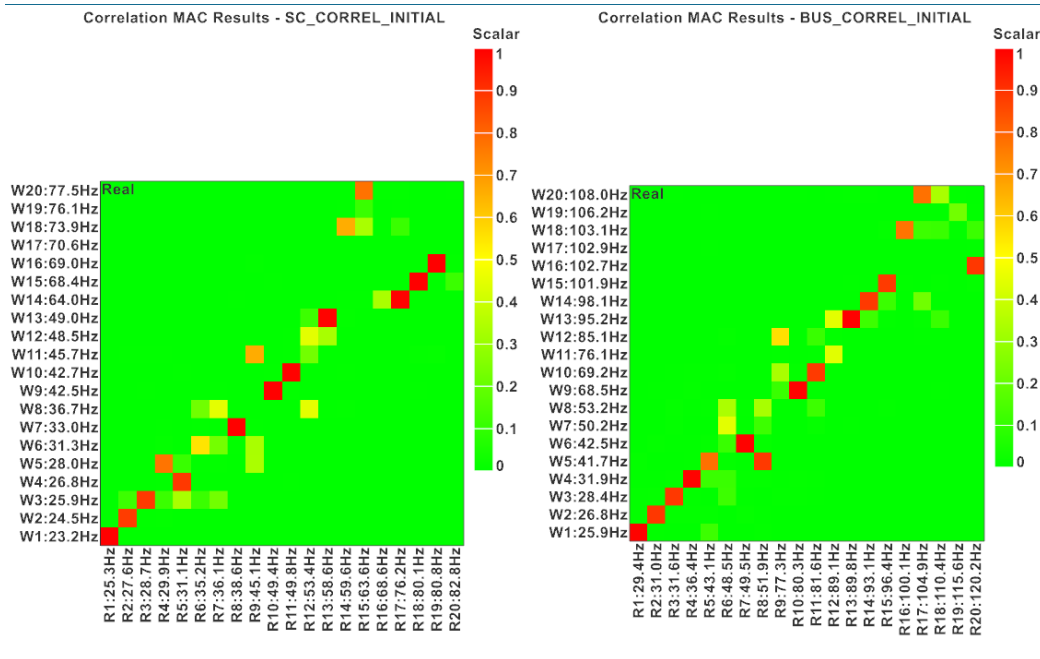


Figure 7: Initial MAC Matrices for Both Models

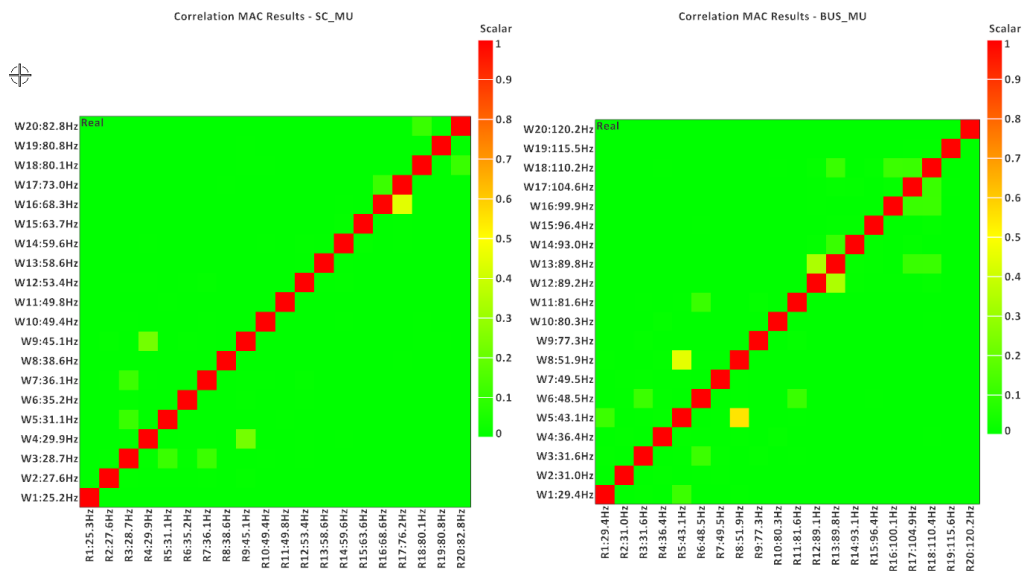


Figure 8: Final MAC Matrices for Both Models

5 Conclusions

Model Update Sets are a valuable addition to Simcenter 3D FE Model Update. They allow optimization of model parameters across multiple FE Model/Test configurations. This creates a single FE model that

has been validated across all test configurations. The model can be used for further product development with increased confidence.

