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Shaker Fatigue Testing Optimized with ALGOR FEA

When Hamler Test and Analysis (HTA), a consulting firm located in Cookeville, TN, needed to perform shaker fatigue testing of a compressor blade from a gas turbine engine, they knew where to turn. They used linear, dynamic, finite-element analysis (FEA) software from ALGOR, Inc. of Pittsburgh, PA, to simulate the test and determine the optimal setup. "ALGOR FEA allowed me to do 'virtual' testing," said Jesse Hamler, president and chief technical officer of HTA. "I was able to simulate different ideas and hardware configurations without having to spend time or money to physically make the hardware for each setup. I saved weeks of trial-and-error testing, if not months."

Applying FEA to Experimental Structural Testing. HTA provides testing, design and FEA consulting services, specializing in vibration measurement and experimental vibration analysis tools such as impact testing, modal analysis, operating deflection shape analysis and rotating machinery analysis – particularly for engine vibration. In conjunction with experimental capabilities, HTA offers a broad range of product design and finite-element analysis services. Hamler believes that experimental validation and correlation of computer models are vital to reducing the cost and cycle time of product development and product support. The company motto is, "One good test is worth more than a thousand expert opinions."

Hamler's first exposure to FEA was early in his professional career. "I didn't use FEA often in my first two engineering positions, but I realized what a valuable tool it is. I decided that if I was going to pursue consulting, I wanted to be knowledgeable in both experimental and analytical methods. So one of my primary reasons for attending graduate school was to learn more about FEA. I learned a lot about the theory behind the finite-element method, and I even had to program my own FEA codes for simple problems. The first commercial FEA code I learned was ANSYS Classic."

While working as a consultant, Hamler acquired ALGOR FEA software because, it provided the greatest capability for the cost. "Direct CAD integration with Alibre was nice," he said, "since it's a very affordable and capable CAD package." ALGOR's easy-to-use single user interface, FEMPRO®, supports all popular CAD solid modelers. "Also, ALGOR had more flexible licensing. In other words, some FEA programs require that you buy a full-featured license to get certain dynamic analysis capabilities that are important to me, such as frequency response. With ALGOR, I was able to purchase only the analysis capabilities I really needed – linear static stress and linear dynamics."

Hamler described the benefits of using ALGOR FEA: "It opens doors to business opportunities other than testing, and it's a great tool that supplements experimental structural analysis."

Linear Dynamic Analysis of a Shaker Fatigue Test. For one application, HTA was contracted to perform physical fatigue testing of a compressor blade from a stationary gas turbine engine used for power generation. Electro-dynamic shaker testing was required to verify the client's analytical vibratory high-cycle fatigue-life prediction methodology. The first phase of this shaker testing involved vibrating several blades to failure at the first bending mode, and the second phase involved testing several blades to failure at the first torsion mode.

Hamler explained that in the first phase of testing, the primary challenge involved attaining an acceptable blade-tip response displacement at the first bending mode frequency of 2900 Hz. The target response was dictated by blade stress levels required by the customer during testing. Because displacement is directly proportional to acceleration but inversely proportional to the square of frequency, the target displacement would be difficult to achieve at 2900 Hz even with the gain in response at resonance. This challenge was overcome by mass loading the end of the blade with a special investment cast clamp, which lowered the first bending mode frequency to approximately 850 Hz. This simple change made it possible to achieve the desired bending mode tip displacement and, consequently, the required blade stress levels. The optimization of the correct amount of mass was determined by experimental trial and error.

After completing the first phase of testing, Hamler recalled, "I knew that finding a solution to failing a blade at the first torsion mode for the phase-two testing would be far more challenging. So a trial-and-error solution was not feasible due to time constraints, and ALGOR FEA was used to direct the testing in the right direction."

Hamler noted the difficulty in exciting an angular mode shape with linear movement. Initial sine sweeps of the mass-loaded test setup from phase one indicated that the first torsion mode had dropped from 8400 Hz to 1450 Hz with the addition of the tip mass, and an adequate response from the new 'mass-loaded' torsion mode did not appear to be attainable on the shaker. The gain in response obtained at a torsion mode is minimal when the excitation is linear motion. A linear or rotary shaker system was not commercially available that could provide enough excitation to achieve the desired torsion mode response with the test setup from phase one. Using ALGOR FEA, however, it was evident that a sufficient torsion mode response could be attained with reasonable levels of linear excitation by substantially increasing the mass moment of inertia about the nodal axis or nodal line of the first torsion mode (axis of rotation with zero displacement).

