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CAD geometry preparation issues effecting FE simulation accuracy

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Abstract

When generating a design for a complex assembly, large amounts of detail are produced in the CAD model. Whilst this level of detail is paramount in generating a Bill-Of-Materials (BOM) and visualising mechanical conformance, it can be detrimental to additional finite element (FEA) operations. Complex CAD-centric assemblies must be prepared for FEA, such as removing unwanted parts, and part geometry defeaturing. Part defeaturing can be considered the most important step in CAD FEA preparation as it can be the largest error contributor. However, the removal of certain features has the potential to create artificial stress risers in the part, that can result in false positive FEA solutions. Additionally, if bulk material is added/removed by defeaturing, structural and thermal properties of the parts can be greatly altered leading to inaccurate solutions.
Conversely, if these features are left in, they can lead to poor quality mesh that can lead to inaccurate results, non-converging solutions, excessive computing time and power requirements.
From discussions with industry partners, the main barriers to them using FEA effectively are the issue around proper defeaturing to ensure accurate results, and the time needed to perform model preparation. The work presented here is aimed at understanding and defining the effects that changes in geometry and mesh attributes can have on simulation results. Certain solutions which have already been evaluated, such as rapid part removal for assembly preparation, are also included. Additionally, this work highlights how current automated defeaturing solutions are not suitable for more complex FEA simulation preparations.

Keywords: CAD, FEA, Mechanical design, defeaturing

1. Introduction

Finite Element Analysis (FEA) has many uses in mechanical engineering. Numerous applications require an in depth understanding of a component or assembly's solid body mechanics, stress distribution, natural frequencies etc.

Because raw material costs are increasing [1,2], and supply chains are being stretched, older practices of over engineering are become less financially viable than they once were. Manufacturers who may have forgone the use of FEA in the past are now starting to review its viability within their business practices. However, the completed CAD-centric model for manufacturing, including a comprehensive bill on materials (BOM), is not always suitable for additional FEA simulations. A complete BOM CAD model may consist of thousands of individual components, many of which might not be required for the simulation at hand. Leaving such components in the simulated assembly model will require additional computing power and can take considerably more time to solve [3]. Therefore, it is important to remove components that are not inherent to the desired solution, in efforts to reduce solver time, and remain in budget. Yet here can be seen the contradiction. Is time to be spent removing unwanted parts for the assembly, or during simulation time?

In addition to the removal of unwanted parts, individual part geometry needs to be considered. FEA generates a mathematical representation of the component under scrutiny. The model is made up of a series of elements connected by nodes that represents the geometry of the component. This process takes irregular shapes of the model and breaks them down into a series of recognisable volumes called elements [4]. The meshing of the components is one of the most important steps in FEA, as it can have a great effect on simulation accuracy or can lead to false-positive results. An understanding of mesh principles and their effects on simulation results is critical to performing accurate FEA simulations. It is important to understand that the act of meshing a component changes the geometry of the model based on size of type of meshing element used [5]. If the ratio of component size to element size is low, the computational time will be quicker but the resultant mesh will be rough and can oversimplify the component's geometry. Conversely, a high ratio will produce a much more accurate representation of the component's geometry due to the small element size, but the mesh could consist of thousands if not millions of elements, that will take a long time to solve, requiring more computing power. Therefore a balance must be struck between accuracy, computing requirements, and time when selecting an element size.

In addition to element size, element quantity also is critical to ensuing simulation accuracy. Certain CAD features can lead to mesh irregularity. Geometric details necessary for manufacture such as holes, slots, radii, indents, and sharp corners, can result in localised smaller element sizes, leading to mesh transition irregularities, and poor mesh quality [6]. Whilst the removal of small holes and slots, etc, is necessary to improve mesh uniformity, their removal from the FEA-abstracted model will change the model geometry increasing uncertainty in the estimated simulation. Additionally, the presence of sharp corners (from the removal of radii) can lead to the introduction of false positive stress rises, or stress singularities [7].