The optimization process tends to predict smaller errors than are actually achieved when the Design Variables are optimized and the updated FEMs solved. For maximum model improvement, multiple optimize/update FEMs/solve FEMs cycles can be performed. The practical limit is likely determined by the solution time of the FEMs, which in the case of the spacecraft model was 2 to 3 minutes.

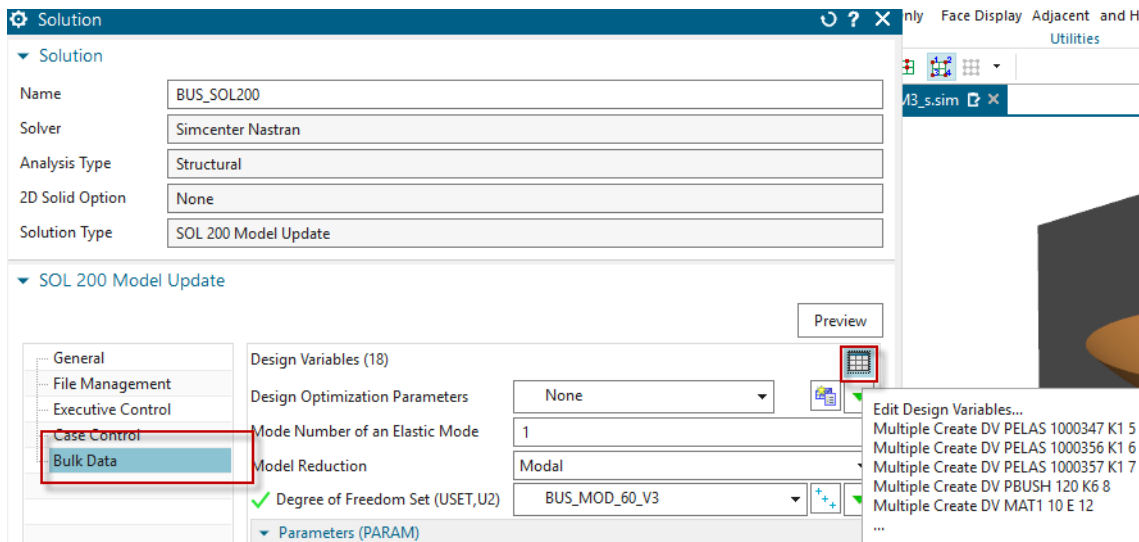
The use of a reduced model for optimization means that many optimization strategies can be tried rapidly. There is no single strategy that works for all models. The method used here reduced the overall errors from 29.6% to 0.05% in three optimization cycles.

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

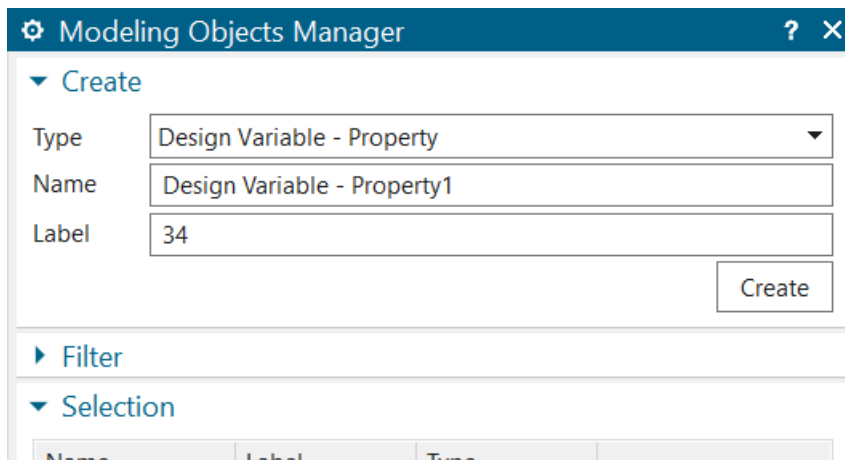
Appendix A – Detailed Steps for Creating Bus Only Model Update Solution