An initial ALGOR analysis predicted that by making such modifications, the first torsion mode would occur at a lower frequency than the first bending mode, and the desired blade stress levels could be obtained with acceleration levels that were attainable from the shaker. However, ALGOR results also predicted that if the total mass increase were

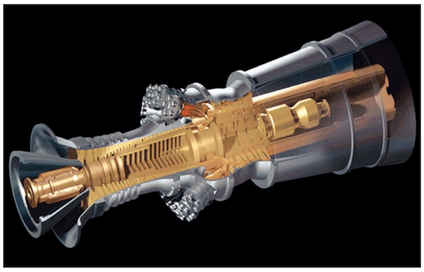

Figure 1. Hamler Test and Analysis (HTA) used ALGOR FEA software to analyze the compressor blades of a gas turbine engine like the one shown here. (Image courtesy of The National Energy Technology Laboratory.)

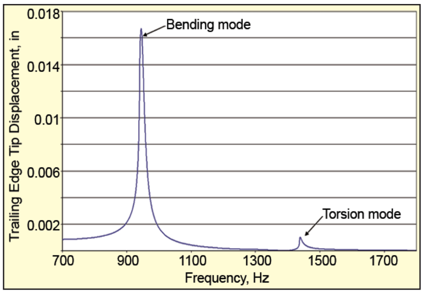

Figure 2. Blade tip displacement versus frequency for a shaker sine sweep. Note the drastic difference in resonance response between bending and torsion modes.

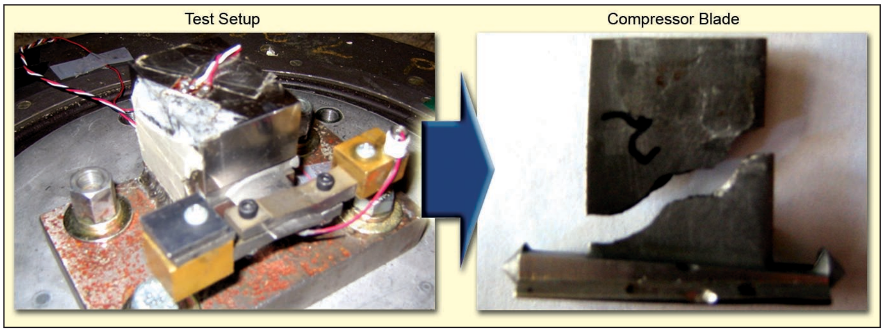

Figure 3. At left, a photograph shows the weighted compressor blade test setup for the second phase of shaker testing, where the blade was vibrated at the first torsion mode until it broke (right).

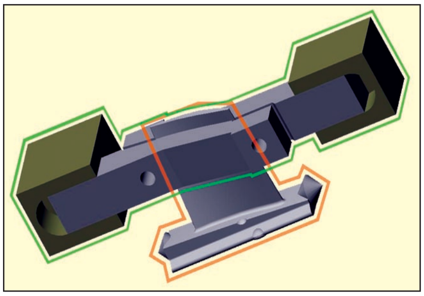

Figure 4. Alibre Design was used to create this CAD model of the weighted compressor blade assembly. The compressor blade is highlighted in orange and the weights and clamps are highlighted in green.