Whilst there are numerous defeaturing methods and analysis techniques to estimate the effect feature removal will have on simulation accuracy [8,9,10], there is no standardised approach to this issue.

An additional barrier to the use of FEA in industry is the standard tools available in typical CAD packages. Most packages defeaturing techniques are too aggressive and offer little or no control over the automated processes for the abstracted model generation. This leaves manual adjustment as the only model manipulation option to ensure the most accurate solution. This in turn increases the number of man-hours and therefore the cost.

The ultimate aim of this work package is to review the defeaturing techniques and disseminate them into a usable CAD package add-on that industry can use. One that can offer the versatility in defeaturing needed to ensure that FEA simulation results are viable, and that error source generation is identifiable. The work presented here highlights some of the issues currently faced with using typical CAD automated defeaturing techniques, and how the incorporation or exclusion of features can affect mesh generation, and result accuracy.

2. Mesh size effects

As said above mesh quality and size are two of the most important factors when consideration simulation accuracy. Figure 1 shows an example CAD-centric design of a machine tool structure.

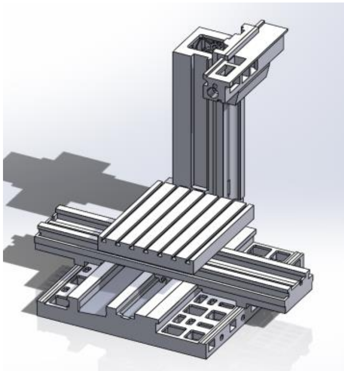

Figure 1. example CAD model of a machine tool structure

Ignoring all other factors, the following shows how element size can affect FEA model geometry, solver time, and solution variance. This model has external dimensions of 3400 mm x 3400 mm x 2740 mm. A modal analysis was performed of this model, with results for the first 5 natural frequencies resolved. (All simulations were run on an 11th gen Intel i9-11900K with 64GB of RAM utilizing 8 cores). Figure 2 shows the element size used, and resultant number of elements in the model, and the time it took to solve the simulation.

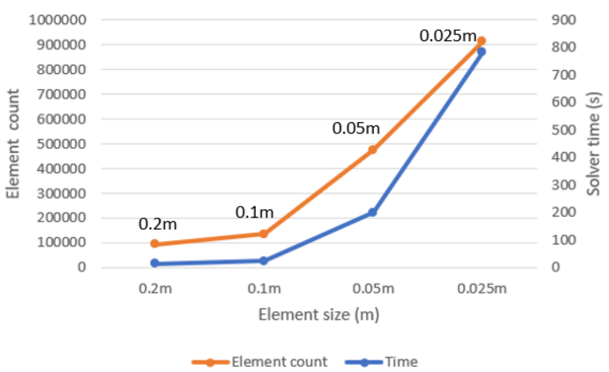

Figure 1. how element size effects element count and solver time.

As can be seen, adjusting the element size and thus the element count can greatly affect the time taken to solve the simulation. With regards to the effect that element size has on accuracy figure 3 shows the results for the first 5 natural frequencies of the model when simulated with element sizes of 0.2m, 0.1m, 0.05m and 0.025m.

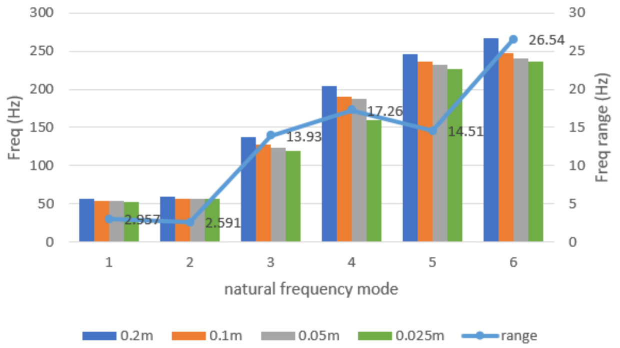

Figure 3. Frequency difference due to changing element size.

