Characterization of MSC/NASTRAN & MSC/ABAQUS Elements for Turbine Engine Blade Frequency Analysis

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ABSTRACT

An accuracy study of MSC/NASTRAN and MSC/ABAQUS three dimensional element types was conducted for turbine engine blade natural frequency analysis. Linear, quadratic, hexahedral, and tetrahedral elements were used with different mesh densities in the frequency and mode shape predictions. These results were compared to bench test data and laser holographic mode shapes. Recommendations are made on the selection of finite element meshes for future analyses.

Introduction

Prediction of engine blade natural frequencies and mode shapes is critical to the design and development of turbine engines. Avoidance of resonance conditions within the engine is critical to maintaining component life. Mode shapes are important in determining areas of high stress concentration. Prediction of the resonance frequencies and mode shapes with the finite element method is the first way to determine operating conditions to avoid.

Today, solid geometry models are readily available and can be brought into MSC/PATRAN with relative ease. Solid finite element meshes that can be used on the solid model have a poor reputation for the accurate prediction of resonant frequencies. Mesh densities of these models are thought to have an important effect on the predicted results[1]. This report investigates the performance of several MSC/NASTAN and MSC/ABAQUS solid elements of various mesh densities.

Problem Definition

Hexahedrons and tetrahedrons are common three dimensional finite elements found in linear or quadratic formulation. Further, the analyst may also choose from full integration, reduced integration, incompatible mode, and hybrid element formulations. These different options are analogous to the tools used by a mechanic in that each one is appropriate for a specific job. For engine blades, the dynamic movement is dominated by bending and twisting in the airfoil. Therefore, elements that accurately model bending will be optimal for blade analysis. Solid elements may performed poorly in modeling bending because of shear locking.

Shear locking, or parasitic shear, is caused by an inaccuracy in the displacement field of a linear quadrilateral or hexahedral element.

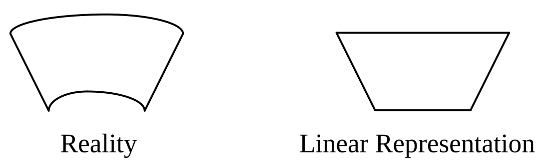


Figure 1: Two representations of beam deflection under bending

On the left is the deformed shape of an infinitesimal particle when placed under a uniform bending load. The top of this particle is placed into tension, the bottom into compression. The figure on the right is a linear element representing the infinitesimal particle. Again, the top is in tension, bottom in compression, but the linear element is unable to accurately model the displacements caused by curvature. A shear stress, which does not occur in the infinitesimal particle, is introduced into the element by this deformation state. This extraneous shear "absorbs" strain energy and the element reaches equilibrium with smaller nodal displacements. Consequently, the element does not predict the bending displacements accurately and will have overly stiff behavior.

Shear locking is exacerbated by elements with large aspect ratios Elements tend to stiffen and lose accuracy as their aspect ratio increases due to increased shear locking. To illustrate, a long beam in bending will have greater displacements and curvature than a shorter beam with an identical load. This curvature is what a linear element fails to simulate and instead creates a spurious shear term that affects the strain energy. So the longer the bar, the greater amount of curvature, and therefore, more spurious shear.

Shear locking can also be decreased by increasing the number of elements that model the bending. As more elements are added the response in each element behaves increasingly linear and therefore will more accurately model the bending displacement.

MSC/ABAQUS Element Integration

The third factor that affects element accuracy is formulation. Below, different types of MSC/ABAQUS element integration are discussed.

Full Integration Elements (C3D8, C3D20, C3D4, C3D10)

Fully integrated linear hexahedral elements (C3D8) use two integration points in each coordinate direction. Therefore, fully integrated linear hexahedral elements have eight (2x2x2) integration points. Visually, these points make a smaller cube within the element. Quadratic hexahedral elements have three integration points (3x3x3) in each direction, creating 27 integration points per quadratic hexahedral element[2].

Reduced Integration (C3D8R & C3D20R)

A technique to relieve shear locking is used in reduced integration elements. These elements use fewer integration points and will often decrease shear locking in certain classes of problems because some terms in the Gauss integration are eliminated. Solution times for these elements are also reduced. In MSC/ABAQUS, only the hexahedral elements can use reduced integration. A pitfall of using reduced integration elements is the potential to model the object without enough stiffness. What is known as hourglassing will occur[3]. Hourglassing is a phenomena seen only in elements with one integration point. With only one integration point at the centroid, a displacement field can be introduced that causes no strain at the integration point. Some hourglass stiffness is included in the MSC/ABAQUS reduced integration element formulation to prevent this lack of stiffness. Using a higher mesh density in the direction of bending will therefore increase the accuracy of the results.

Incompatible Mode (C3D8I)

Incompatible mode elements are another attempt at relieving shear locking in linear hexahedral elements. These elements have an additional degree of freedom that enhances the ability to model a displacement gradient through the element. In a sense, these elements act like quadratic elements. Usage of the incompatible mode elements generate results comparable to quadratic elements with a lower computational cost. A drawback to these elements are their sensitivity to element distortion. These distortions end up making the elements too stiff.

MSC/NASTRAN Element Integration

MSC/NASTRAN has three types of integration available for the CHEXA element: reduced shear integration with and without the use of bubble functions and isoparametric integration [4]. Reduced shear integration minimizes shear locking problems as well as avoiding hourglass modes. Bubble functions minimize Poisson’s ratio locking which occurs in bending elements. Reduced shear integration with bubble functions is the default integration scheme. Isoparametric integration is the only form available for the CTETRA element.

ANALYSIS & RESULTS

Initial predictions were generated with MSC/ABAQUS. The entire blade geometry was modeled and surface interface elements were used to accommodate the mesh transition from the airfoil to the platform. Subsequent prediction with MSC/NASTRAN used only the airfoil geometry to avoid meshing difficulties. The results of the MSC/NASTRAN solutions are compared to a MSC/ABAQUS airfoil model, using its most accurate element. Figure 2 shows a typical MSC/ABAQUS blade model.

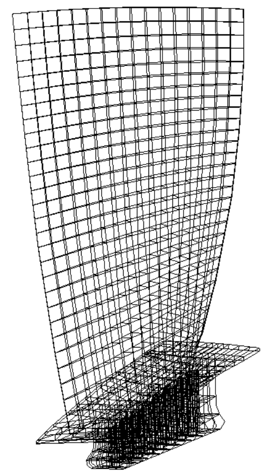


Figure 2: MSC/ABAQUS Finite Element Model of f110 Blade

Initial sets of results presented are for models created with various edge lengths and one blade thickness element. These edge lengths are directly related to the mesh density. After determining a trend for each element, an edge length was selected and mesh seeds were used to increase the number of thickness elements. These results were compared either to two sets of experimental data or to the MSC/ABAQUS airfoil prediction mentioned.

