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The Impact of Damage to the Compressor on the Operating Parameters of the Pratt & Whitney 206B2 Turbine Engine

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Abstract. The article presents the impact of damage to the centrifugal compressor of the P&W 206B2 turbine engine, built in the EC-135p2 helicopters EC-135p2. The damages are caused by sucking the foreign bodies to the inlet, what results in the changes of exploitation parameters of the engine and thermodynamic parameters of operating medium. On the basis of the parameters, measured during engine operation, such as: rotation speed of the rotor of the compressor – n_1, the rotation speed of the turbine shaft of the drive – n_2, the gas temperature at the outlet of the turbine driving of the compressor – $T_{4.2}$, and the fuel flow rate - $\dot{m}_\mathrm{p}$, distributions of these parameters in various cross- sections of the engine were determined and compared. Then, on their basis, the CFD analysis of air flows in new and damaged compressors was performed.
Keywords: mechanics, aircraft engines, compressor centrifugal, compressor damage

1. INTRODUCTION

An aircraft radial flow compressor, is a part of an engine which is the most vulnerable to damages because of it construction, location in the engine, and nature of its work. Thus, construction elements of the compressor are made of titanium alloys, ensuring both adequate mechanical strength and relatively low weight. It is dictated by designers', striving for optimization of the engine's power-to-mass ratio. For this reason, the most important element of the compressor, i.e., the rotor having small mass has to be simultaneously resistant to [1]:

- damages by foreign bodies getting the engine together with the sucked air,
- tensile stresses resulting from centrifugal forces,
- bending stresses caused by air flux, flowing between the turbine blades.

The compressor is the second, in the sequence, after the engine inlet, the component of the aircraft engine. Its task is to deliver adequate amount of air, necessary to proper burning process of fuel-air mixture in a combustion chamber and to increase the air pressure up to the required value. Each its damage causes decrease in the engine power (or complete loss of engine efficiency), what in extreme cases, defined by a producer, qualifies it for repair. Modern aircraft engines, such as P&W 206B2 ones, are equipped with a computer controlling their work, i.e., Electronic Engine Controls system. This system is continuously monitoring the parameters of engine operation, such as:

- mass flow rate of fuel – $\dot{m}_{\mathrm{p}}$,
- temperature of gases in outlet cross-section from the drive turbine – $T_{3.1}$,
- rotation speed of drive turbine's rotor – n_1,
- rotation speed of compressor turbine's rotor – n_2,

When the elements of the compressor are damaged, the EEC system automatically increases the rotation speed of the turbine rotor n_1, by increase in the fuel supply $\dot{m}_{\mathrm{p}}$, in order to ensure continuous and stable engine operation.

The most frequent reasons of the compressor failure are Foreign Object Damages (FODs), i.e., sucking the foreign objects in form of sand, dust, water drops, and the elements left on the aircraft during service works, e.g., protecting wire or washers and nuts (Fig. 1), [2].

Sucking the foreign objects by the compressor takes place, first of all, during the helicopter take-off, its landing, and ground tests on such unpaved terrain as beach or dirt roads.

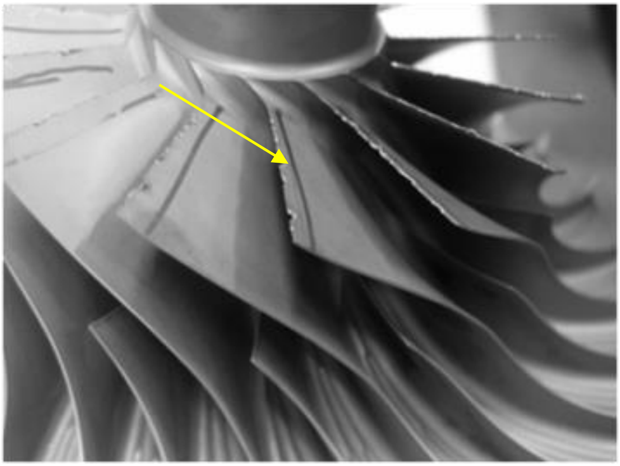

Fig. 1. View of the compressor rotor damaged by foreign objects [2]

During its operation, the main engine's rotor produces strong blast of air. Spatial distribution of the air velocity close to the EC135p2 helicopter is shown in Fig. 2 [3]. It was taken in Ref. 3, that blasts of air, generated by the main rotor, the velocity of which is higher than 15 m/s are dangerous both for people and devices. The air velocity lower than 15 m/s is only at the distance of about 25 m from the helicopter.