As can be seen in figure 3 simply changing the element size does influence the model's natural frequency ranging from 1 or 2 Hz to over 25 Hz. The lower element size allows for the inclusion of more elements within the model, which in turn increases the number of nodal interactions allowing for more degrees of freedom. This reduction in constraint reduces the perceived natural frequency of the model as the model has more flexibility. This is more noticeable at the higher mode numbers which generate more dynamic responses. That said the natural frequency of the fifth mode is a localised deformation in which increasing the nodal count has less of an effect.

2.1. Mesh quality

Changing the element size also affects the quality of the mesh. Ideally the mesh structure needs to be as unform as possible throughout the model. A poor structure can affect the model's stiffness characteristics as the element nodes become less effective. To combat this, the software might either adjust the volume of the models as can be seen in Figure 4 or will automatically add in smaller elements to fill gaps where the larger element cannot be fitted. This in turn can affect the dynamics of the model due to non-uniform loading of the nodes.

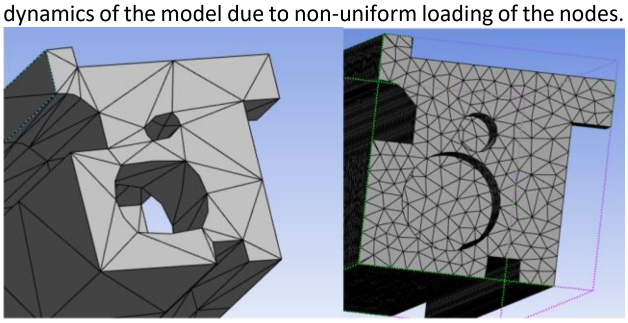

Figure 4. effects of geometry due to element size L- 0.15m, R-0.25m

As can be seen in figure 4 using an element size of 0.15 m has resulted in the geometry of the part being deformed, as compared to the model using 0.025 m element size which has a more uniform mesh with no deformity.

3. Geometric Defeaturing

As previously stated, to take a CAD-centric model, to an abstracted FEA model will require the removal of parts not required for the FEA dynamics, and the geometric defeaturing of parts to remove undesirable features.

3.1. Part removal

Part removal is necessary in FEA model preparation as it can substantially reduce the number of elements in an FEA model. Parts that do not have a role in the desired simulation will simply take up computational resource and elongate the solver time.

Additionally, items such as fasteners, that are needed for the BOM in the CAD model, should also be removed. This is because simplified threads in CAD models often cause interference, as only the drill size is used in the CAD not the thread size leading to an overlap in geometry. When meshed, the interference between the bolt and the holes can lead to severe mesh irregularities.
The removal of these parts is generally straightforward but can be time consuming in its preparation. The CAE engineer will review the CAD-centric model, manually removing the unwanted parts. This can result in many hours of work as complex assemblies can have thousands of parts that need reviewing.
A solution to this is to tag induvial CAD parts within the assembly in which it is being designed. All CAD parts will have part specific user defined properties, such as material, finish, supplier, who designed it etc. By adding an additional custom variable to the part properties that can flag the part for removal, when the design is ready to be defeatured a simple macro can be run that will group these parts together for suppression. Figure 5 shows a completed CAD design for a machine tool base used as an example.

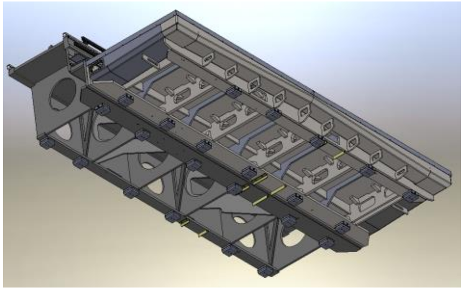

Figure 5. Holistic CAD model of a machine tool bed

All the parts in this assembly shown in figure 5 have had a part property field added named "remove". The parts that need removing have the *remove* field checked, and the parts to remain have the field unchecked. A macro was written for use in Solidworks® that when used will review the status of the *remove* property for all parts in that assembly. If the field is checked, the associated parts are grouped together and highlighted as shown below in figure 6.