MSC/ABAQUS Linear Hexahedral Elements Results (C3D8, C3D8R, C3D8I)

Figure 3 shows that increasing the C3D8 mesh density by reducing edge length causes the calculated frequencies to decrease. With more linear elements in the model shear locking is lessened. Also, aspect ratio improves as the mesh density increases to further reduce shear locking.

In Figure 4, increasing the mesh density by reducing the edge length causes the calculated frequencies to drop, again, caused by aspect ratio effects and decreased shear locking with additional linear elements. However, this figure shows that the frequency results obtained with the C3D8R were well under experimental values because of hourglassing.

Figure 3: Effect of Mesh Desity with C3D8 Elements

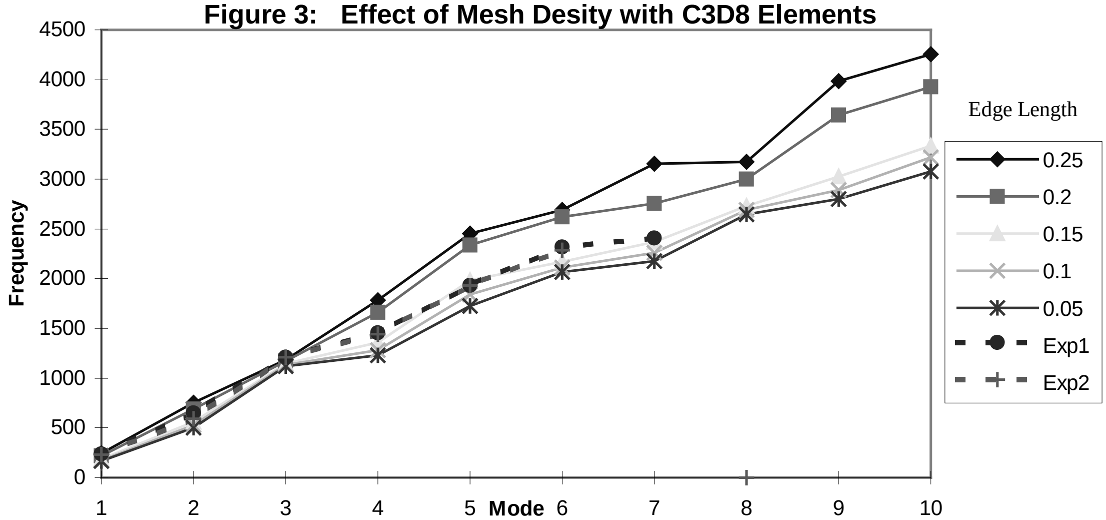


Figure 4: Effect of Mesh Density with C3D8R Elements

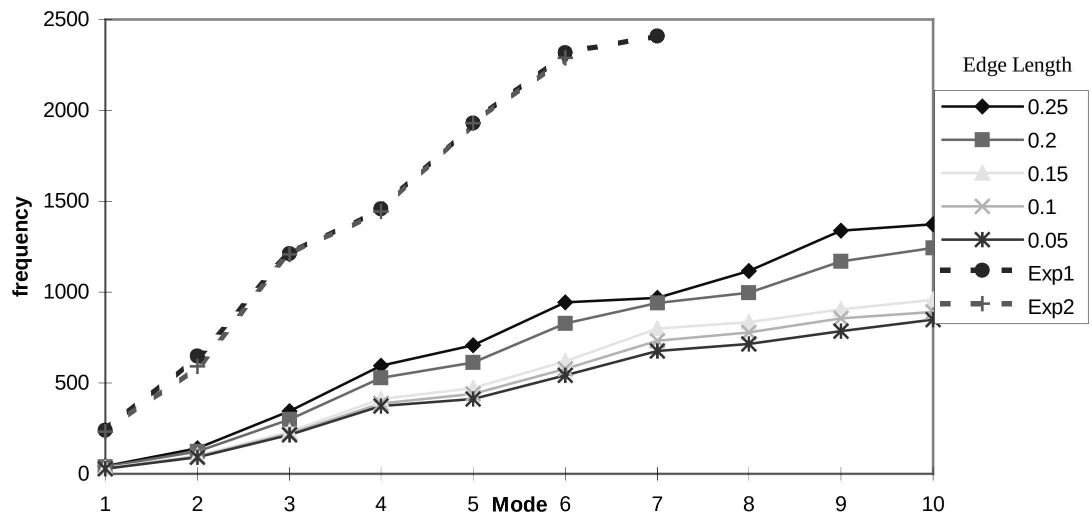


Figure 5: Effect of Mesh Density with C3D8I Element

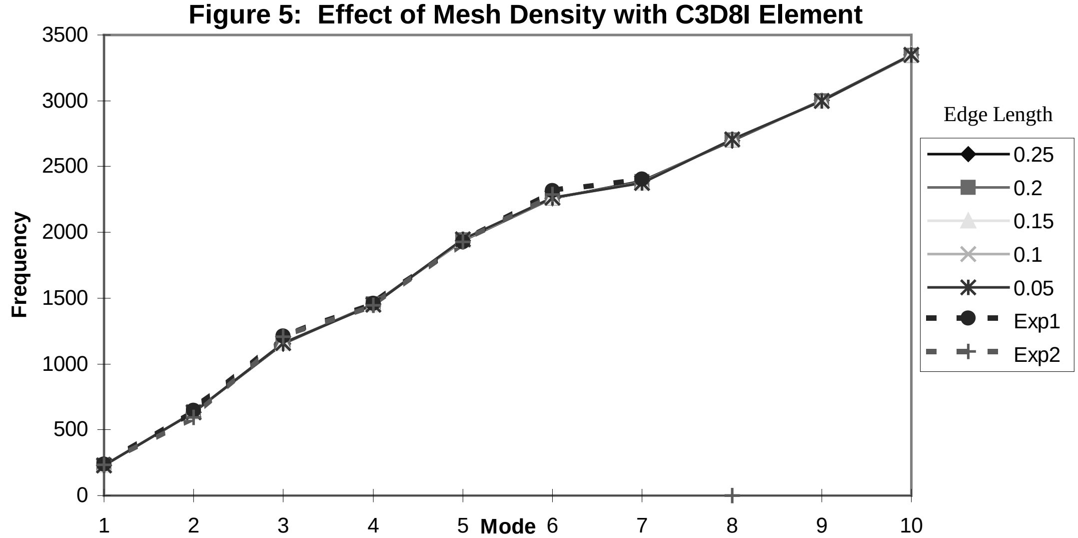


Figure 5 indicates that C3D8I elements are insensitive to mesh density for the edge length range considered. Results from the C3D8I and that computed values fall close to experimental.

