ENHANCED LIFE, RELIABILITY AND PERFORMANCE

Reprinted from February 2020 HYDROCARBON ENGINEERING

Rambabu Chundru, Elliott Group, USA, discusses how finite element analysis applied to compressor impeller design can enhance compressor life, reliability, and performance in oil and gas and petrochemical applications.

Centrifugal compressors play a critical role in the oil and gas and petrochemical industries. They are process critical in oil and gas recovery, gas/oil separation, gas gathering and boosting, gas transportation, gas treatment, and gas processing. Rotating speeds are often a limiting factor in improving aerodynamic performance. Stress levels in centrifugal compressor impellers often prevent operation at higher speeds, which would provide increased performance. When designing compressor impellers, three criteria are considered: maximum stress, maximum deformation, and avoidance of excitable vibration modes. Addressing these criteria through finite elemental analysis (FEA) during the design process can help to enhance compressor life, reliability, and performance.

Impeller stress

Compressor impeller allowable spin speed is usually calculated using linear elastic FEA. The allowable spin speed limits the maximum stress in the hub and cover such that it does not exceed the minimum specified yield strength of the impeller material. This limits the amount of impeller deformation after the spin test to a relatively small and acceptable value.

While gross areas of the impeller do not experience yielding, local areas of the impeller at discontinuities, such as the impeller blades, can experience stresses that exceed the yield strength at spin speed. This introduces localised yielding that resolves at lower speeds as residual compressive stresses, which are beneficial in increasing the impeller fatigue strength. Permanent deformations at the critical impeller locations such as the bore, eye seal location, and tip are further evaluated to ensure that they are within acceptable limits. Figure 1 shows an FEA stress plot for an Elliott impeller. Here, the maximum stress is at the impeller cover and is set equal to the minimum yield strength.

An impeller's spin speed can be increased beyond the minimum yield strength up to a tolerable yielding (defined as yielding only to an extent that does not render an impeller unsuitable for further functioning). The finite element method plays a vital role in defining the plastic or permanent deformation limits. An elastic-plastic analysis (FEA) is used to set the plastic spin speed limits. During plastic deformation, kinematic hardening causes a shift in the yield surface in stress space. In uniaxial tension, plastic deformation causes the tensile yield strength to increase. In kinematic hardening, the yield surface remains constant in size and translates in the direction of the yielding. Most metals exhibit kinematic hardening behaviour for small strain cyclic loading. An initially isotropic material is no longer isotropic after it yields and experiences kinematic hardening. Kinematic hardening is used generally for small strain, cyclic loading applications. A multi-linear kinematic hardening material model is used in FEA to define the plastic limits. Figure 2 shows the stress-strain behaviour in kinematic hardening.

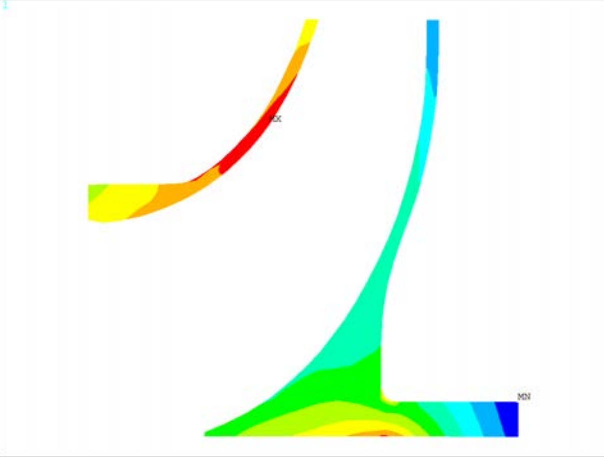

Figure 1. Finite element analysis (FEA) stress plot.

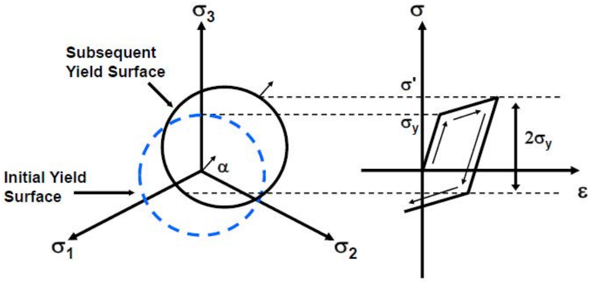

Figure 2. Kinematic hardening.

