Optimization of Turbine Blade Dovetail Geometries using Abaqus and Isight

Abaqus Technology Brief

Summary

The reliability of a gas or steam turbine is strongly dependent on the blade structural design. If efforts to raise the efficiency of a turbine increase the severity of the temperature and pressure operating conditions, then greater structural demands will be imposed on the blade. Improvements in both turbine reliability and efficiency will therefore require better materials, analysis tools, and optimization methods.

To meet the challenges of a competitive marketplace, engineers must design blades in the shortest time and at the lowest cost while meeting multiple design objectives. In this Technology Brief, we show how the Abaqus finite element and Isight design exploration tools can be used for this task. A two-level optimization approach is taken to minimize the contact pressure and stress in the dovetail region of a turbine blade. It will be shown that this technique is more robust than a single-level technique that considers a similar number of design variations.

Background

With respect to achieving high levels of system efficiency and reliability, the blades of a gas or steam turbine play a critical role. To that end, computational simulation is commonly used to predict the failure conditions for a given blade design, and accurate modeling and material properties are essential to produce realistic results. Finite element analysis is a powerful tool for estimating blade stresses, and the addition of design process automation and optimization tools allows optimal designs to be achieved in a reasonable amount of time.

In land-based power generation units, the blades are connected to the turbine disk by a dovetail joint or fastener, as shown in Figure 1. In this Technology Brief, an optimization analysis is performed to obtain the geometry of a turbine blade dovetail under the influence of centrifugal loading. Abaqus/Standard is included in an Isight simulation workflow ('simflow') to minimize contact pressure and Mises stress.

Instead of using a single optimization process that considers all design variables, a two-level approach is taken in which a Design Of Experiments (DOE) analysis precedes the direct optimization. In this way the most critical variables are identified prior to the most intensive computations; several different optimization algorithms can thus be explored more efficiently. The two-level results using several different optimization algorithms will be compared, and those results as a whole will be compared to the outcome of a single level optimization.

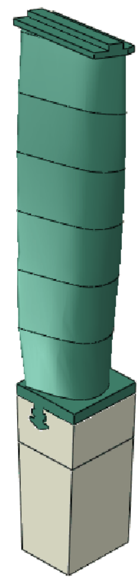

Figure 1: Geometry of blade and disk sector model

Key Abaqus Features and Benefits

- Integration of Abaqus finite element analysis with Isight design space exploration to determine optimal solutions
- Cyclic symmetry capability in Abaqus/Standard allows for the efficient modeling of structures characterized by a repetitive sector
- Robust contact modeling in Abaqus/Standard

Finite Element Model

The geometry of the airfoil is created using Eblade, an airfoil aerodynamic design optimization software package from SIMULIA. The coordinate data points describing the 3D airfoil shape are imported into Abaqus/CAE. The geometries of the remaining parts (shroud, platform, and disk) are constructed directly in Abaqus/CAE. It is assumed that the geometry of the cross section of the contact region in the dovetail is the same in the blade platform and disk.

The mesh of the blade and disk sector model is also created in Abaqus/CAE and is shown in Figure 2. In this investigation, only centrifugal loading is considered. Cyclic symmetry conditions are enforced, and the bottom of the disk is held fixed. A nonlinear static procedure is used in the stress analyses. The construction of the model in

Figure 2: Complete blade and disk sector mesh

Abaqus/CAE is automated using a Python script in order to parameterize the geometric dimensions and automatically apply the contact and boundary conditions as the geometry is changed during the optimization process.

Optimization Approach

A two-level optimization process is performed. In the first level, DOE analyses are executed to sample the design space and create approximate representations of the blade's response to loads. The approximation is constructed by interpolating from a set of finite element results obtained by sampling the design variables in specified ranges.

Two DOE sampling methods are used: the Response Surface Model (RSM) and Elliptical Basis Function (EBF) approaches. The two approximate models are then optimized on contact pressure and Mises stress in the blade dovetail. The most critical design variables are identified from the optimization results.