With mesh density trends developed for these three elements, the 0.25 edge length was used with mesh seeds to see the effect of added thickness elements. Figure 6 shows increasing the number of C3D8 elements through the blade thickness causes the computed frequencies to increase slightly . Increasing the number of elements through the thickness increases shear locking because of higher aspect ratios and yet reduces shear locking by making the response per element more linear. The aspect ratio effects apparently override this gain and there is still a net increase in stiffness.

Figure 7 indicates that the response of the C3D8R stiffens and reaches experimental levels as thickness elements are added. This is because of the increased hourglass stiffness introduced with each additional thickness element. Frequencies are still below experimental especially past the fourth mode.

Figure 8 exhibits the insensitivity to thickness element changes of the C3D8I element. The C3D8I elements show good frequency results even with one element through the thickness.

Figure 6: Effect of Increased C3D8 Blade Thickness Elements

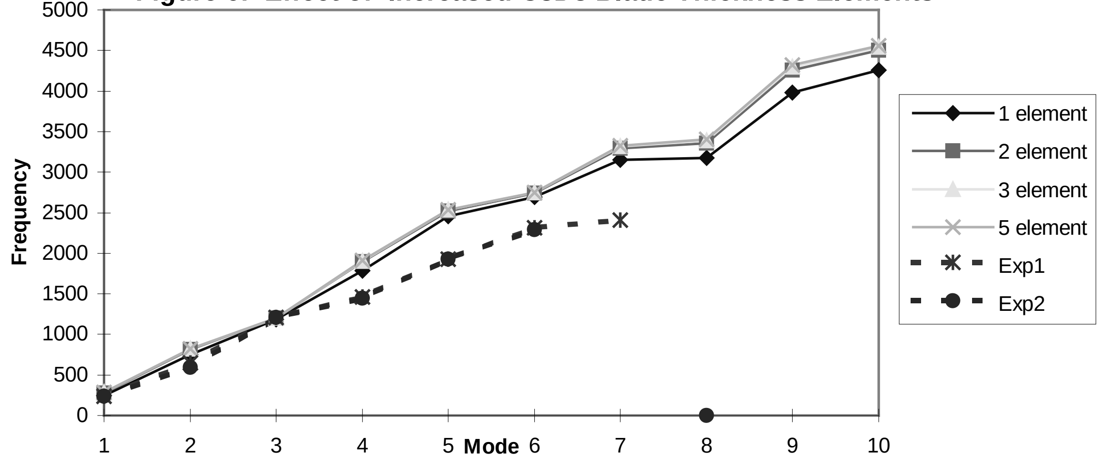


Figure 7: Effect of Increased C3D8R Blade Thicknes Elements

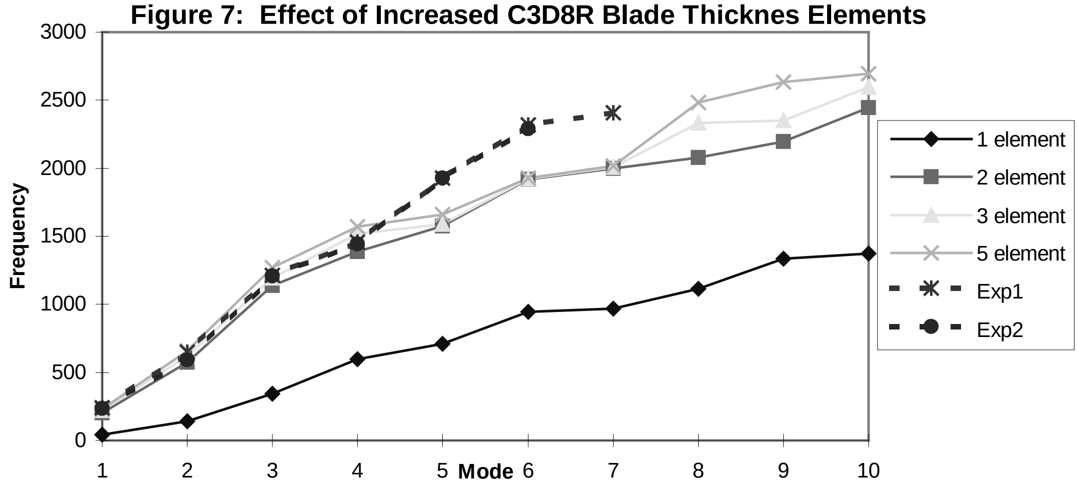
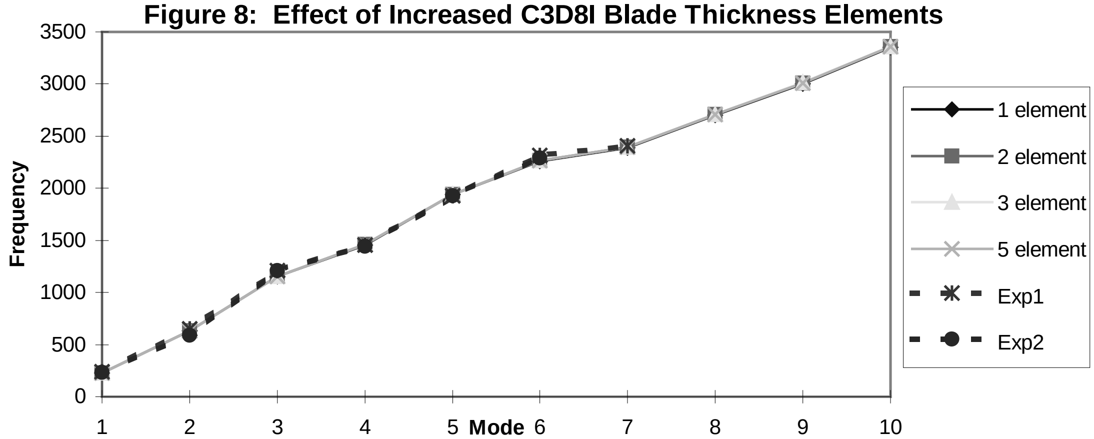


Figure 8: Effect of Increased C3D8I Blade Thickness Elements



Results from the mesh density study showed that the C3D8 element clearly tends to shear lock, but mesh refinement tends to improve its response. As additional thickness C3D8 elements are added predicted response worsens. The C3D8R performed poorly with one element through the thickness with improving response as elements are added to the thickness. Of the linear hexahedral elements available in MSC/ABAQUS, the C3D8I is clearly the most accurate for modal analysis.

