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Fluid - Structure Interaction Analyze For The Centrifugal Compressor 3D Impellers

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Abstract. The article deals with the issues of the 3D impellers strength analysis for the different centrifugal compressors. Two air compressors are considered, the first for General industrial use, the second for turbocharging the internal combustion engine. The third compressor is designed for the turboexpander unit that operating at high pressure medium. The materials of the impellers were steel, titanium and aluminum alloys. The expediency of using the Fluid-Structure Interaction approach for the strength analysis is considered for these compressors. With the FSI approach, a coupled CFD-FEA solution is performed. Gas-dynamic forces from the medium pressure are taken into account in the impeller strength or vibration analysis. The Ansys package is selected as the program for analysis. CFD models are built and configured in the Ansys CFX. The FEA solution carried out in the Ansys Static structural. The results of strength analysis are compared with and without pressure forces for all impellers. As a result, there were no significant differences in the two solutions for the air compressors. However, for high-pressure compressors, the results of the coupled solution showed the need to take into account the CFD solution. Based on the obtained data, a graph of the reliability coefficient dependence on the increase in the suction pressure in the range from 1 to 100 bar is plotted.

Keywords: centrifugal compressor, 3D impellers, FSI, CFD, FEA, coupled solution, strength analysis.

1. Introduction

Centrifugal compressor high-head 3D impellers are widely used in aircraft helicopter engines, turbocharging units of internal combustion engines, and turbo expanders. The basis of research in centrifugal compressors is an experiment [1-3], but the labor and

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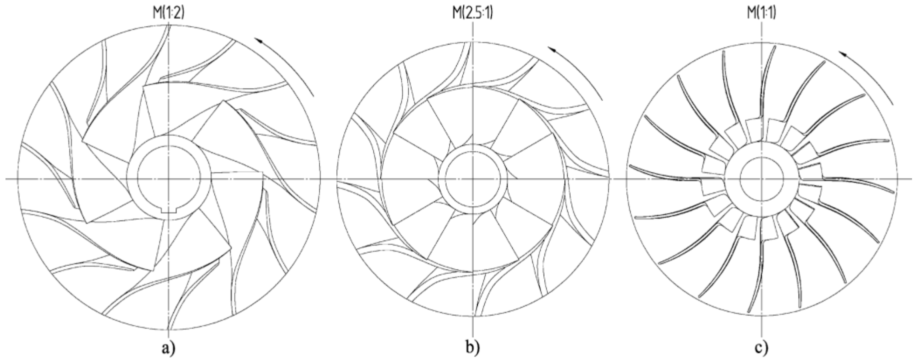
cost are high. Computational fluid dynamics (CFD) has significantly expanded the compressor equipment design capabilities analysis [4-12]. This makes it easier to study different compressor designs. Currently, virtual stands are widely used for the design, modernization and fine-tuning of power engineering equipment [13-15], which allow using digital methods to conduct many virtual tests to determine the performance characteristics of the machine being created.

Impellers strength analysis is important to ensure the compressor operation reliability. For this purpose, finite element methods (FEA) are used, which can be used to determine the maximum stresses that occur in the hard impeller geometric shapes [16, 17].

The Fluid-Structure interaction (FSI) approach is used for accurate strength analysis [18-20] and vibration characteristics [21]. It is an interdisciplinary approach that couples solutions of FEA and CFD. This approach has a wide range of applications. It becomes possible to analyze the designed 3D impellers with high reliability. With the FSI approach on the "cold" model, it is possible to reverse the use of the deformed "hot" model to refine the gas-dynamic calculation of the impeller. This approach is also used for studies in critical modes, such as rotating stall [21-24]. FSI can be used with multi-objective impeller optimization [25, 26]. In this case, the objective parameters are energy (efficiency and pressure), strength (stress, strain) and vibration characteristics (natural frequencies). This ensures that possible negative features in the designed impellers are taken into account. Also, the analysis can be performed when cracks occur, which is very time-consuming to perform in full-scale experiments [27, 28].

Therefore, the aim of the study is to consider the effect of the FSI approach on various impellers. To estimate the change in the safety factor due to the influence of gas-dynamic forces acting from the medium pressure on the impeller. The objects of research are: first stage industrial centrifugal compressor impeller with splitter blades (Fig. 1a), the turbocharger impeller with splitter for the internal combustion engine (Fig. 1b) and the impeller for the turboexpander unit (Fig. 1c). All impellers are unshrouded types. The main parameters of the impellers are shown in table 1.



a) b) c)

Fig.1. The investigated impellers: a) Industrial use; b) Turbocharger b) Turboexpander

Table 1. - The impeller parameters.

Impeller purpose	z_2	ψ_t	Π_{0-2}	M_u	u_2, m/s
Industrial use	14 (7+7)	0.69	1.44	0.80	275
Turbocharger	12 (6+6)	0.75	1.62	1.13	382.9
Turboexpander	16	0.74	1.31	0.75	322.5

2.Methods

The Ansys package is selected as the program for analysis. CFD models are built and configured in ANSYS CFX (Fig. 3. a). The stationary flow is calculated. The design mode of operation of each centrifugal compressor is simulated. The turbulence model is chosen RANS-SST. The computational domains are a complete 2π impeller, gap and labyrinth seals circumference. The pressure behind the seals is equal to the suction pressure. For the industrial use centrifugal compressor, the computational domain was only the impeller.