The second level of the process then consists of a final optimization on the design variables identified as critical from the EBF DOE results, with no approximation of the model response. The same optimization methods used in the first level analysis are used in the second level, targeting about 100 design evaluations.

<u>Design of Experiments Analyses</u>

The RSM and EBF approximate representations are both based on finite element results data corresponding to design variables chosen using the Optimal Latin Hypercube sampling technique. Optimal Latin Hypercube is a modified version of the Latin Hypercube technique, where the combination of factor levels for each factor is optimized, rather than randomly combined. EBF, which uses the Mahalanobis distance as its basis function, provides a more accurate approximation than the Radial Basis Function approach, which uses the Euclidian distance for its basis function. 56 sampling points are used for the RSM model and 146 sampling points are used for the EBF model.

The cross section shape of the dovetail is initially assumed as shown in Figure 3 with all dimensions shown in

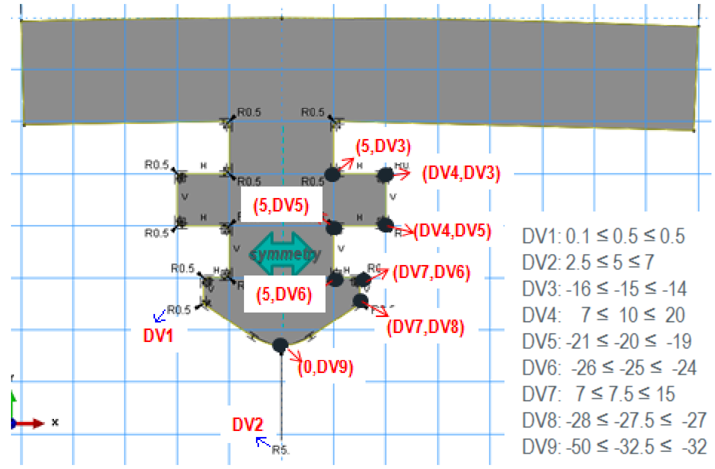

Figure 3: Design variable initial values and ranges for the Design of Experiments analyses

mm. This simple cross section is chosen mainly to demonstrate a typical parameterization method and to investigate the optimization processes. Assuming symmetry, the dimensions of only one side are considered. All nine design variables specifying the dimensions of the dovetail, DV1 through DV9, are selected in the first optimization level to minimize the contact pressure and Mises stress around the dovetail.

DV1 is the radius used to round off the inside corners (i.e., fillet) and outside corners (i.e., round) on each side edge of the dovetail cross section. DV2 is the radius on the bottom point of the dovetail. Design variables DV3 through DV9, noted as black circles in Figure 3, represent x or y coordinate values of the corner points on the dovetail. The initial values of the design variables and their allowable ranges (i.e., constraints) are shown. The constraints are chosen to prevent lines describing the shape from crossing each other. Figure 4 shows some of the various geometries of the dovetail cross sections generated by the DOE runs used to build the approximate models.

Optimization Results

Once the RSM and EBF representations are created, the first optimization analysis is performed; the results for the various methods used are listed in Table 1. Overall,