MSC/ABAQUS Quadratic Hexahedral Elements (C3D20, C3D20R)

The C3D20 elements, in Figure 9, show good frequency prediction with meshes far coarser that that for the linear elements. Only when the edge length reaches 1.25 does of shear locking become evident.

Figure 10 indicates that the C3D20R element provides results comparable to the C3D20 element. They appear to be more accurate than the C3D20 element at the higher modes because of reduce shear locking.

Thickness element effects were studied with an edge length of 0.5. Figure 11 shows increasing C3D20 elements through the thickness had negligible effect of calculated results. Apparently, the parasitic shear from higher aspect ratios is accounted for by additional accuracy by increasing the number of elements in the bending direction.

Figure 9: Effect of Increased C3D20 Mesh Density

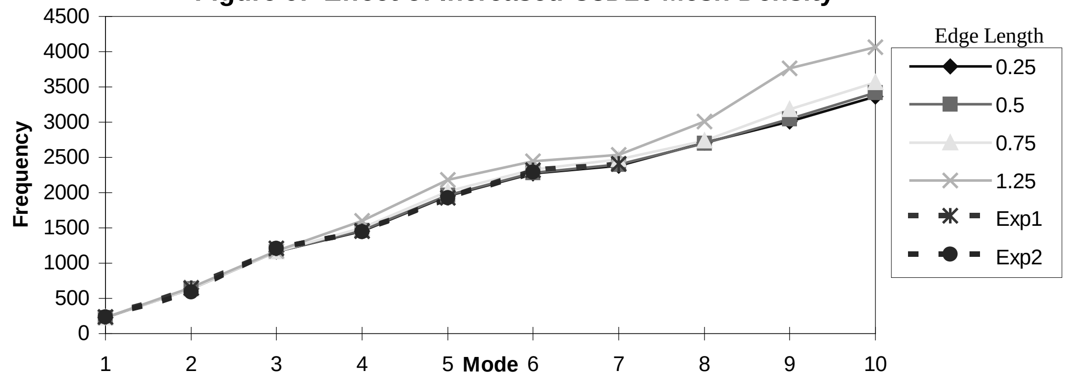


Figure 10: Effect of Increased C3D20 Mesh Density

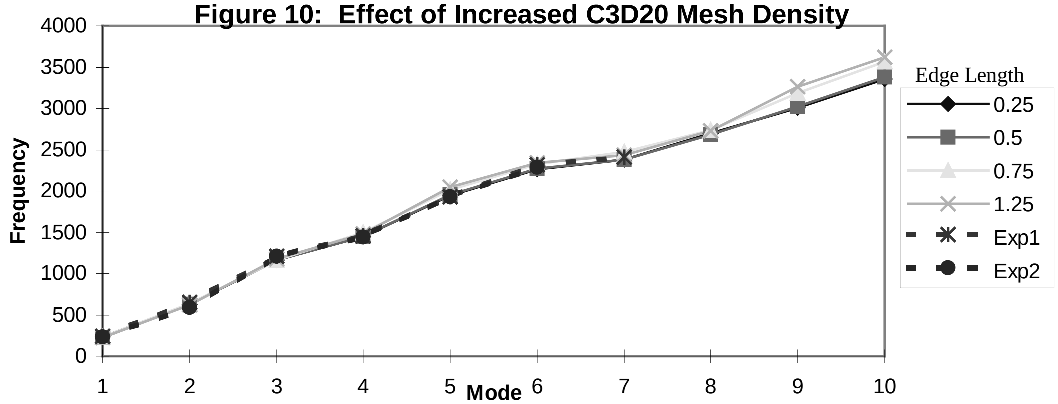


Figure 11: Effect of Increased C3D20 Blade Thickness Elements

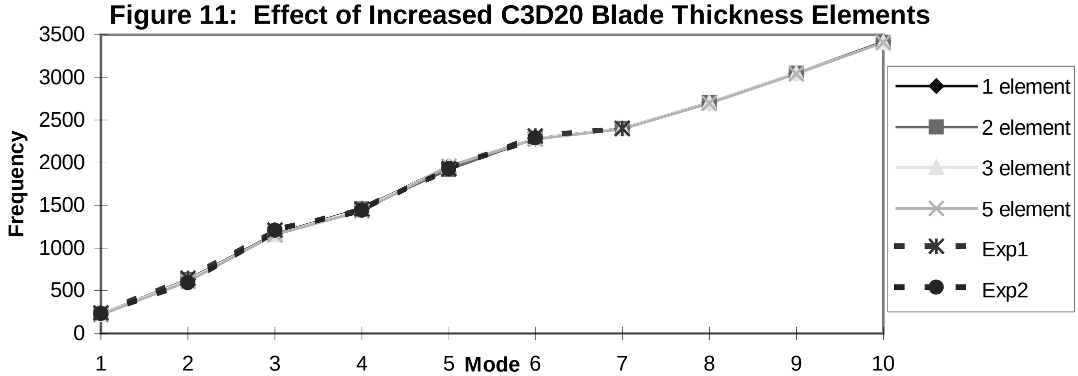
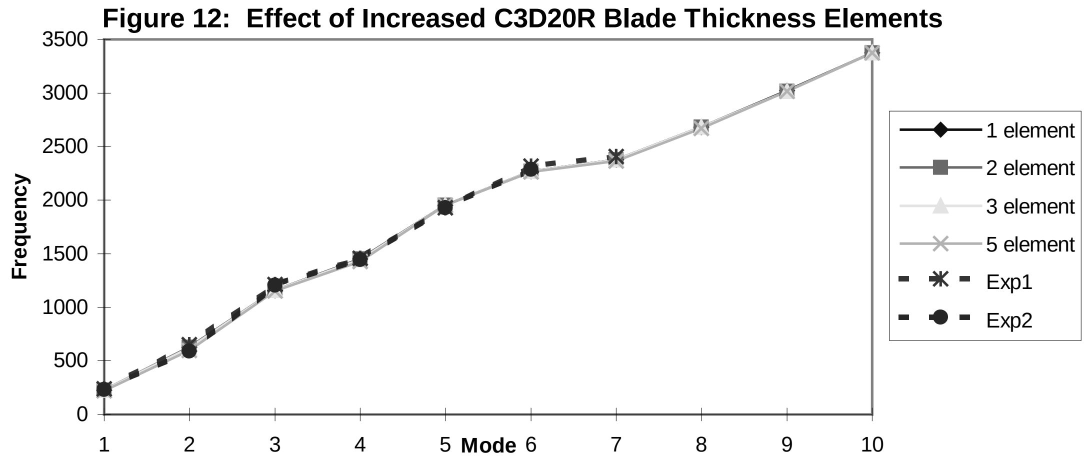


Figure 12 shows the effect of additional thickness elements on the C3D20R. It behaves similarly to the C3D20. Note that there is no element hourglassing when only one element is used through the thickness as was seen with the C3D8R element, because the C3D20R has 8 integration points.