The total inlet temperature T*=298 K, the total inlet pressure P*=98000 Pa are set for industrial use impeller. Mass flow rate at the outlet is 7.64 kg/s. For the turbocharger impeller, the total inlet temperature is T*=288 K, and the total inlet pressure is P*=98400 Pa. The mass flow rate at the outlet is 0.374 kg/s. Analysis of the turboexpander impeller was studied at different suction pressures: 1, 20, 40, 60, 80, 100 bar at total inlet temperature T*=293 K. The mass flow rate was recalculated to ensure the calculated flow rate.

The Ansys static structural software module is used to perform strength analysis using finite element methods. The grid independence of the solution was checked using the double-counting method. Two unstructured tetrahedral meshes with the number of elements 1187278 and 3442764 were constructed. It was found that increasing the number of elements does not affect the calculation results. Fig. 2 shows the appearance of two calculation grids for the turbocharger and turboexpander impeller.

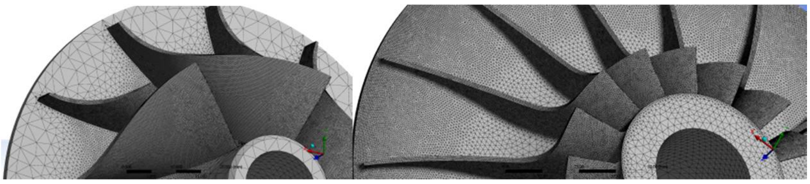
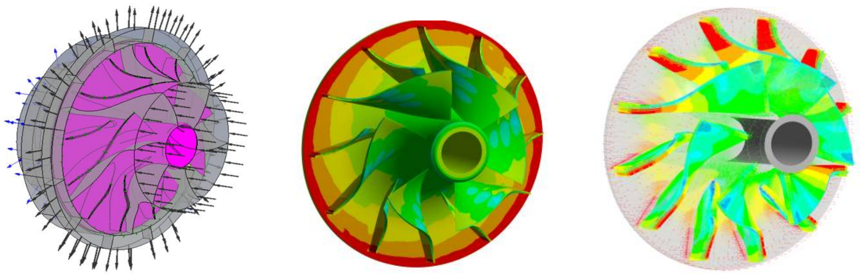


Fig.2. Computational grids for strength analysis

The results of CFD modeling were imported into the FEA solver. The temperature distribution (Fig. 3b) and pressure distribution (Fig. 3c) were imported.



a) CFD model b) temperature import c) pressure import

Fig.3. CFD model (a) and the result of importing gas dynamic parameters: b) temperature; c) pressure.

For the first impeller, pressure and temperature were imported only on the surface of the interscapular channel. An intermediate stage was used, so pressure after the return vane channel was applied to the main disk surface. For the remaining impellers, a complete problem was simulated, taking into account leaks through the gap and labyrinth seals. The selected materials for strength analysis are shown in table 2.

Table 2. - The impeller material’s description.

Impeller purpose	Material	$\sigma_{\text{В}}$,MPa	$\sigma_{\text{Т}}$, MPa	ρ, kg/m^3
Industrial use	Steel 38ХГСА	1910	1570	7850
Turbocharger	Titanium alloy ВТ5	900	750	4500
Turboexpander	Aluminum alloy АК6	390	275	2750

Data processing was performed using simulated value of the equivalent Mises stress according to the formula (1):

$$\sigma_{von-mises} = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]} \qquad (1)$$

The strength analysis was carried out using the formula of the safety factor (2):

$$n = \frac{\sigma_t}{\sigma_{\max von-mises}} \qquad (2)$$

3.Results

Industrial centrifugal compressor 3D impeller strength analysis with and without viscous three-dimensional flow showed a slight deviation of the maximum stresses and deformations. In Fig. 5, the maximum equivalent stress is observed near the output edge of the blade. The stress is below the material tensile yield strength, the safety factor n=2.13.

