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THE COMPARATIVE ANALYSIS OF THE SELECTED CONSTRUCTION TYPES OF AXIAL COMPRESSOR STAGE INCLUDING THE MODAL ANALYSIS

The article concerns the issues of the scope of optimization of the gas turbine jet engine. These issues include limiting the weight and number of engine parts. One way to reduce the weight and number of components, including the compressor assembly, is to use the BLISK's replacement construction. The replacement construction should meet the strength requirement and the vibration spectrum as well. The paper presents a comparative analysis of the influence of rotational speed on the characters and the vibration frequency of the single rotor stage of the high pressure compressor. The analysis was carried out for two different design solutions of the blade-disk connection: the classical and integral. The comparative analysis focused on three important from the point of view of operation, the engine operating ranges: work on the ground (idle) and work during take-off and climb the aircraft.

1. INTRODUCTION

Jet engines with high bypass ration are the most popular power plants for the jetliners. CFM56 is the most common power plant for midrange jetliners. The engine powers Airbus A320-family planes, Airbus A340 and Boeing 737. The CFM56 engine structure is shown in Fig. 1. One of the most important objectives of optimization work in the area of aircraft engines is to reduce their mass as well as the number of parts. The CFM56 engine, depending on the version, has a mass from 2700 kg to 4000 kg. One way to reduce the weight and number of components is to use the BLISK's replacement construction. The replacement construction should meet the strength requirement and the vibration spectrum as well. During take-off and climb, the rotors of the compressor are subjected to high inertial forces resulting from high rotational speeds. Additional changes of flow parameters, through the compressor flow channel and aerodynamic forces exerting on blades, can cause vibrations. These operating conditions have crucial influence on durability and safe operation of the jet engine. Shape of the compressor assembly, connection type

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between the disc and blades and material from which the compressor and blades are made of, have a significant influence on normal modes frequencies.

The problem of numerical analysis of the vibrations of the rotating structure components is described in works by Chromek L. [1], Jamroz T. [2], Salunke Nilesh P. [3]. There is also increase in the number of publications devoted to the BLISK's integral constructions [4,5].

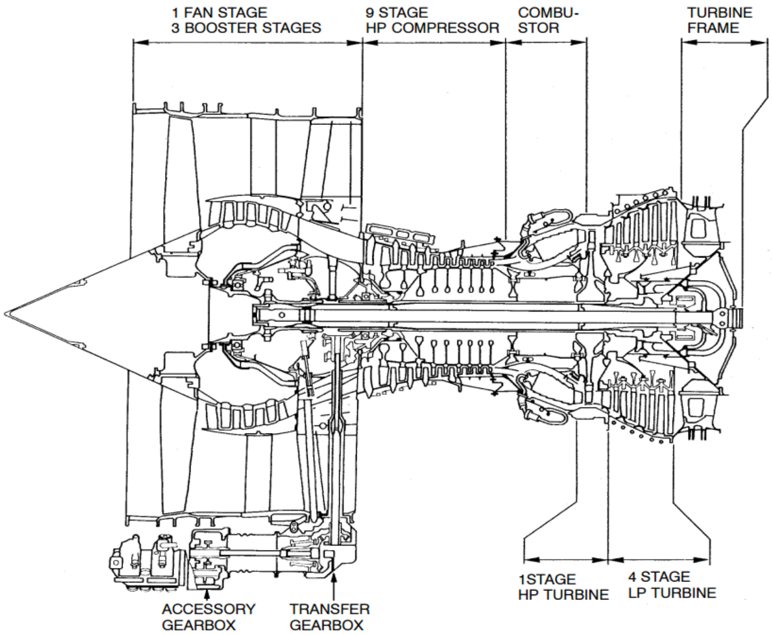


Fig. 1. Diagram of the CFM56 engine [6]

The purpose of this article is to examine how the type of blade-disc connection affects the frequency and form of vibration of the single-stage of compressor rotor, operating at different rotational speeds. Analysis is performed for two design solutions with different connection types between the blade and the disc. First, a classic design with a trapezoidal blade joint is analysed, currently used in CFM56 engine. Second, the classic design is replaced by the BLISK-type design where a mechanical connection between the disc and the blade is eliminated. The disc and blades form one part – the bladed disc (BLISK). The main advantage of the BLISK is a significant weight reduction (up to 30%) and improvement in engine efficiency. Elimination of the mechanical joint allows reducing both loads on disc and air leakage between the disc and blades. [4,7]