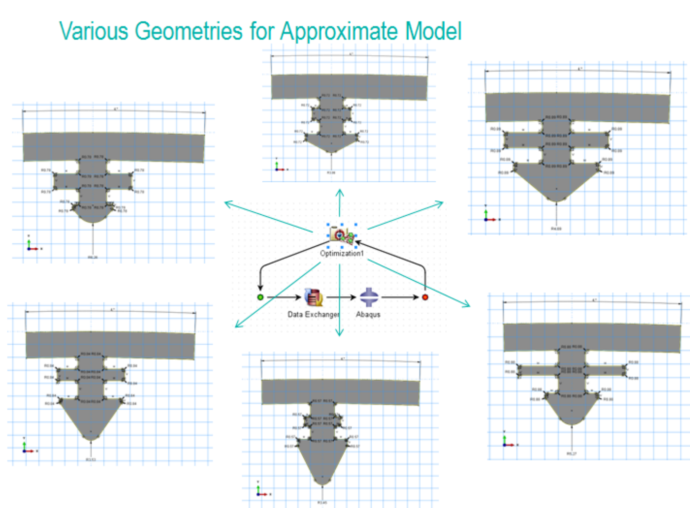

Figure 4: Dovetail geometries generated by the Design of Experiments analyses

Approx. Model	Optimization Method	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	CPRESS	Mises
RSM	Downhill Simplex	0.4	4.7	-15	7.01	-20	-25	7.3	-27	-33	170.4	174
	Evol	0.3	3.7	-16	7	-21	-24	7	-27	-34	222	174
	Hooke-Jeeves	0.3	2.5	-16	7	-20	-26	7	-27	-35	122	121
	LSGRG	0.4	2.5	-16	7	-20	-26	7	-27	-32	180.9	165
	MOST	0.2	2.5	-16	7	-21	-24	15	-27	-32	130.3	130
	NLPQL	0.4	2.5	-16	7	-20	-26	7	-27	-32	180.9	165
	NSGA-II	0.2	6.4	-14	19.1	-19	-26	7.7	-28	-48	150.1	135
EBF	Downhill Simplex	0.4	5.6	-15	9.5	-20	-26	8.6	-27	-34	127.7	176
	Evol	0.3	7	-15	11.8	-20	-26	8	-28	-32	77.42	97.4
	Hooke-Jeeves	0.2	7	-15	11	-20	-26	8.8	-27	-32	87.74	132
	LSGRG	0.3	6.9	-15	12	-20	-26	9.2	-27	-32	76.56	124
	MOST	0.3	6.9	-15	12	-20	-26	9.2	-27	-32	71.58	107
	NLPQL	0.3	6.8	-15	12	-20	-26	9.2	-27	-32	76.33	103
	NSGA-II	0.2	6	-15	13.2	-20	-26	8.5	-27	-33	92.56	118

Table 1: Optimized contact pressure and Mises stress for the RSM and EBF approximations

the EBF representation produced lower values of contact pressure (CPRESS) and Mises stress. Of the EBF results, the CPRESS and Mises results for the Evolution (Evol) optimization method are lowest.

Note that the values of design variables DV5, DV6, DV8, and DV9 change little with the various optimization methods. We can therefore set the values of these variables as constant in the second level optimization. The initial values for all the design variables in the second level optimization are set to those obtained using the Evolution method with the EBF representation.

Isight provides tools to assess the sensitivity of the approximate model optimization results to the individual design variables. Figure 5 shows the global effects on contact pressure and Mises stress for both approximate representations. These plots show that the results prove to be insensitive to design variables DV4, DV7, and DV9 for both approximate models, meaning that changes in these variables will have little impact on the final optimized result.

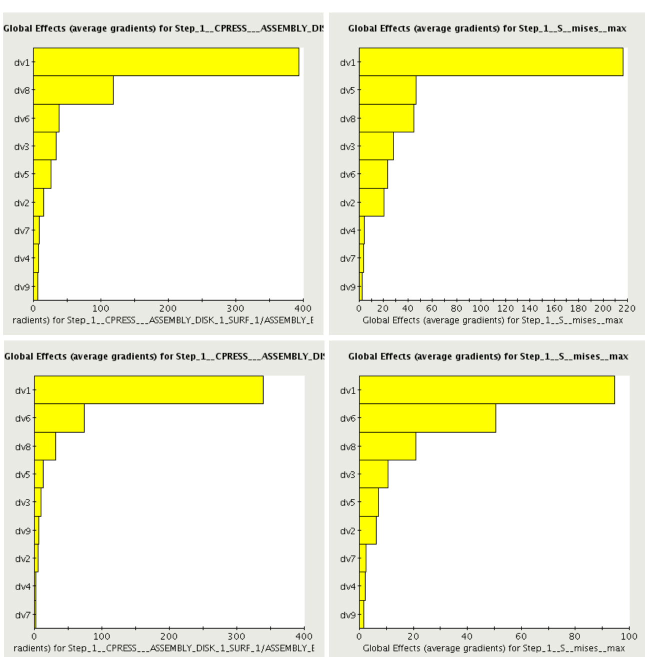

Figure 5: Global effects of each design variable on contact pressure (left) and Mises stress (right) for the RSM (top) and EBF (bottom) approximate representations