Of the quadralateral hexahedron elements in MSC/ABAQUS both the C3D20 and C3D20R elements provide accurate frequency results with course meshes. Of the two, the C3D20R is slightly more accurate. Actual values are tabulated below.

Table 1: Error Between C3D20R Model Against Experimental Results

Mode	C3D20R Length=0.25	Exp 1	Exp 2	Error 1	Error 2
1	228.71	239.4	234	-11Hz / 4.465%	-5 Hz / 2.260%
2	630.76	648.4	592	-18 Hz / 2.720%	39 Hz / 6.547%
3	1160.4	1212	1208	-52 Hz / 4.257%	-48 Hz / 3.940%
4	1451	1458	1444	-9 Hz / 0.480%	7Hz / 0.484%
5	1949.6	NA	1930	NA	20 Hz / 1.015%
6	2267.1	2317	2288	-40 Hz / 2.153%	-21 Hz / 0.913%
7	2377.4	2407	NA	-30 Hz / 1.229%	NA

NA: Not Available

MSC/NASTRAN Linear Hexahedral

Figure 13 compares MSC/NASTRAN linear CHEXA results from different mesh densities to the results of the MSC/ABAQUS C3D20R. Linear CHEXA results were extremely close to the C3D20R. Only at the highest mesh density, 1.25, did stiffening due to shear locking occur.

Figure 14 shows the addition of additional elements through the thickness of the airfoil had negligible effect on results. A 0.25 edge length was used to create the mesh. As elements were added the response was slightly stiffer due to increased shear locking because of poor aspect ratios. The response is only slightly stiffer because with the additional elements in the thickness direction the response is better approximated over each element.

Figure 13: Effect of Increased Linear CHEXA Mesh Density

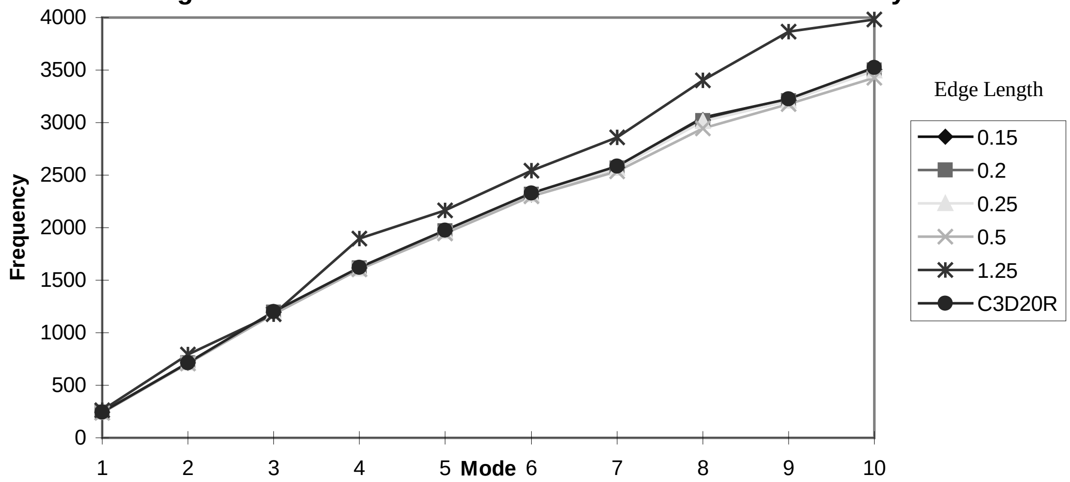
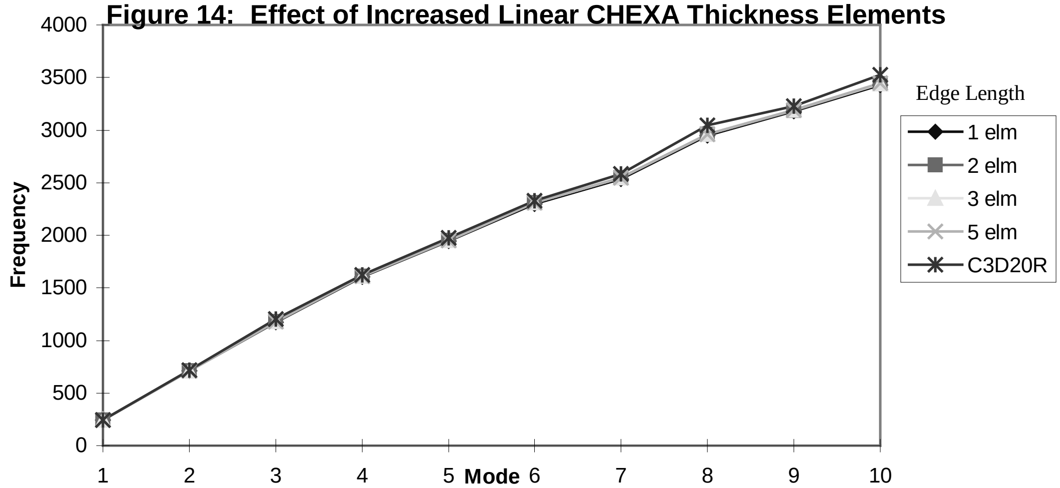


Figure 14: Effect of Increased Linear CHEXA Thickness Elements



Numerical values comparing the linear CHEXA results to the C3D20 is presented later in Table 2.

NASTRAN Quadratic Hexahedral

Figure 15 indicates that as edge length increases and aspect ratios increase, the predicted response is lower than that of the C3D20R. This is contrary expectations that increased aspect ratios would cause higher frequencies. Element hourglassing would cause the drop in frequency but it is not known if this is reason for the frequency drop.