2. CAD AND FEM MODEL

The CAD model of the considered compressor stage (the disc and blade with dovetail joint) is created using reverse engineering techniques. The Atos Compact Scan 3D scanner is used for the measurement. Lens configuration allows to measure geometry with 0.008 mm accuracy. As a result of the measurement, a point cloud on blades surfaces is created (Fig. 2a). On the basis of scanned point cloud, exact CAD model is created using Siemens NX 9.0 software (Figure 2b). The CAD model of the disc is created from available documentation. Tetrahedral and hexahedral elements are used to create a finite element model of the compressors stage assembly. The total number of grid elements created was 443508 and 757536 nodes. Particular attention was paid to the quality of the mesh at the blade lock. It was compacted to avoid stress concentrations (Fig. 3a).

a) b)

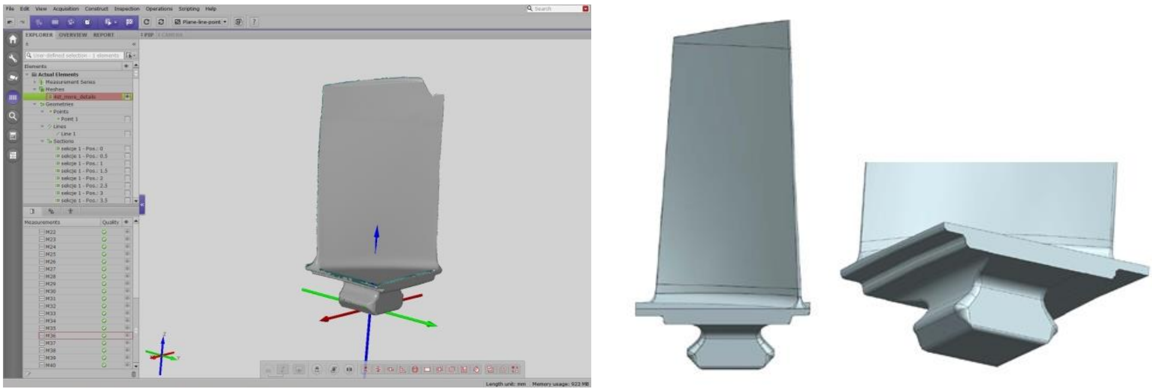


Fig. 2 a) Geometry of the blade after 3D scanning, b) CAD model of the blade and dovetail joint

It is assumed that analysed stage of the high-pressure compressor is made of Inconel 718 alloy (density of 8193.3 kg/m3), which is commonly used for that type of structures. It has excellent strength characteristics at high temperatures up to 700°C. The strength properties of the material were taken from studies [8,9].

a) b)

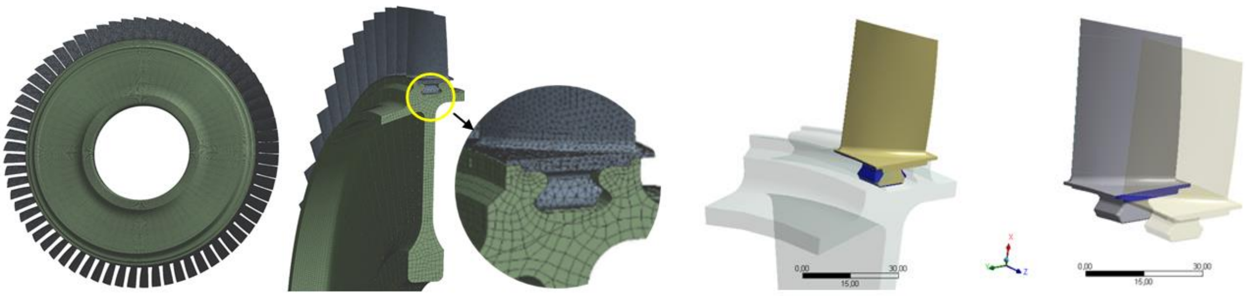
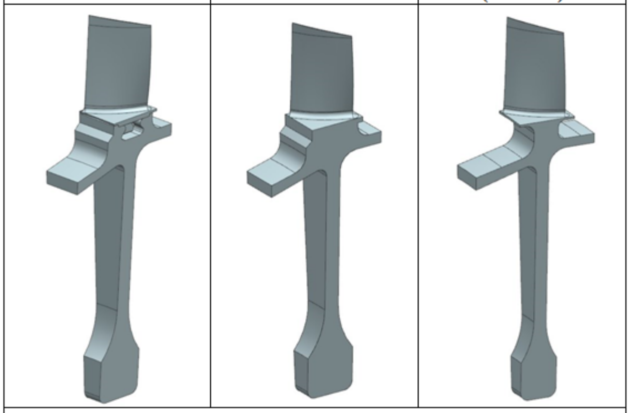