Define Design Variables

Design Variables are defined at the simulation level in Simcenter 3D. Using the Bus_SOL200 as an example, first make that solution active, then right-click and select **Edit**.



Click the **Bulk Data** tab and click **Edit Design Variables**



- At the top of the dialog, select the type of Design Variable (Property, Composite Property or Material) and then click **Create**. The lower part of this dialog (not shown) is where Design Variables can be listed and managed.

Design Variable - Property

▼ Modeling Object

Name: Design Variable - Property1

Label: 34

▼ Properties

Description: []

Card Name: DESVAR/DVPREL1

▼ Design Variable (DESVAR)

Label: []

Initial Value: 1

Lower Bound: []

Upper Bound: []

Fractional Change: []

▼ Property Relation (DVPREL1)

Type: PBAR

* Physical Property: None

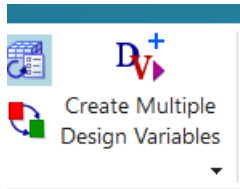
Property Field: []

Relation Definition: Assigned at Export

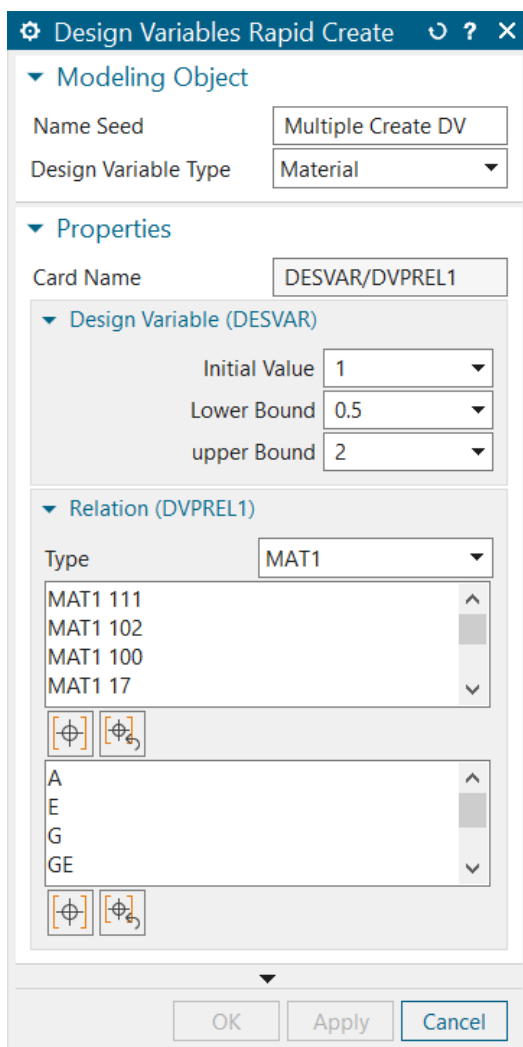
OK Cancel

- Complete the dialog. Assign a name and then select the property or material and the field to be used as the Design Variable at the bottom of the dialog. The middle portion is used to assign limits to the variation of the Design Variable value.
- Click **OK** to complete the Design Variable definition.

A faster way to define many Design Variables is to click the **Create Multiple Design Variables** button from the **Correlation** tool bar.



This displays the following dialog:



The dialog is set up to define multiple Design Variables for materials of type MAT1. The bottom two controls are for selecting which materials to include and which properties Design Variables will be created for.