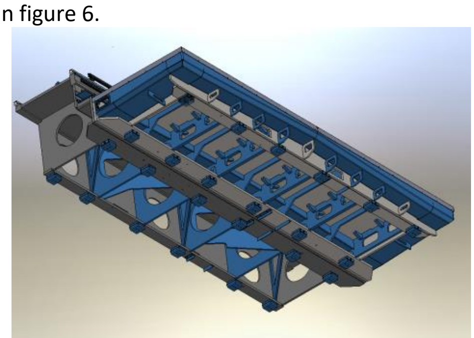

Figure 6. CAD model of a machine tool bed, with parts highlighted for removal.

The macro then generates a new file configuration within the CAD assembly. Within this new configuration all the parts returned with the *remove* field checked are suppressed, leaving the down selected model, as shown below in figure 7.

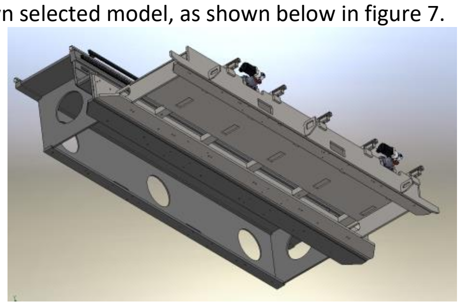

Figure 7. resultant down selected CAD model.

Suppressing the parts in this way allows the user to switch between the CAD-centric model and the new down abstracted model with-in the same file directory resulting in better traceability.
Providing the designer checked the *remove* field during the design process when individual parts were added to the assembly, this method of part removal can result in an abstracted model generated in minutes as opposed to the many hours it would take to do it manually and retrospectively.

3.2. Geometry defeaturing

Geometry defeaturing of CAD parts is the removal of unwanted features from individual parts. As previously stated, features such as, radii, holes, slots etc, will cause mesh irregularities that can alter the FEA model's dynamics. Whilst defeaturing is necessary to ensure the best mesh structure possible, care must be taken not to defeature the part to the extent that the part is no longer representative. Additionally, the removal of certain features will potentially create artificial stress rises, that the removed curved feature would have controlled.
Currently, to ensure optimum part defeaturing, manual intervention is almost always required, and the man-hours dedicated to part defeaturing can be high, especially if the assembly is extensive and consists of many parts.
Most CAD packages have a part-automated defeature or simplification tool, that can speed up this process. Certain CAD software can successfully return a comprehensive defeatured assembly, that maintains part individuality and retains the part relationships. However, the techniques used in most cases can be overly aggressive and lack any comprehensive feature-based control. For example, a popular CAD software commonly used in industry only has two forms of defeaturing large assemblies. The first is a silhouette-based result that removes all features and returns the assemblies' outline shape. For the assembly shown in figure 1, the result of this process is shown in figure 8.

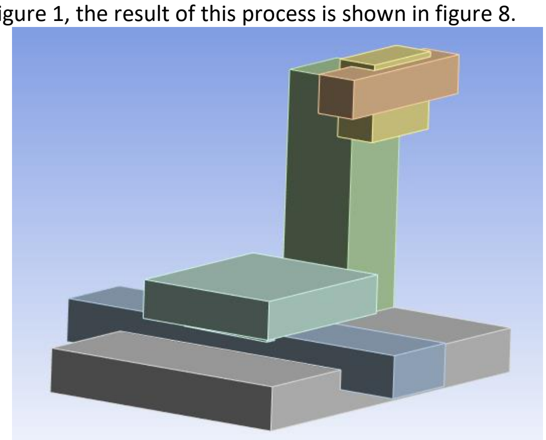

Figure 8. silhouette of machine tool structure.

As seen in figure 8 this level of detail is far removed from the level of detail in figure 1 and bares very little representation of the original CAD model. The second mode of assembly defeaturing in this software does allow for feature selection, however, this feature-based process does not allow for the removal of individual features, but removes all related features. For example, the radii of a square hole cannot be removed in isolation, the entire hole must be removed. Additionally, to perform accurately, selection must be done manually, again increasing the input time. When running the process automatically, the control of what features to keep or remove is rudimentary allowing very little control over the result. An example of this is shown in figure 9.