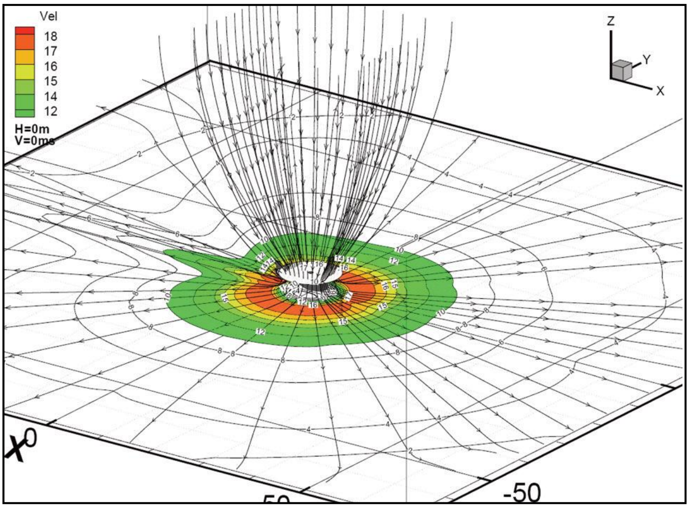

Fig. 2. Spatial distribution of air velocity around the helicopter, that is on the ground in windless weather [3]

The captured solid particles, having high kinetic energy, in contact with metal surface of the compressor cause its mechanical damage.

The compressor of an aircraft engine is also vulnerable to erosive damages. Figure 3 shows damage of the wall of a flow channel occurring near the compressor's steering set.

Most frequently such damages are caused in a seaside location or close to chemical plants [4]. Sand specks, taken with the sucked air, hit repeatedly the same place of metal surface the compressor element causing micro-indentations (material fatigue).

Presence of sand grains, their summary mass, influences also the engine efficiency. Next, water in form of drops, reaching the engine, left on the surface, a thin layer of sediments (sludges) e.g. of calcium or magnesium. Particles of the deposited chemical compounds can react with a metal surface creating corrosive pittings.

Fig. 3. View of a damage to the walls of flow channel near the steering compressor set (photo P. Rutkowski)

Formed in this way, deformations of surfaces of the compressor's elements influence on [5]:

- change of geometry of blades and inter-blade channels,
- change of mechanical properties of blades
- possibility of vibrations of a compressor's rotor.

The aim of this work is to estimate the influence of damages of the compressor's rotor, caused by foreign bodies sucking, on its operation parameters. Also, characteristic parameters of air flow in the new and long-time exploited compressors will be compared.

2. INFLUENCE OF COMPRESSOR DAMAGES ON ENGINE PERFORMANCE

To determine thermodynamic parameters of a working factor, in particular specific cross-sections of the engine (Fig. 4), a demonstrative version of "GasTurb" program [6, 7] was used.

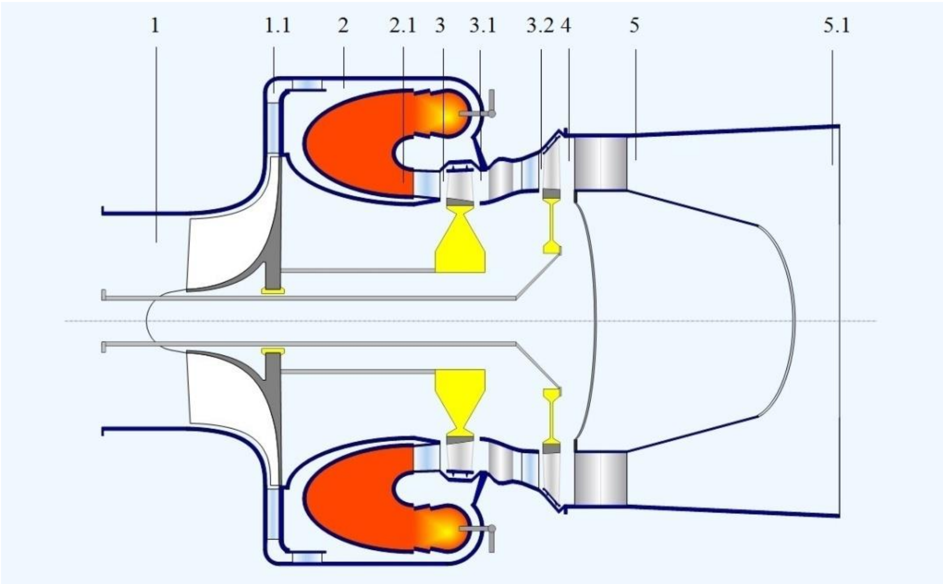

Fig . 4. Specific cross section of the tested engine: 1 – inlet cross-section, 1.1 – diffuser, 2 – combustion chamber, 2.1 – outlet cross-section of the combustion chamber, 3 – high pressure rotor turbine, 3.1 – cross-section of the outlet of high-pressure turbine, 3.2 – power turbine, 4 – cross-section of the outlet of the power turbine, 5 – inlet cross-section to the outlet system, 5.1 – outlet system (developed: B. Przybyła) [4]

This application allows for calculations, analyses, and simulations of various types of turbine engines as well as for determination of operation characteristics of compressors and turbines.