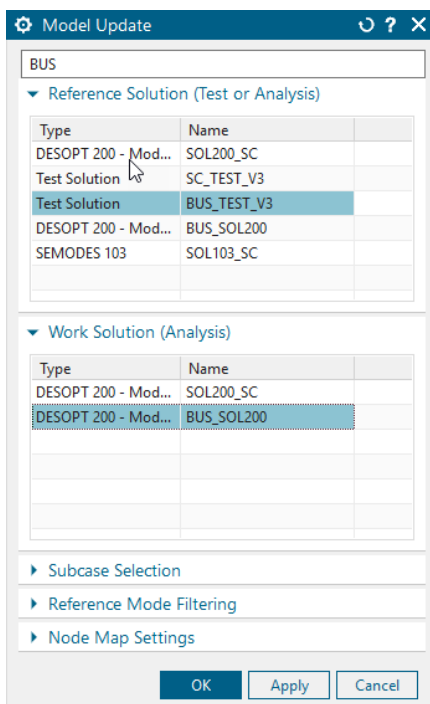
Define Model Update

From the **Model Update** group of the **Correlation** tab of the main toolbar, click **Model Update**.



This opens the Model Update dialog box.

- Set the **Name** to **BUS**.
- Under **Reference Solution**, select **BUS_TEST_V3**.
- Under **Work Solution**, select **BUS_SOL200**.



Click **OK**

The **BUS** Solution is created and is exposed in the Simulation Navigator.

Define Targets

We will optimize the first 15 frequencies and mode shapes: The goal is to reduce the difference between each paired test and analysis frequency, as well as between the paired mode shapes, the latter being quantified in terms of the MAC.

- ☞ Select the **Frequencies (20)** node under the **Targets (40)** node.
- ☞ Expand the **Correlation Details View**.
- ☞ Using SHIFT-Select, **deactivate** Frequency Targets **16 through 20**.

▼ Correlation Details View

Id	Ref Mo...	Ref Freq	Weight	
<input checked="" type="checkbox"/> 7	7	50.170	1.000	
<input checked="" type="checkbox"/> 8	8	53.367	1.000	
<input checked="" type="checkbox"/> 9	9	64.327	1.000	
<input checked="" type="checkbox"/> 10	10	65.046	1.000	
<input checked="" type="checkbox"/> 11	11	78.130	1.000	
<input checked="" type="checkbox"/> 12	12	81.881	1.000	
<input checked="" type="checkbox"/> 13	13	91.617	1.000	
<input checked="" type="checkbox"/> 14	14	94.784	1.000	
<input checked="" type="checkbox"/> 15	15	98.027	1.000	
<input checked="" type="checkbox"/> 16	16	98.798	1.000	
<input checked="" type="checkbox"/> 17	17	101.903	1.000	
<input checked="" type="checkbox"/> 18	18	102.214	1.000	
<input checked="" type="checkbox"/> 19	19	104.003	1.000	
<input checked="" type="checkbox"/> 20	20	107.749	1.000	

Columns

- ☞ Do the same for Mode Shape Targets **16 through 20**.

There are now **30** optimization targets.

Appendix B – Model Update Theory

5.1 Error Calculations

The errors are calculated as shown in Equ. 1 and Equ. 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 Cross Orthogonality.

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

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

5.2 Objective Function and Weights

Weights are part of the optimization objective function shown in Equ. 3, where T_{errors} are the errors in the active targets and $DV_{changes}$ is the normalized change in a Design Variable. A and B are user-defined weights.

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

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

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 variation in value for the associated Design Variable; a weight of zero allows complete freedom. It can be thought of as the 'inertia' of the Design Variable.

5.3 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, like in the case of FRF optimization. However, since the Least Squares algorithm converges extremely quickly in comparison to the two other algorithms, it is the default optimizer for Simcenter 3D Model Update.

5.4 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.

5.5 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 been found to be much better, from a probabilistic standpoint, than purely random search within the optimization space. Heuristic search techniques developed over the past 40 years in optimization and machine learning based on Charles Darwin's theory of natural selection can be exploited 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 operator, and the probability associated to cross-over. The elitism flag is turned on in some specific cases. The methodology employed within Simcenter 3D Model Update involves two reproduction plans, namely the steady-state reproduction with or without elitism.