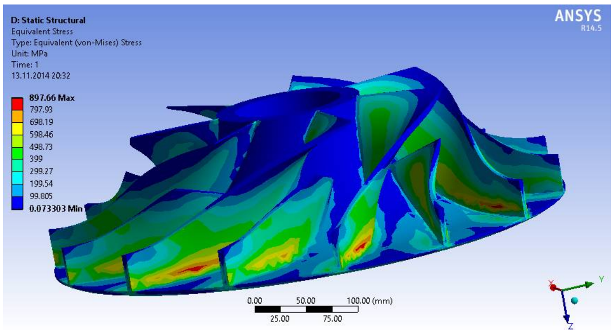
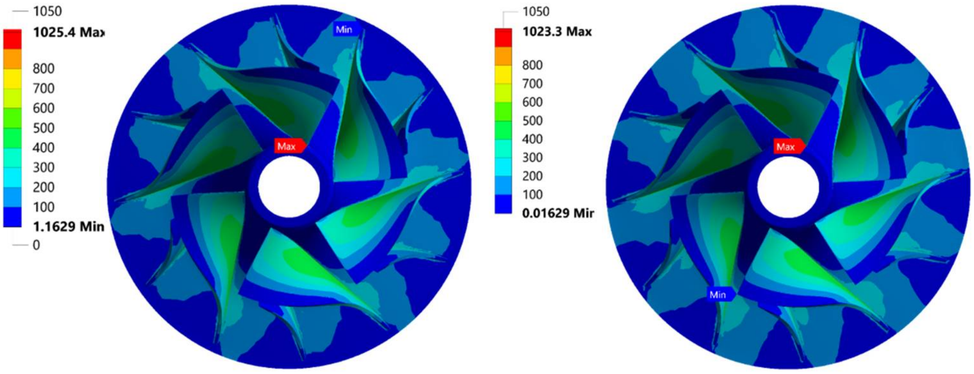


Fig.4. Equivalent stresses distribution, taking into account the three-dimensional flow.

The analysis was performed for an impeller with pressure ratio П0-2 =1.44, that operating at a low inlet pressure equal to the ambient pressure, that's why the impact is so small.

Further, a higher-loaded impeller operating at u2=382.9 m/s and with a large pressure ratio is considered.The resulting stress distribution patterns differ little qualitatively and quantitatively (Fig. 5). In this model, the strength was studied taking into account pressure influence from the gaps on the impeller.



a) b)

Fig.5. Stress distributions: (a) including CFD; (b) excluding CFD

The last step is to calculate the turboexpander centrifugal compressor impeller unit operating at high pressure of the working medium. The working environment is supported by real gas – natural gas. The safety factor dependence on the inlet pressure is plotted in Fig. 6. As a result, the safety factor decreases every 20 bar by an average of 9.7%. Relative to the calculation at 1 bar, at 100 bar the margin ratio is reduced by 40%. The strength studies results of all impellers are summarized in the table 3.

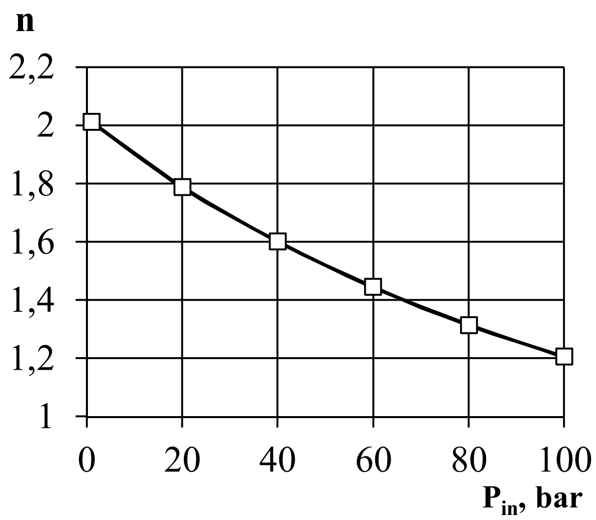


Fig.6. Safety factor dependence on the suction pressure.

Table 3 Results centrifugal compressor impellers research on the strength.

Impeller purpose, Pin, $\bar{m}$	**σ_{max}, MPa**	**$\sigma_{max\ FSI}$, MPa**	**Δ,%**	**n_{FSI}**
Industrial use 0.980 bar, 7.64 kg/s	897	898	0.1	2.1
Turbocharger 0.984 bar, 0.374 kg/s	1023	1025.3	0.2	2.0
Turboexpander 1 bar, 0.22 kg/s	136.7	136.7	0.0	2.0
Turboexpander 20 bar, 4.6 kg/s	136.7	153.8	12.5	1.8
Turboexpander 40 bar, 9.7 kg/s	136.7	171.7	25.4	1.6
Turboexpander 60 bar, 15.1 kg/s	136.7	190.4	39.3	1.4
Turboexpander 80 bar, 21.0 kg/s	136.7	209.3	53.1	1.35
Turboexpander 100 bar, 27.1 kg/s	136.7	228.2	66.9	1.2

4.Conclusions

The FSI approach makes it possible to analyze the effect of pressure forces on various impellers. Two high-pressure impellers operating in air centrifugal compressors are considered. The third impeller runs on natural gas at different suction pressures from 1 to 100 bar. Calculations of the first two impellers showed a small difference between calculating only centrifugal forces and taking into account gas forces. The coupled calculation for a high-pressure impeller showed that the influence of the medium pressure is significant. The safety factor changes from 2 to 1.2 as the suction pressure increases. The study showed that for design purposes, the coupled calculation for atmospheric compressors may not be applied. At the same time, as the literature shows, it is possible for such compressors to study the reliability and vibration characteristics at critical conditions or to take into account design defects of the impellers.

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