Initial conditions, required for calculatios, were taken on the basis of the data obtained during the checking the engine operation on the ground (Table 1), values described in available literature [8], and in general taken parameters, necessay for initial design of turbine engines, such as: isentropic and politropic efficiencies of compressors and turbines, the power consumed for drives of aggregates, and calorific value of aircraft fuel [9].

Table 1. Parameters of the tested new and exploited Pratt&Whitney 206B2 engine

Parameter	Symbol	Unit	New engine	Exploited engine
Rotation speed of high-pressure rotor's turbine	n_1	[rev/min]	53300	53526
Nominal power turbine spool speed	n_2	[rev/min]	39130	39130
Temperature of gases at outlet of high-pressure turbine	$T_{3.1}^{*}$	[K]	1030	1088
Mass flow rate of fuel	$\dot{m}_{\mathrm{p}}$	[kg/s]	0.038	0.042
Pressure ratio of compressor	π_{s}	-	7.1	6.95
Coefficient of pressure loss at inlet	σ_{wl}^{*}	-	0.99	0.99
Burner exit temperature	$T_{2.1}^{*}$	[K]	1308	1361
Isentropic efficiency of combustion chamber	η_{ks}^{*}	-	0.99	0.99
Fuel heating value	W_{u}	[MJ/kg]	42.8	42.8
Overboard bleed	$\dot{m}_{\mathrm{pl}}$	[kg/s]	0.1015	0.1015
Power offtake	P_{WX}	[kW]	30	30
Mechanical efficiency of compressor turbine	η_{mHP}	-	0.99	0.98
Burner pressure ratio	β_{KS}	-	0.97	0.97
Pressures ratio in a channel between turbines	β_{IT}	-	0.975	0.98
Pressures ratio in a channel after a power turbine	β_{KT}	-	0.98	0.98
Pressures ratio at engine outlet	β_{RW}	-	1.03	1.15

Other initial parameters were taken as default parameters for the turbine's helicopter engine. Table 1 presents working parameters for the new and exploited (after 660 hours work) the Pratt&Whitney 206B2 engines. Next, simulations of operations of both engines were performed using "GasTurb" program. The calculation results are shown in Table 2.

The parameter, which determines a value of fuel consumption in the turbine helicopter engines is the specific fuel consumption c_j [kg/(s·W)].

Table 2. Characteristic parameters for the new and exploited Pratt&Whitney 206B2 engine

Parameter	Symbol	Unit	New engine	Exploited engine
Effective power	P_e	[kW]	343.2	343.4
Specific fuel consumption	c_j	[kg/(s·W)]	$1.11 \cdot 10^{-7}$	$1.21 \cdot 10^{-7}$

On the basis of the data, obtained in "GasTurb" program, the diagram of changes of total pressure, total temperature, and the rate of mass flow of the working medium through the engine in its characteristic cross-sections (Fig. 5) has been performed.