Figure 16 exhibits increasing the number of thickness elements decreased the stiffness of the model. A 0.5 edge length was used for meshing. The drop off is not as severe as seen with the changes of edge length. Again it appears that as the aspect ratio increases, the stiffness drops.

Figure 15: Effects of Increasing Quadratic CHEXA Mesh Density

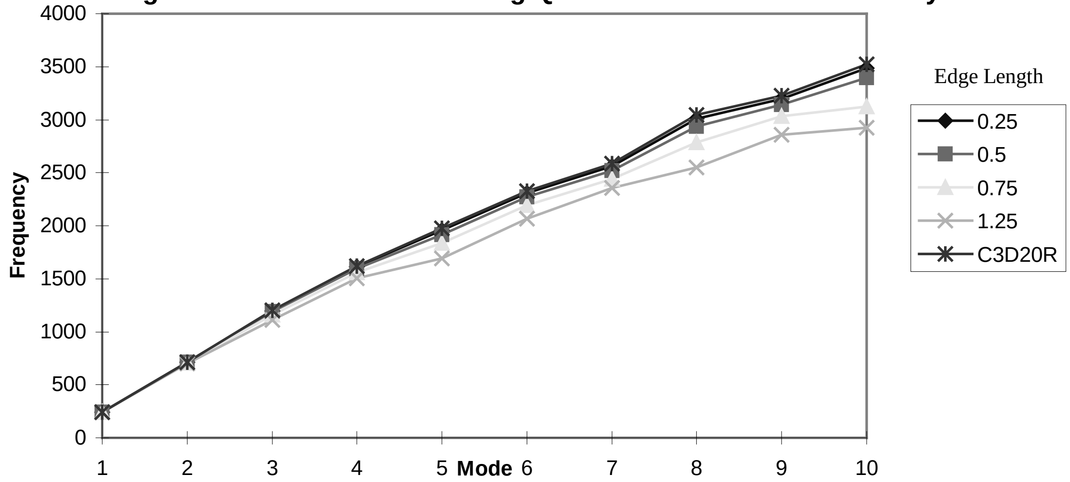
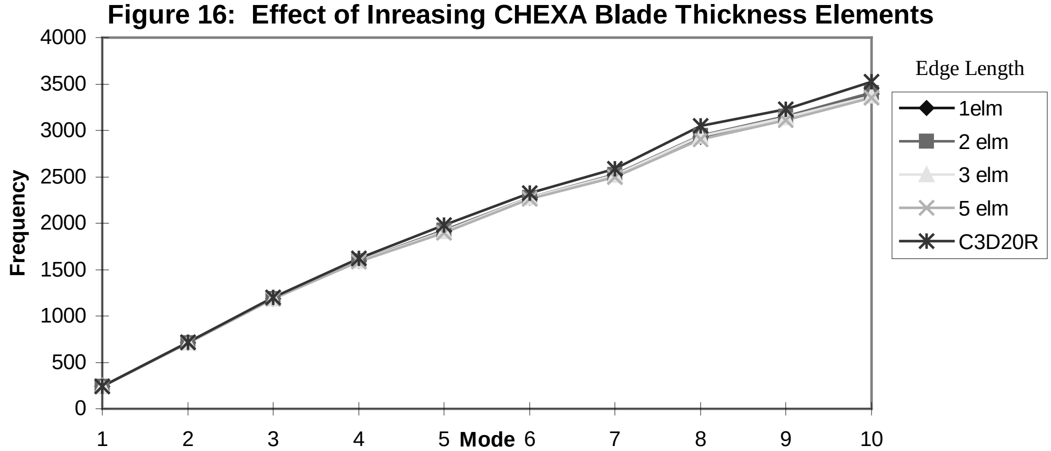


Figure 16: Effect of Inreasing CHEXA Blade Thickness Elements



Numerical values comparing the quadratic CHEXA results to the C3D20R are presented later in Table 2.

MSC/NASTRAN & MSC/ABAQUS TETRAHEDRAL ELEMENTS

Figures 17 & 19 show that the MSC/NASTRAN and MSC/ABAQUS linear tetrahedrals produce excessively stiff results. Even when increasing the mesh to over 40,000 elements the solution was still inaccurate. Further increases in mesh density might end up converging to an accurate solution, but it would be highly inefficient.

Figures 18 & 20 show that the quadratic tetrahedral elements are not as sensitive to mesh density and require far fewer elements to converge to a solution. Quadratic tetrahedrals of 0.25 edge length from both systems predicted results extremely close to that of the C3D20R element.