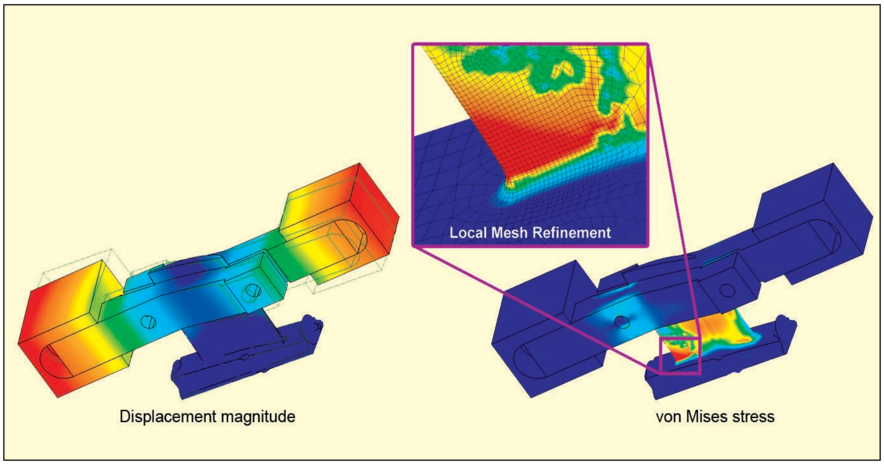

Figure 5. Natural frequency (modal) and frequency response analyses of a weighted turbine engine compressor blade were performed using ALGOR FEA software to simulate a shaker fatigue test. Color-coded contours (left) show displacement magnitude in compressor blade. A wireframe of the undisplaced shape illustrates the torsion mode movement. Display of stress contours (right) indicates area where a crack was most likely to initiate. Close-up (inset) shows that finite-element mesh was made finer in the area of highest stress.

too large, the torsion and bending modes would become coupled. So increasing the mass moment of inertia about the torsion mode nodal axis would require that concentrated masses be applied at a significant radial distance from the nodal axis, while also minimizing the mass increase near the nodal axis. Designing hardware that could meet these requirements and physically attach to the blade would prove to be challenging. Furthermore, such hardware would have to be feasible to manufacture.

Using Alibre Design, Hamler created a CAD model of a clamp that could attach to the compressor blade and support a weight on each side of the torsion mode nodal axis. The blade-weights-clamps assembly measured 3.5 in. wide × 1.14 in. deep × 0.86 in. high. Hamler opened the CAD model in ALGOR to set up for linear dynamic analysis. "ALGOR's direct support for Alibre made my job very easy," he said.

In the FEA model, the surface at the base of the compressor blade was fully constrained. Loads were applied as 17 g acceleration in the Z direction, with excitation at the first torsion mode and first bending mode natural frequencies of 420 Hz and 622 Hz, respectively. Damping was determined experimentally and included in the FEA model. ALGOR modal and frequency response analyses were performed to predict the proper size and location of each weight. This way, shaker experiments and the fabrication of weight assemblies were minimized.

The initial test design incorporated a 1.25 oz trailing-edge weight and a 0.8 oz leading-edge weight. FEA results indicated that this design would produce an acceptable response on the shaker, but each weight was initially made to have a weight of 1 oz, with the assumption that the resulting experimental response would still be in the vicinity of the FEA prediction. If needed, the shaker excitation level could be adjusted to compensate for any difference. But the first run with the 1 oz weights indicated that the response was significantly lower than the FEA prediction of the 1.25 oz and 0.8 oz weight setup even at the maximum available excitation level from the shaker. The next logical step was to tune the test setup to replicate the FEA model. Two pieces of steel flat stock were bolted to the top of the trailing edge weight, giving it a total weight of 1.25 oz. Then the leading edge weight was milled down to 0.8 oz. This small weight adjustment provided a night-and-day difference in response on the shaker, as predicted by FEA.

Experimental results closely matched FEA predictions. "Testing was a success, and the blades failed as predicted," said Hamler. "I was surprised that the FEA model was able to predict the real-world response of a structure so accurately.

"This was a valuable exercise in how FEA can drastically reduce experimentation and troubleshooting involved with non-standard testing objectives," concluded Hamler. "I would say that using FEA cut the testing time in half at the very least. Without FEA, virtual testing is not an option, and an experimental solution becomes an expensive and time-consuming iterative process."

Future Plans for ALGOR FEA. Hamler plans to continue using ALGOR software for upcoming HTA projects. "I plan on using ALGOR FEA to complete modal and harmonic analyses in support of a proposal I am drafting for a potential project. Furthermore, at some point in the near future, I plan to expand my software capability to include nonlinear material models."

Jesse Hamler earned a B.S. degree in mechanical engineering at Georgia Institute of Technology and is currently pursuing an M.S. in mechanical engineering at Tennessee Technological University. Previously, he worked for Cummins Inc. in Columbus, IN, as a senior mechanical development engineer and for Cummins Filtration in Cookeville, TN, as a senior test engineer. Currently, he is an analytical engineer – stress analyst for Vextec Corp. near Nashville, TN, as well as a consultant. For more information about Hamler Test and Analysis, please visit www.hamlertestandanalysis.com.

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