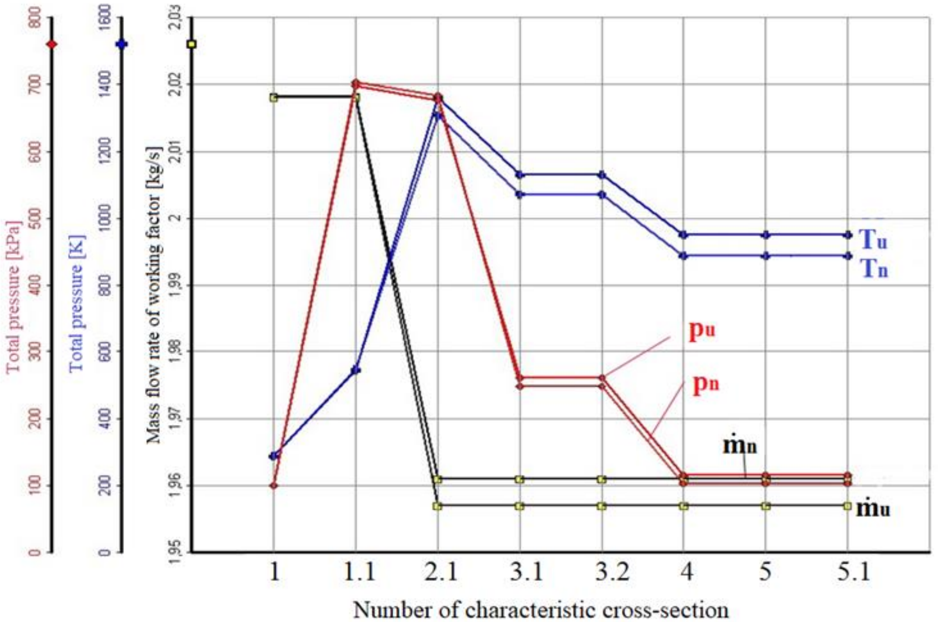

Fig. 5. Distributions of total pressure, total temperature, and mass flow rate of working factor for the new ("n") and exploited ("u") engines

It was stated that in each of the analysed cross-section, the values of the considered parameters of the exploited engine operation are higher than the values of new engine parameters.

Significantly noticeable increase in the values of parameters can be observed in a hot section of the engine, i.e., from the outlet cross-section of the combustion chamber (section 2.1) to the cross-section of the outlet system (section 5.1). For the analysed engines, it is caused, first of all, by decrease in compressor efficiency, as well as by decrease in efficiency of high-pressure and power turbines.

While between the cross-sections 1-1.1 (engine inlet – diffuser) the changes of values of the parameters are small ($\Delta T \approx 3$ K, $\Delta P \approx 7$ Pa), in the cross-sections from 2.1 to 5.1 (i.e., from the outlet of the combustion chamber to the engine outlet), these changes are significant ($\Delta T \approx 50$ K, $\Delta P = 6 \div 19$ Pa).

Of course, the exploited compressor's rotor has lower efficiency, so for the constant rotation velocity it delivers smaller amount of air. The EEC system continuously controls the engine operation and keeps continuous and stable generation of the torque, produced by the engine. The torque is transmitted to a drive shaft and next, through a main gear, to the power rotor and fenestron, thus increasing amount of the fuel delivered to the combustion chamber during further exploitation. This in turn causes increase in the temperature and pressure of the exhaust gas stream in the combustion chamber. Simultaneously, rises the velocity of the exhaust gas at the outlet of the combustion chamber, so grows the kinetic energy of the exhaust gas. In the high-pressure turbine, the higher torque is produced, which is also transmitted by the shaft to the compressor. As a result, rotation velocity of the compressor's rotor increases, too.

Thus, the exploited engine's compressor can deliver indispensable amount of air for the combustion process of a fuel-air mixture in the combustion chamber. In the calculations, also the fact of decreasing efficiency of the high-pressure turbine and power turbine has been taken into account. The calculations showed also the change of mass flow ratio of the working medium, flowing through the engine, especially through its hot section. The reason of increase in amount of the working medium is larger fuel supply to the combustion chamber.

3. ESTIMATION OF THE COMPRESSOR CONDITION ON THE BASIS OF CAD/CAM SIMULATION

On the basis of calculation results, obtained in GasTurb program (Table 2, Fig. 5) and the parameters listed in Table 1, the Computational Fluid Dynamics (CFD) simulation was performed for the new and exploited compressor's rotors [10]. At the beginning of investigations, the authors have only the exploited compressor's rotor, which has been removed from the helicopter's compressor. In order to determine a shape of new compressor's rotor, so-called, reverse engineering technology was used. First, the exploited compressor's rotor, with the marked characteristic points (Fig. 6) has been scanned using 3D scanner and its model in form of a cloud of points has been obtained (Fig. 7).