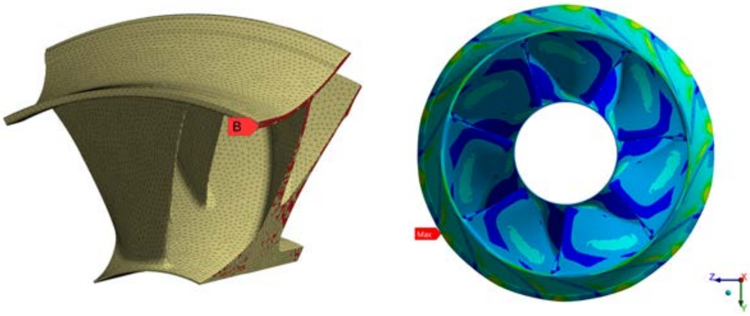

Figure 3. Impeller cyclic FEA model (left) and plastic strain (right).

Impeller deformation

Elliott performed a cyclic symmetry elastic-plastic analysis on an impeller with speeds beyond the material elastic limits. Impeller bore, eye seal, and tip locations are considered critical as they influence the functionality. These locations are permanently deformed and new elastic limits are established, inducing compressive stress at critical locations. During compressor operation, the stresses will be within the new elastic range of operation. Spin tests were conducted on the impellers to compare the results with FEA deformation results at critical locations. The test data shows FEA predicted growths are conservative (worst case). Based on the FEA, and as confirmed by the test, the spin speed could be increased by 9% using the elastic-plastic FEA method for this high-flow coefficient impeller.

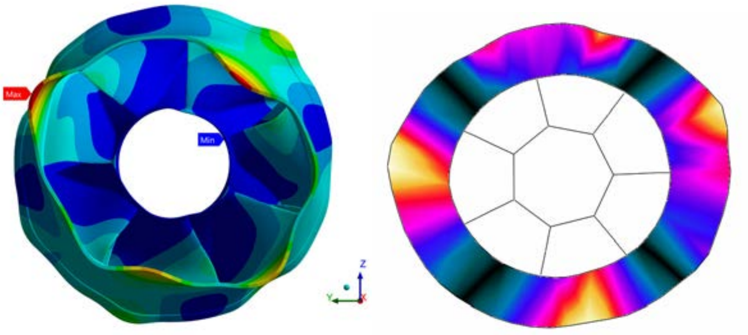

Figure 4. FEA frequency of 572 Hz (left) and test frequency of 566 Hz (right).

Table 1. Impeller frequencies: FEA vs Test (Hz)

Nodal dia.	FEA	Test	% Difference	Leading edge	FEA	Test	% Difference
ND0	791	789	0	LE0	1097	1041	-5
ND1	523	527	1	LE1	1112	1138	2
ND2	572	566	-1	LE2	1151	1202	4
ND3	646	670	4	LE3	985	1007	2

Impeller excitable vibration modes

Rotating blade and disk failures cause a fairly small percentage of machine shutdowns, but these types of failures can require extensive repairs and downtime. Plant downtime due to equipment failures is expensive. Failures can be minimised by carefully designing the equipment and avoiding resonance conditions. An impeller typically has potential for excitation of either blade or disk modes. Nodal diameter mode shapes, commonly referred to as nodal diameters, contain lines of zero out-of-plane displacements that cross the entire disk. The number of nodal diameter modes is equal to the number of blades divided by two rounded to the nearest integer. An impeller with 15 blades has seven nodal diameters. The centrifugal compressor stage is designed so that the number of impeller blades and the upstream excitation source are not equal to avoid circular mode excitation. The one-diameter mode is usually coupled to the shaft and is difficult to excite. The two-diameter mode should be avoided as it can be excited very easily. It is not necessary to avoid the higher order modes beyond the number of blades divided by two, as they are not easily excitable.

FEA plays an important role in determining the natural frequencies of the impellers. The impeller blade leading edge and blade diameter modes are excited by upstream return channel vanes. The disk hub tip modes are excited by the downstream diffuser vanes. For resonance to occur, not only does the frequency have to match, but the mode shape must also match with the upstream excitation.

Conclusion

The FEA cyclic symmetry elastic-plastic stress analysis method determines the compressor impeller's acceptable stress, plastic strains, and deflections at critical locations. Modal analysis helps identify natural frequencies and mode shapes. If there is a significant resonant condition identified during the stage design phase based on FEA results, the stage will be redesigned to avoid potential failures. Modal testing of an impeller is another method to determine the natural frequencies but it is expensive to make design changes after the parts have already been manufactured. Table 1 and Figure 4, respectively, show the FEA modal test data and mode shapes for an Elliott refinery impeller. FEA frequencies and mode shapes closely match the modal test results, confirming why FEA is recommended during the initial compressor impeller design process.

MKT.5232.0220