Optimization Method	Total Iterations	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	CPRESS	Mises
Downhill Simplex	111	0.31	6.70	-14.72	11.79	-20.36	-26.00	8.06	-27.58	-32.00	83.79	111.10
Evol	101	0.32	7.00	-14.84	11.56	-20.36	-26.00	8.78	-27.58	-32.00	58.46	105.70
Hooke-Jeeves	101	0.30	7.00	-14.72	11.82	-20.36	-26.00	7.98	-27.58	-32.00	80.97	102.20
LSGRG	72	0.30	7.00	-14.76	11.82	-20.36	-26.00	7.98	-27.58	-32.00	77.37	97.42
MOST	118	0.33	6.98	-14.76	11.86	-20.36	-26.00	7.98	-27.58	-32.00	76.93	137.00
NLPQL	51	0.30	7.00	-14.76	11.82	-20.36	-26.00	7.98	-27.58	-32.00	77.37	97.42
NSGA-II	81	0.30	6.22	-15.88	10.61	-20.36	-26.00	9.98	-27.58	-32.00	51.23	110.00

Table 2: Second level optimization results

The second level optimization results are presented in Table 2 (cells in yellow show variables that are set to constant values). The analysis options are modified in order to obtain about 100 total iterations for the design evaluation.

By comparing the results in Tables 1 and 2, we find that gradient-based methods such as LSGRG and NLPQL cannot provide a better solution than that obtained using the EBF approximate model. Particularly, in the case of LSGRG and NLPQL, the result is the same as the initial starting point. However, the direct and exploratory methods can provide improved results as shown in Table 2. The Evolution method shows a smaller contact pressure compared to the initial starting point, but the Mises stress is slightly higher. The contact pressure and Mises stress results for the original and optimized designs are shown in Figure 6.

Table 3 shows the results of the some selected methods when a single-level optimization approach is used. These results are generated by allowing all design variables to change in a single optimization; no use is made of an initial optimization of an approximate model. Each optimization is defined to obtain approximately 250 total design evaluations, which is about the same as the combined number of evaluations for both the first level and second level corresponding analyses. Only the NSGA-II method provides similar results to that obtained previously. However, it provides a higher Von Mises stress compared to the two-level approach.

Optimization Method	Total Iterations	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	CPRESS	Mises
NLPQL	31	0.10	7.00	-14.01	20.00	-19.00	-24.00	15.0	-28.00	-32.00	85.36	147.80
Evol	251	0.50	5.72	-15.20	9.48	-20.12	-24.96	8.46	-27.52	-32.00	131.0	170.60
NSGA-II	241	0.33	4.44	-16.00	9.65	-19.50	-25.65	9.45	-27.85	-34.22	55.44	125.60

Table 3: Single-level optimization results, obtained without the use of initial approximate representations

Conclusions

We have shown that a two-level optimization approach can provide a more robust design technique than simply using a single direct optimization on all design variables. By initially exploring the design space with an approximate model, the dominant design variables are first identified. The second optimization can then be focused on a smaller number of parameters, thus allowing for faster analysis or the use of a larger number of optimization techniques for the same number of total iterations.