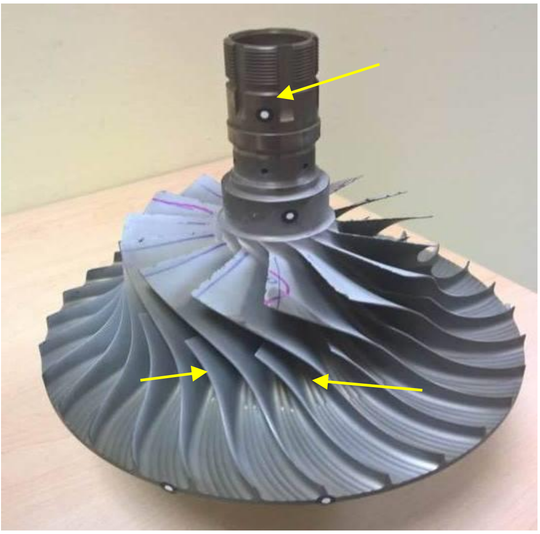

Fig. 6. Compressor rotor prepared for 3D scanning

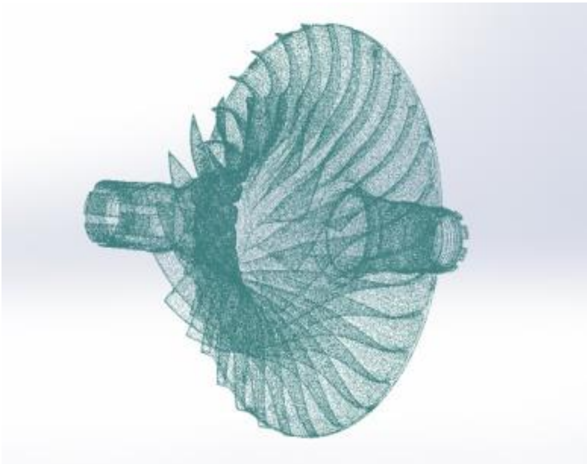

Fig. 7. The scanned compressor rotor in form of a cloud of points

Next, connecting automatically the points, a surface model has been obtained that is reflection of the exploited compressor's rotor (Fig. 8).

This model was placed, in previously created virtual hull of the compressor. For modelling of a shape of a channel, dimensions of real inlet, pictures, and drawings of the engine and geometry of compressor's rotor were used.

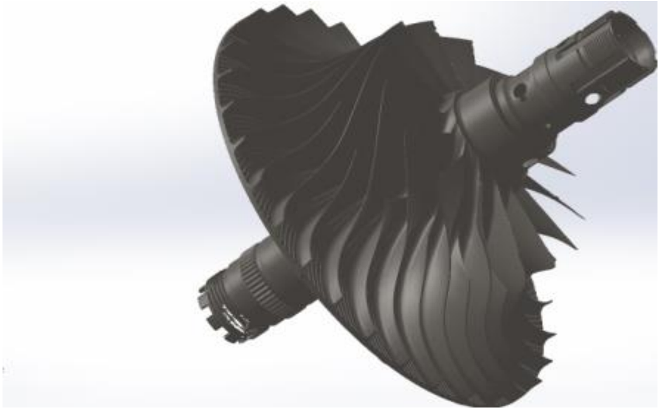

Fig. 8. Surface model of the exploited compressor's rotor

In the next step of modelling, due to removal of characteristic and adequate dimensions of the channel's model from the rotor's model, the solid model of the overflow channel of the compressor's rotor has been obtained (Fig. 9).

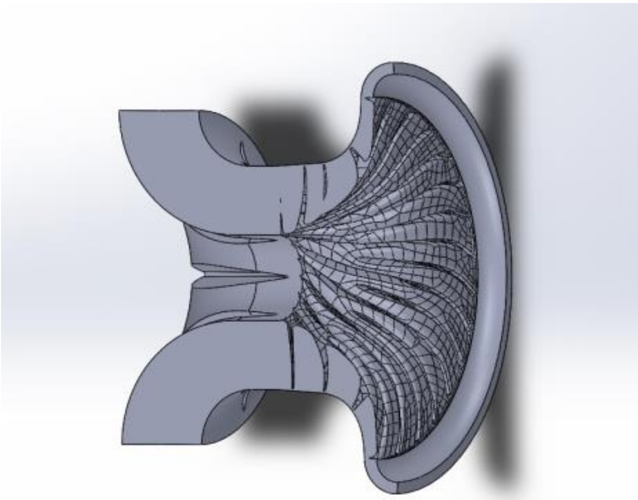

Fig. 9. Ready duct of the compressor for further the CFD analysis

A model of the compressor rotor of the non-exploited (new) engine, has been developed on the basis of 3D scan of the exploited compressor's rotor. After creation of the surface model (Fig. 8), new surfaces have been superimposed on it (Fig. 10), so that the blades curvature can the most precisely reflect geometry of a real rotor [11, 12].