Figure 17: Effect of Mesh Density on C3D4

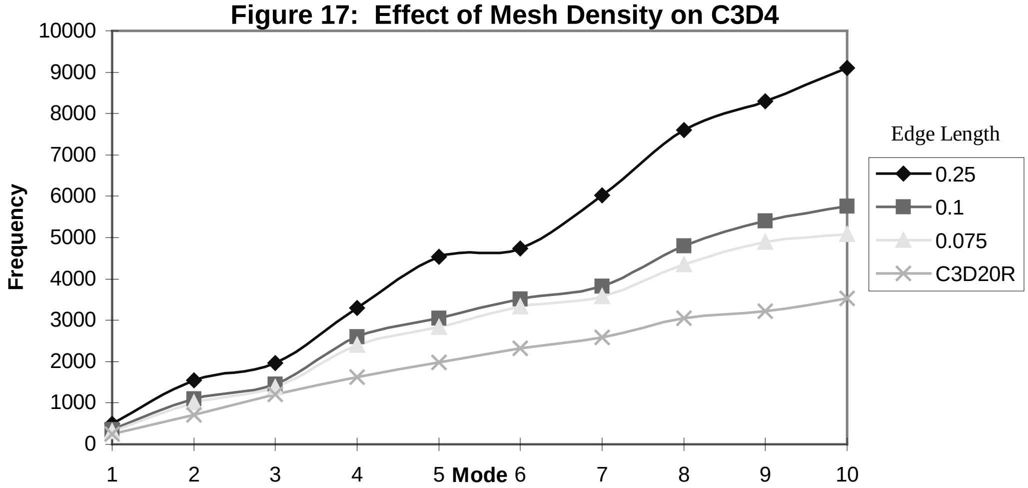


Figure 18: Effect of Mesh Density on C3D10

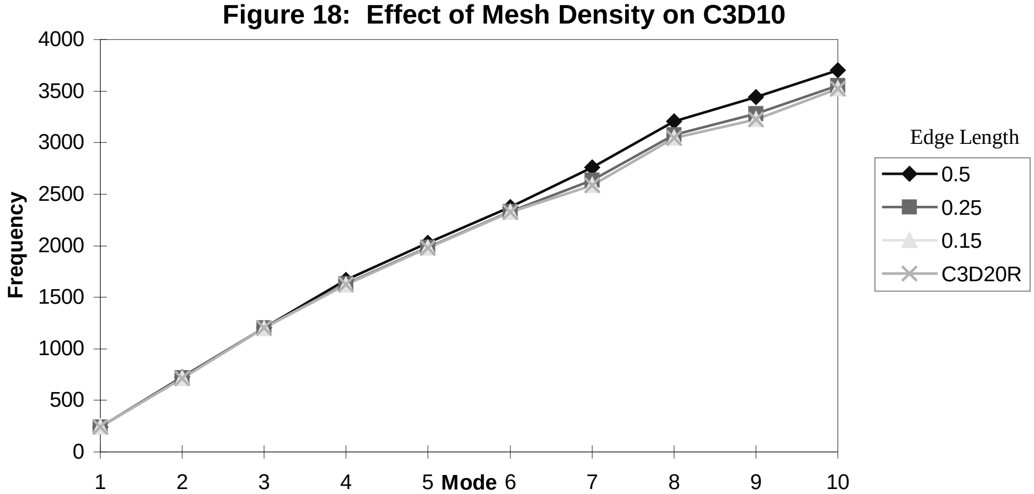


Figure 19: Effect of Increasing Linear CTETRA Mesh Density

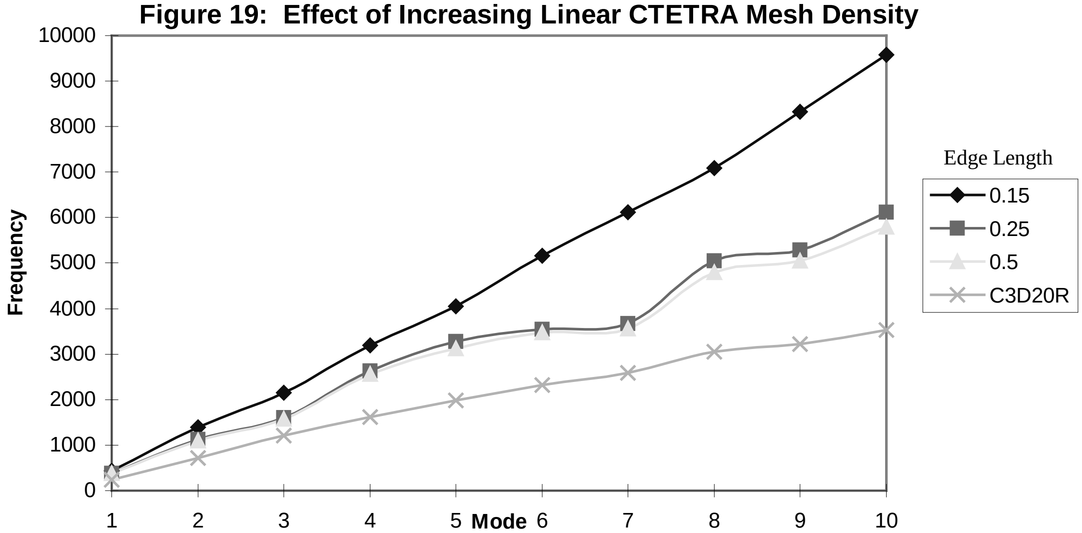
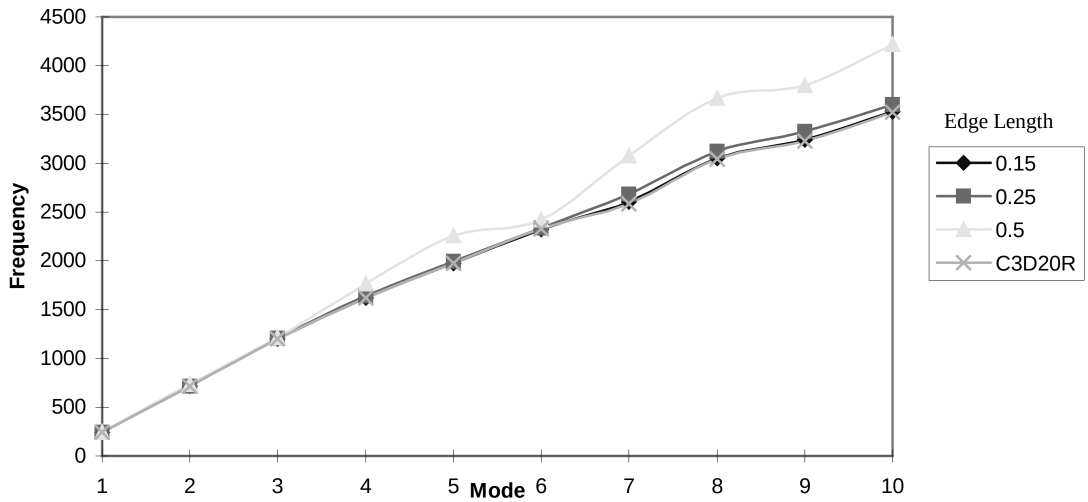


Figure 20: Effect of Increasing Quadratic CTETRA Mesh Density



The advantage of the tetrahedral is that it can model most solid geometry without complicated revisions to the geometry. This savings in time makes the quadratic tetrahedral very economical for many analysis jobs. Table 2 summarizes the frequency results from the MSC/NASTRAN elements and compares them to the MSC/ABAQUS C3D20R. The value in next to the element name signifies the element edge length for the results. All presented results used one thickness element.