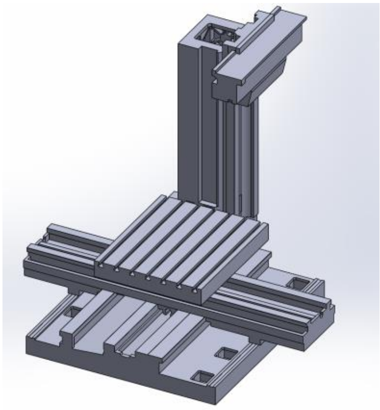

Figure 9. partial defeature of machine tool structure.

As can be seen in figure 9 the defeaturing process has left in several features that should have been removed, namely holes in the base and the detail inside the column. To further remove these features additional process such as extrusions or subtractions will be needed to finalize this model for FEA.

4. *Geometry defeaturing effects*

As geometric defeaturing will have an effect on the model's geometry, it is important to understand how this will affect the FEA simulation results, especially when using pre-defined automated procedures. The models in figures 1 and 6, were subjected to a modal and thermal simulation. In the thermal simulation heat was applied to the back of the column, with results being taken over the column length to show how the temperature of the column varied.
The modal results are shown in figure 10 and the thermal results are shown in figure 11. As can be seen there a marked variation in the two sets of results. In the thermal result the heat transfer is far lower in the nominal model than in the defeatured one. This is due to the removal of the air gap in the defeatured model. In the model results, the frequencies changes for every mode varying from a few hertz to over a hundred. Again, this is due to the change in geometry and thus the change in mass and dynamics.

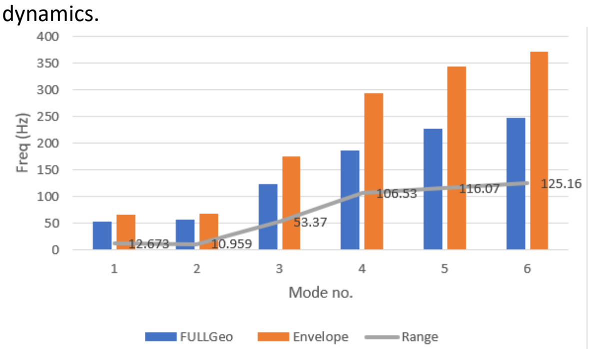

Figure 10. frequency response from the nominal and defeatured models

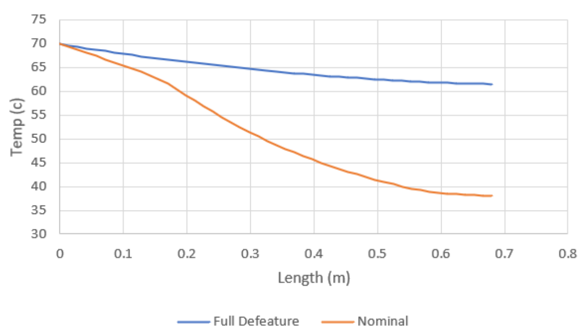

Figure 11. thermal response from the nominal and defeatured models

Whilst this is an extreme case of variance due to the effects of geometry change it highlights the issues that can arise in simulation accuracy when automated defeaturing procedures are used with no regard for their affect.

5. Conclusion

The work presented here highlights how changing FEA variables can affect simulation accuracy. As FEA is being applied more frequently in industry by companies that have never previously used it, it is important for them to understand how small changes in mesh, and geometry can have large effects on result accuracy. It is also important for them to be aware that greater accuracy does come at the price of longevity and man-hours involved, which will incur greater cost.
The ultimate aim of this work package is to generate automated adaptive model preparation techniques that can provide FEA results efficiently and accurately. This will involve automated feature-based defeaturing that can be adaptive to the CAD involved. Part of this work has already been highlighted here. By simply incorporating a custom property into the part design, unwanted parts can simply and quickly be excluded from the model, without the need of manually selected them.
The work for automatic geometric assembly defeating is ongoing with the results to be published in due course.

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