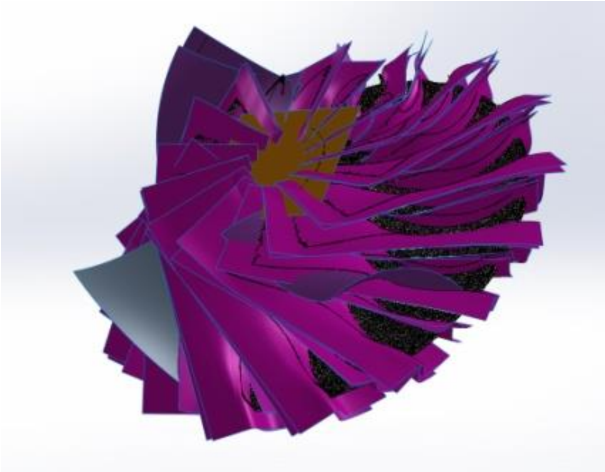

Fig. 10. The superimposed surfaces on the model of the exploited compressor motor

Next, due to the adding and subtracting processes of the adequate surfaces, the rotor's model of non-exploited engine has been obtained (Fig. 11).

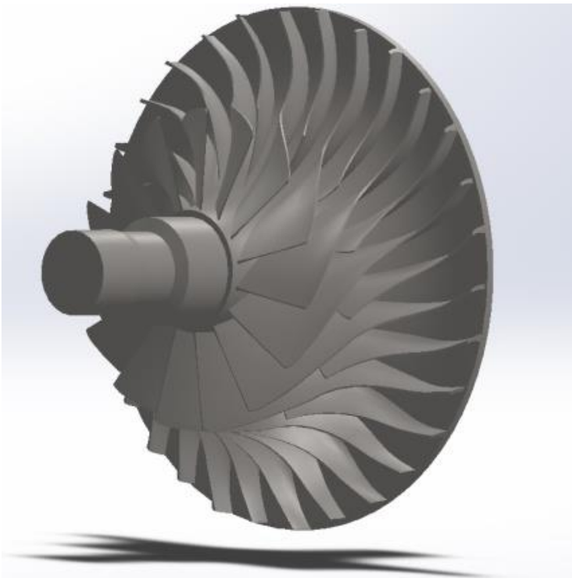

Fig. 11. Model of compressor rotor of the new engine

Next modelling steps, connected with location of the rotor's model of the new engine in a virtual channel of the compressor, as well as creation of a model of an overflow channel for CFD analysis were analogous as for the model of compressor's rotor of the exploited engine.

For the modelling process, the pressure losses, occurring in the slots between blades and the hull, were neglected. As a working medium, the air of 298 K temperature was taken.

Moreover, the static pressure was assumed at the outlet of the compressor, which is equal to 1013 hPa and a flux of the air mass at the outlet which equals 2.035 kg/s.

Further investigations consisted in carrying out the simulations of the working medium's flow through the channel of the compressor of non-exploited engine (Fig. 12) and exploited engine (Fig. 13).

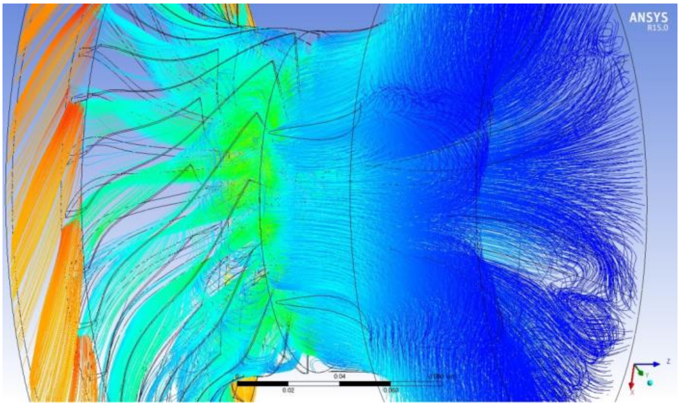

Fig. 12. Visualization of the air flow by the compressor of the new engine

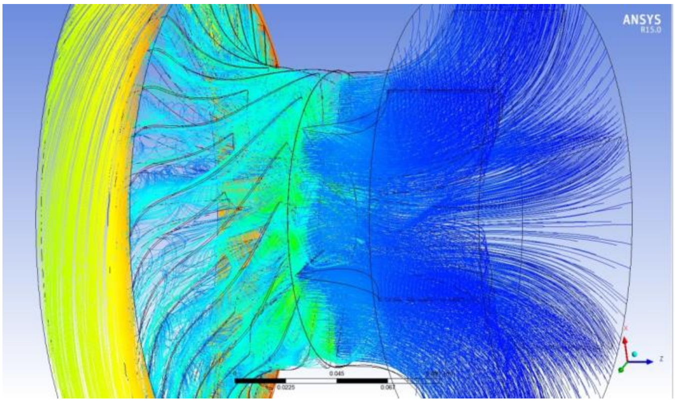

Fig. 13. Visualization of air flow by the compressor of the exploited engine

After the performed simulation of the air flow through both compressors, significant differences were observed in the flow characteristic, pressure distributions, and in the stage of the flow turbulence.