Fig. 3 a) FEM model of the analysed structure, b) Examples of defined contact surfaces

Boundary conditions are defined by cyclic symmetry on side surfaces of the model (slice of the disc with single blade). Additionally the sliding support boundary condition of Frictionless Support type is used at the surfaces between third and fifth stage of the compressor. Such a solution locks one degree of freedom in the direction normal to the surface. The contact surfaces between the disc and the blade are defined with the use of contact boundary conditions (Fig. 3b). The system load was the centrifugal force resulting from the assumed rotational speeds. In this example the aerodynamic forces acting on the blade are not taken into account. In addition, it was assumed that the process is quasi static. The working temperature for the fourth compressor stage was 120 °C (393.15 K).

The BLISK's replacement design, obtained from the previous mass-strength optimization shown in [10] was modified for the comparison analysis purposes. The resulting integral structure carry a load at the same stress level like as the classic joint, was optimized in terms of dynamic. The process was carried out in three steps as shown in Fig. 4a.

a)

Classic design	First evaluation of the BLISK	Final model (BLISK)
		
Slice weight		
0,219 kg	0,225 kg	0.170 kg
Stage weight		
14,885 kg	15,288 kg	11,580 kg

b)

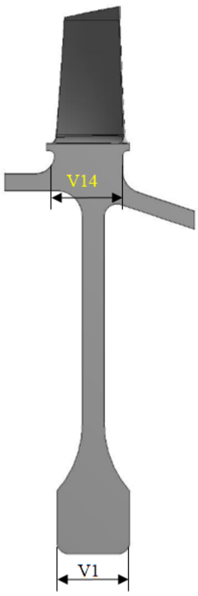


Fig. 4. a) Design stages of the replacement BLISK design, b) Defined geometric variables

The objective function was to minimize mass and maintain the natural frequency in the assumed operating range of rotational speeds. The variables defining the disc thickness (V1) and disk rim thickness (V14) were adopted as the objective function parameters (Fig. 4b). The parameters were selected based on sensitivity study their impact on the objective function. As a result of all modifications (elimination of a blade-disk connection and to reduce the thickness of the disk), the weight reduction of 22% is obtained. Tetrahedral finite elements are used to create FEM model of analysed structure. Boundary conditions and material used in this analysis are similar to the previously analysed classic structures with dovetail joint.

3. COMPARATIVE ANALYSIS

The dynamic analysis of the examined structures (Figs 3 and 4) allowed determining and comparing the natural frequencies at different rotational speeds. It also allowed us to assess the impact of the blade-disk connection type on the natural frequency and form of the vibration of the structure. Results are shown in Table 1. In Figs 5 to 6 vibrations mode shapes are presented.

As a result of the analysis of Campbell diagrams for classic structure with trapezoidal joint (Fig. 7) and BLISK structure (Fig. 8) are created. Excitation frequency is calculated from equation:

$$f = (\Omega \cdot i)/60$$

In equation: Ω [*RPM*] means rotational speed, *i* excitation index/level. The Campbell Diagrams, which are used on a regular basis in the design process of the rotor assembly, allow for alignment control of rotor components (stator blades, rotor blades, bearing discs).