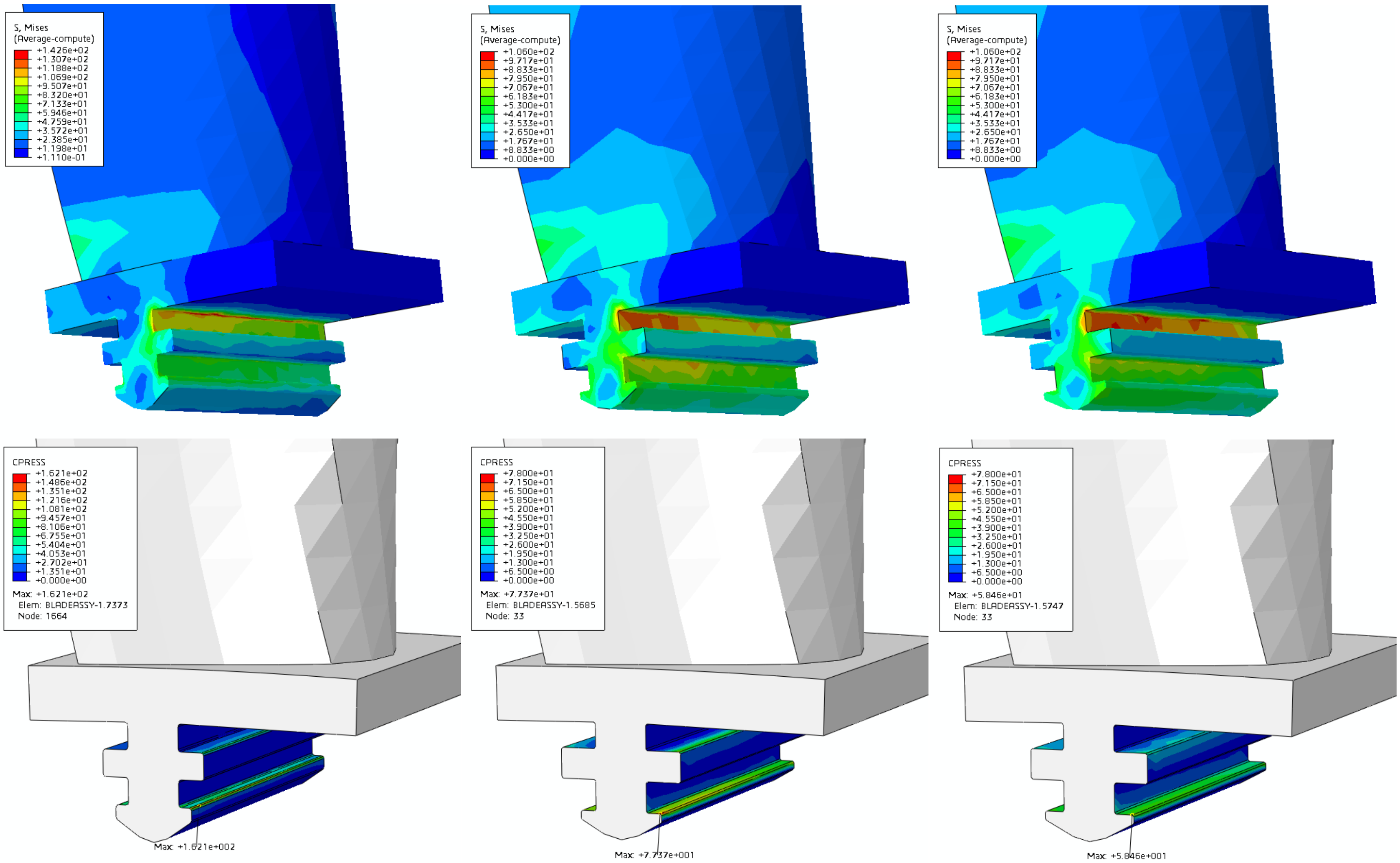

Figure 6: Mises stress and contact pressure results for the (from left to right) original, approximate, and final optimized designs

References

1. Youngwon Hahn and John I. Cofer, IV, 2012. "Design Study of Dovetail Geometries of Turbine Blades Using Abaqus and Isight," ASME paper GT2012-68566, ASME Turbo Expo, June 11-15, Copenhagen, Denmark.

SIMULIA References

For additional information on the Abaqus capabilities referred to in this document please see 'Analysis of models that exhibit cyclic symmetry,' Section 10.4.3, Abaqus 6.13 Analysis User's Guide

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