Damages to the leading edges of the rotor blades of the compressor rotor of the exploited engine cause significant increase in turbulent flow of the air fluxes.

It was observed that behind the leading edges, there occur more flux whirls, that at the larger distance from the compressor's inlet undergo further propagation. In the compressor of the non-exploited engine, the air flow, though of turbulent character too, is characterized by little lower intensity of whirls.

For estimation of a turbulence value, the Turbulence Kinetic Energy (TKE) coefficient was used, the unit of which is m^2/s^2 [13]. This coefficient defines the amount of the kinetic energy contained in a mass unit (in this case, the mass of air flow) of the whirls of turbulent flow.

For the compressor of the non-exploited engine (Fig. 14), it was stated that TKE_n is from 4.9×10^{-4} m^2/s^2 to 11896.4 m^2/s^2. However, for the compressor of the exploited engine (Fig. 15), the kinetic energy of the turbulence TKE_n is between the values 4.7×10^{-8} and 33364.9 m^2/s^2.

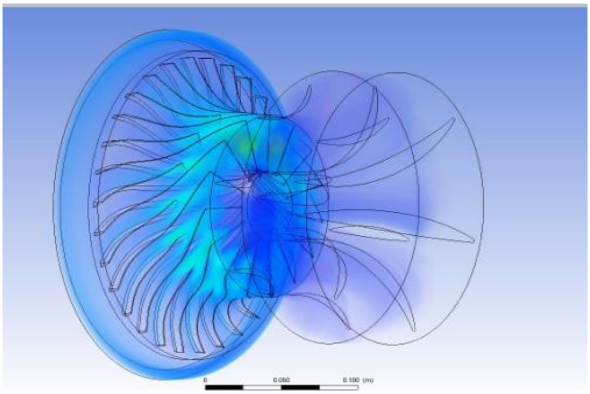

Fig. 14. Visualization of the Turbulence Kinetic Energy in the compressor of the new engine

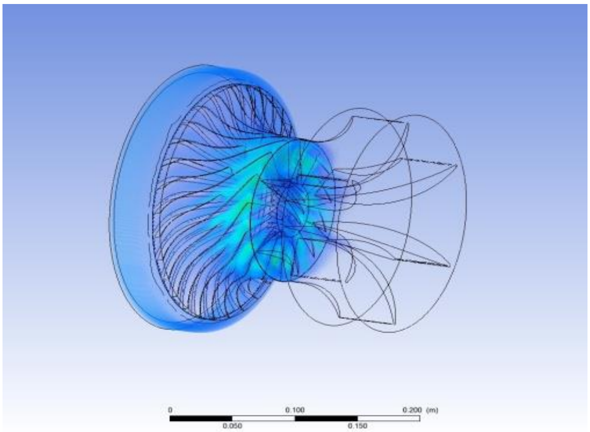

Fig. 15. Visualization of the Turbulence Kinetic Energy in the compressor of the exploited engine

Comparing the obtained results of analysis, it was observed that the highest TKE value in the compressor the exploited engine is three-fold higher than the value of this parameter for the compressor of new engine.

During further analysis, also the differences in pressure distributions of the both investigated compressor's rotors were stated. In the new compressor (Fig. 16), this distribution is more uniform in comparison to the compressor of the exploited engine (Fig. 17).

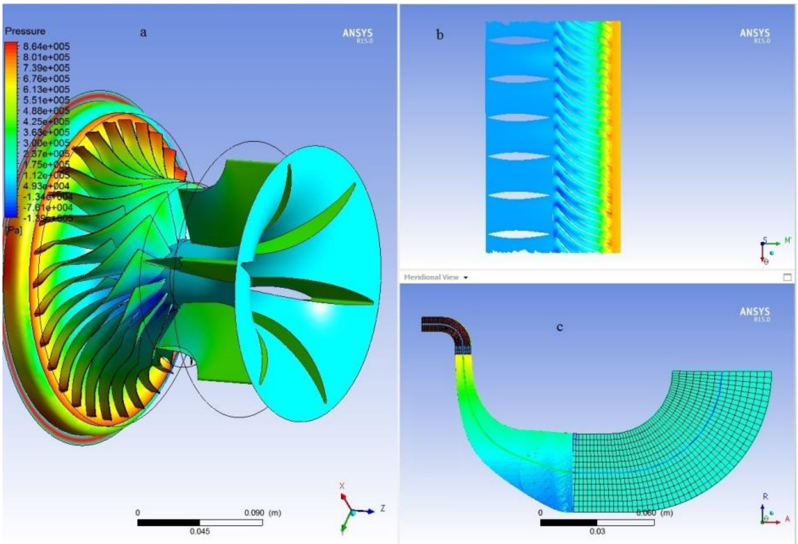

Fig. 16. Visualization of the distribution of pressure in the compressor of a new engine: a – overall view; b – blade to blade view; c – meridional view