Table 1. Influence of rotational speed on normal mode frequencies

Classic structure with trapezoidal joint

	Idle	Climb	Take off
Ω [RPM]	8852.2	12557.3	15326.6
ω_{20} [Hz]	660.77	697.23	729.53
ω_{11} [Hz]	1051.9	1102.5	1147.5
ω_{32} [Hz]	1687.1	1764.1	1832.3
ω_{33} [Hz]	2727.7	2815.1	2884,6

Replacement integral structure - BLISK

	Idle	Climb	Take off
Ω [RPM]	8852.2	12557.3	15326.6
ω_{20} [Hz]	566.44	611.54	651.06
ω_{11} [Hz]	899.25	959.48	1012.9
ω_{32} [Hz]	1420.2	1513.2	1595.8
ω_{33} [Hz]	2218.5	2322.9	2415.9

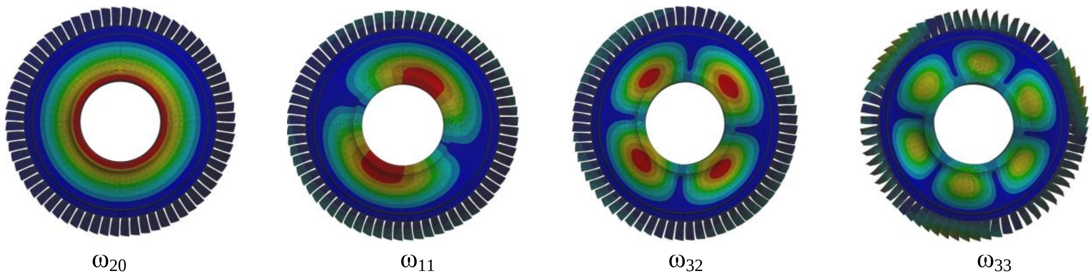


Fig. 5. Normal mode shapes for structure with trapezoidal joint

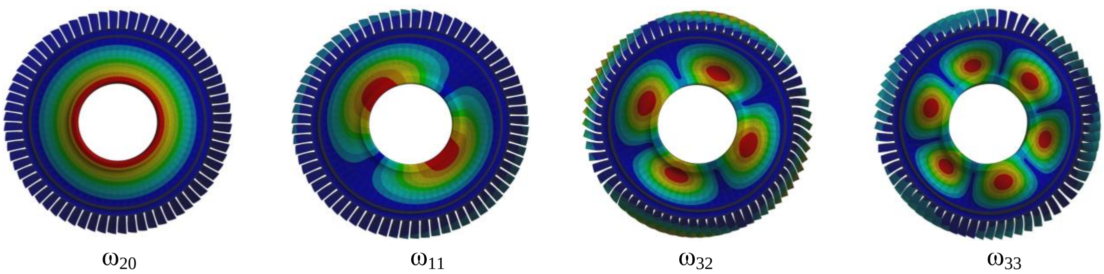


Fig. 6. Normal mode shapes for integral structure - BLISK

The aim is to exclude possible resonances, providing a safe operation of the other components connected and [11]. On both diagrams vertical lines mark idle rotational speed and maximum rotational speed of the high-pressure compressor. As a result of modifications (the BLISK structure), normal mode frequencies for corresponding vibration mode shapes are smaller in comparison to classic structure. Analysis of Campbell diagrams shows that number of possible resonances in operating rotational speed range is significantly reduced for designed BLISK structure (Fig. 7 to 8).