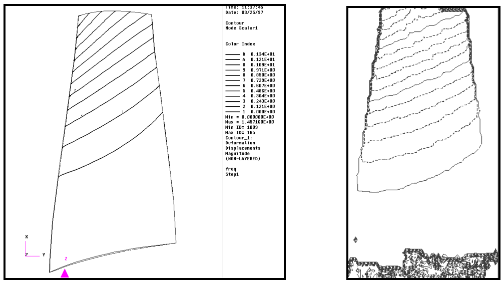
Table 2: Comparison of Airfoil Models

Mode	C3D20R(0.25)	C3D10(0.15)	Linear CHEXA(0.15)	Quadratic CHEXA(0.25)	Quadratic CTETRA-(015)
1	243	243.1	242.2	242.7	242.73
2	716	717.7	713.0	714.7	715.27
3	1203	1200.9	1197.9	1198.2	1202.0
4	1622	1631.6	1614.6	1613.6	1622.1
5	1977	1986	1969.3	1958.4	1977.4
6	2327	2333.6	2317.8	2310.7	2325.1
7	2586	2634	2572.8	2564.8	2601.0
8	3047	3078.2	3024.5	3011.9	3052.4
9	3226	3278.2	3211.1	3199.3	3240.2
10	3525	3556.5	3507.6	3489.4	3531.5

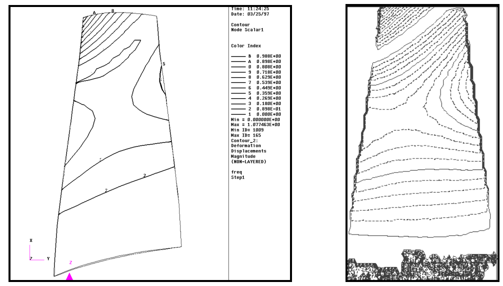
The Table shows that the MSC/ABAQUS quadratic tetrahedral, C3D10, with a mesh density of 0.25 matched the results from the C3D20R extremely well. The MSC/NASTRAN linear CHEXA element with 0.25 edge length also is close to the C3D20R. The quadratic MSC/NASTRAN element with 0.25 edge length is predicted results similar to the C3D20R but at higher modes the results become more dissimilar. For large edge lengths this response is more pronounced. And finally, the MSC/NASTRAN quadratic tetrahedral is, again, very close to that of the C3D20R.

Mode Shapes

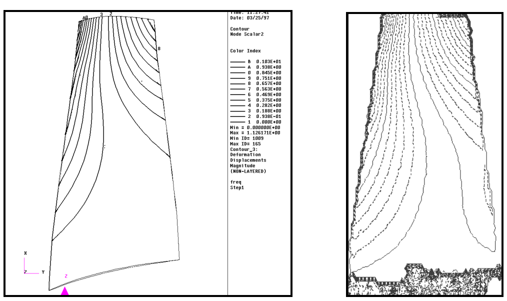
The analytic mode shapes were compared to shapes generated with laser holography. Note that the fringe values between the plots are not of the same magnitude. Therefore, any attempt to directly determine how displacements correlated would be impossible.



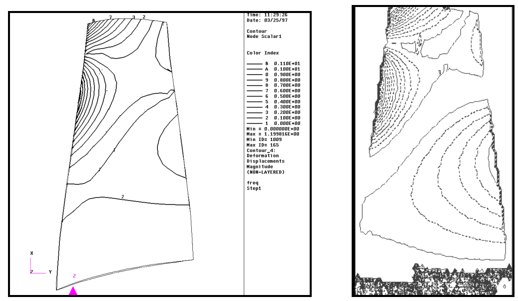
Mode 1



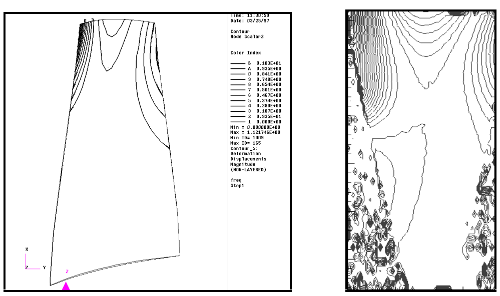
Mode 2



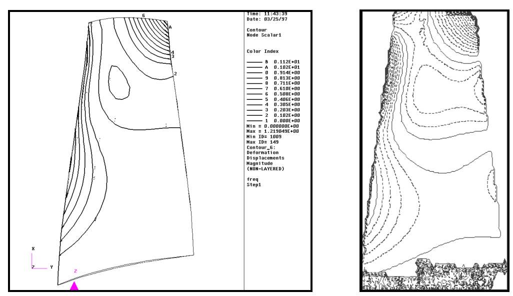
Mode 3



Mode 4



Mode 5



Mode 6

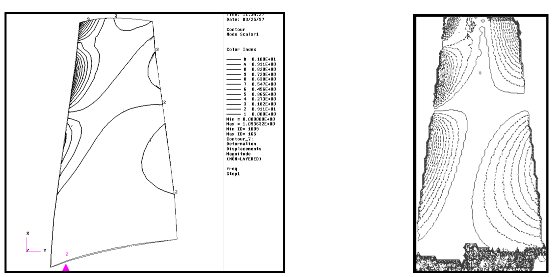


Figure 25: Mode 7

These plots show that the analytic mode shapes correspond well to the holographic data.

6.0 Summary and Recommendations

Frequency analysis of turbine engine blades is a critical part of turbine engine design. Modeling turbine engine blades with solid elements can cause problems if inappropriate elements or mesh densities are used. This report has presented a copious amount of data on frequency results generated by various solid elements with an array of meshes. Based on these results, a background for recommendations on element selection for frequency analysis has been developed. These recommendations will help analysts in the future in the accurate frequency prediction of turbine engine blades. The recommendations follow:

> The C3D20R was shown to be the most economical and accurate element for frequency analysis in MSC/ABAQUS.
>
> The MSC/ABAQUS C3D20 provided the same consistent and accurate results with a slightly longer solution time.
>
> The MSC/ABAQUS C3D8I also provided consistent accurate results with solution times closer to the C3D20R.
>
> The MSC/ABAQUS C3D8R element was inaccurate with one thickness element but as this number increased the results improved. Its accuracy was still inferior to the above elements.
>
> The MSC/ABAQUS C3D8 element response was highly dependent on mesh density. In general, these elements should be avoided for engine blade frequency analysis.
>
> The linear CHEXA element was shown to be the most economical and accurate element in MSC/NASTRAN.
>
> The MSC/NASTRAN quadratic CHEXA element predicted accurate results at 0.25 edge lengths. As the mesh density decreased, the predicted frequencies decreased.
>
> Linear Tetrahedrals from both analysis codes predicted a stiff response, even when over 40,000 elements were used and should also be avoided for engine blade frequency analysis.
>
> The quadratic tetrahedrals from both codes formed as well as the C3D20R elements for the airfoil model considered. Automatic meshing using quadratic tetrahedrals could be the best option, given a complex geometry.
>
> The mode shapes predicted by the analysis codes correlated well with laser holographic test data.

With these recommendations I believe future natural frequency analyses may be conducted in the most economic and accurate manner. The lessons learned apply to any plate like structure that undergoes bending. The element and mesh density conclusions should also apply to static stress analysis.

References

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