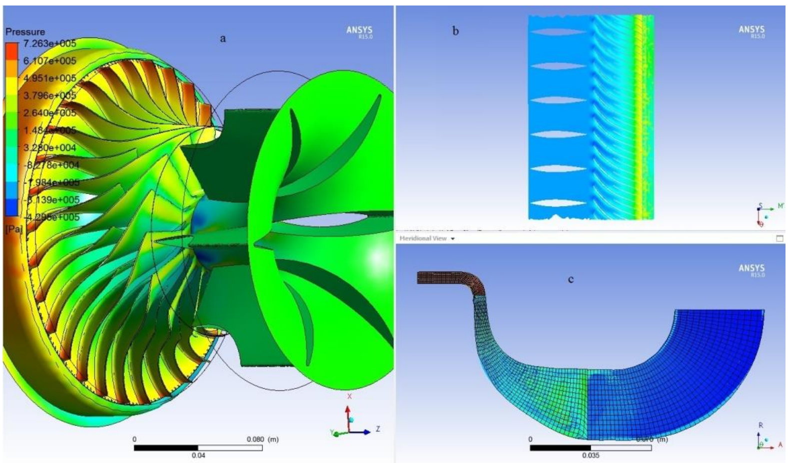

Fig. 17. Visualization of the distribution of pressure in the compressor of the exploited engine: a – overall view; b – blade to blade view; c – meridional view

4. SUMMARY AND CONCLUSIONS

Determination of the technical status of the compressor's rotor has significant influence on further engine exploitation. Damage to the compressor blades do not exclude the engine from further use, however, adequate repair works are needed. These works significantly extend the period of the engine use, what directly influences on lower cost of its exploitation.

In the work, using the GasTurb program, the parameters in characteristic cross-sections of the engine were determined, and after that, on their basis the simulation of the compressor work was performed in ANSYS-CFX program environment.

The obtained results of numerical calculations were compared for the air flowing through the new and exploited compressor's rotors. Increase in fuel consumption of about 9% in the exploited engine in comparison to the new engine was stated. This higher parameter shortens the range of the helicopter operation.

Distinct difference in the flow characteristics of the damaged and new rotors has been observed. The TKE parameter has grown three-fold in the engine, in which the compressor's rotor was damaged and the air flux was much turbulent what caused the decrease in the compressor pressure ratio. In order to deliver adequate air amount, necessary for proper organization of the combustion process, the compressor's rotor has to rotate with higher rotation speed.

In reality, this speed is limited, what in the case of too many damages, disqualifies the engine from its further exploitation. The described method of estimation of influence of compressor damages to the P&W 206B2 engine can be the supplement for the engine checking at the engine test bench, showing changes of the parameters in particular controlled cross-sections of the engine, also these which are not measured, e.g., TKE.

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Wpływ uszkodzeń sprężarki na parametry pracy turbinowego silnika śmigłowcowego Pratt&Whitney 206B2

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Streszczenie. W artykule przedstawiono wpływ uszkodzeń sprężarki promieniowej turbinowego silnika śmigłowcowego P&W 206B2, zabudowanego na śmigłowcach EC-135p2, spowodowanych zasysaniem ciał obcych do wlotu, na zmianę parametrów eksploatacyjnych silnika oraz termodynamicznych czynnika roboczego. Na podstawie parametrów zmierzonych podczas eksploatacji silnika, takich jak: prędkość obrotowa wirnika turbiny wytwornicowej – n_1, prędkość obrotowa wirnika turbiny napędowej – n_2, temperatura gazów na wylocie z turbiny wytwornicowej – $T_{3.1}$ oraz masowe natężenie przepływu paliwa – $\dot{m}_\mathrm{p}$, wyznaczono i porównano rozkłady tych parametrów w poszczególnych przekrojach silnika. Następnie na ich podstawie wykonano analizę CFD przepływu powietrza przez nową oraz uszkodzoną sprężarkę.

Słowa kluczowe: silniki lotnicze, sprężarka promieniowa, uszkodzenia sprężarki