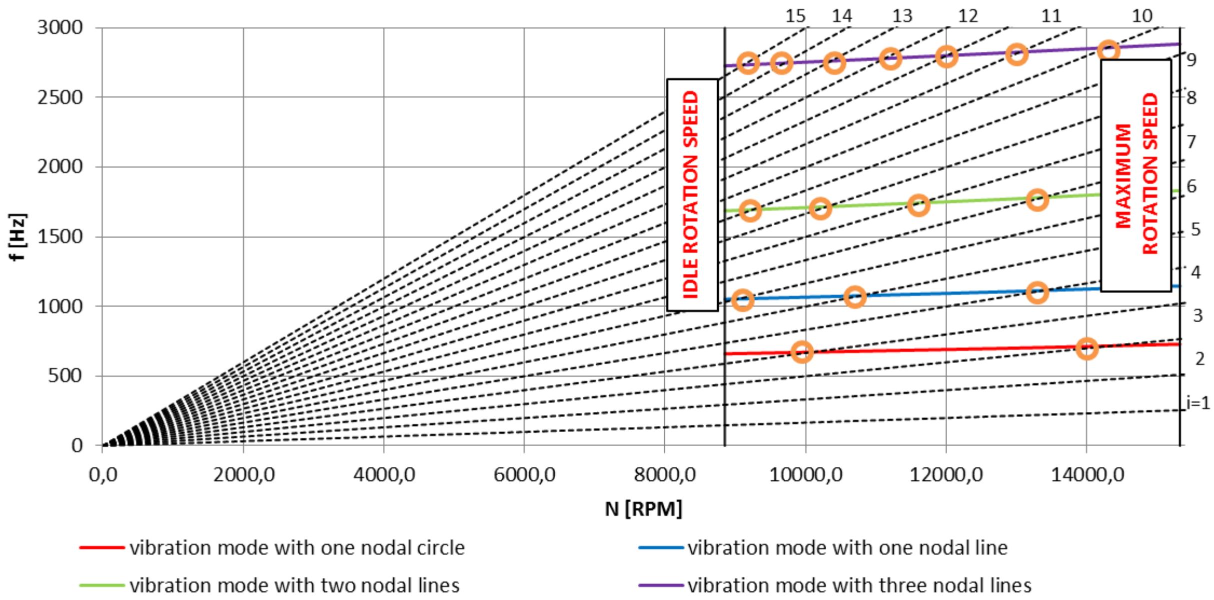


Fig. 7 Campbell diagram for classic structure

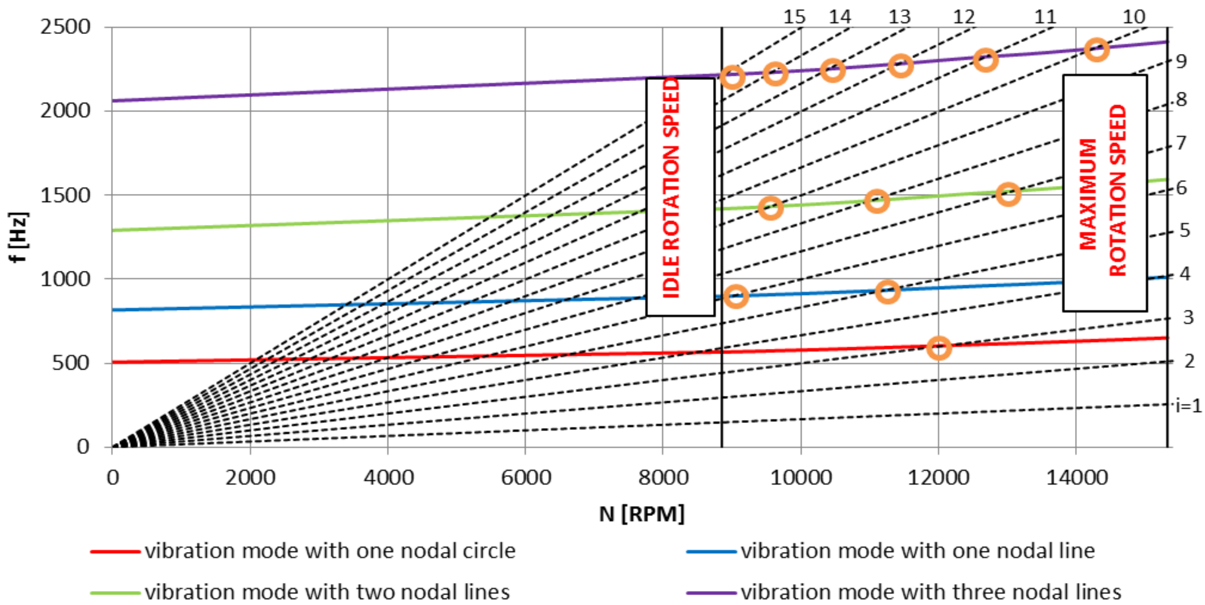


Fig. 8. Campbell diagram for BLISK structure

4. CONCLUSION

In the paper the next stage of optimization of the disc-blade joint of an axial compressor stage is presented. Described in [12] weight-strength optimization stage is focused on reduction of weight where stress levels are close to yield strength of the material and the natural frequencies are maintained at the operating speed range. As a result, weight is reduced by 28%. A structure, correctly designed from strength analysis point of view, doesn't have satisfying dynamic properties. Vibration amplitudes are big and corresponding stress levels exceed yield strength of the Inconel alloy causing damage of the disc structure. The integral construction proposed in this step of optimization (dynamic optimization) was characterized by a greater thickness of the disc. Achieved weight reduction is 22% from the classic structure. Finally, the BLISK normal mode frequencies and amplitudes are similar or lower in comparison to classic structure. The number of possible resonances in operating rotational speed range is reduced. Damping coefficient calculation is subject of further analysis.

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