Research Journal of Applied Sciences 9 (11): 784-788, 2014
ISSN: 1815-932X

Effect of Accounting of Air Bleed from The Flow Passage of The Multi-Stage Axial Low Pressure Compressor on its Design Performances

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Abstract: Comparison of the numerical simulation results of a multi-stage axial low pressure compressor with experimental data is carried out in this study. Also, the estimation of the influence of working fluid bleed from the first stage on the simulation results and compressor workflow is performed. The results obtained are in good agreement with the experimental data and the existing theoretical concepts.

Key words: Axial compressor, numerical simulation, optimization, computational model, compressor

INTRODUCTION

Compressor is the most important component of the Gas Turbine Engine (GTE). And the existence a best compressor determines largely the success of the engine as a whole. This is not only due to the fact that the compressor efficiency and its ability to achieve the desired compression ratio greatly affects the specific fuel consumption but also that the stability of compressor operation determines whether the engine is operating or not (Kulagin, 2003).

Creation of new compressor or deep modernization of the existing is a complex scientific and technical problem because the designer must fulfill the contradictory requirements of gas dynamic efficiency, strength, workability, reliability, achieving an adequate stable operating margin (Popov *et al*., 2014a). Search for the rational form of the compressor flow passage is complicated by the fact that a huge number of factors can affect its workflow. Only one blade geometry can be described by three dozen of variables. In this situation, search for rational configuration is unsolvable problem for the average man because he is physiologically unable to present and analyze so many variables simultaneously.

In this situation, mathematical optimization techniques may come to engineer's relief (Zhdanov *et al*., 2013; Shabliy and Cherniaev, 2014). With their help, rational configuration of the compressor to can be found as an extremum of function of efficiency criteria of n variable variables based on series of mathematical models calculations. This algorithm is implemented in a particular program IOSO (Egorov *et al*., 2006) which effectiveness is repeatedly proven in solving optimization problems (Matveev *et al*., 2013, 2014).

The success in searching for rational configuration of the compressor via optimization techniques is the application of accurate computational models. Currently, the usage of computational methods in gas dynamics gives the most accurate estimated data, because the basis of these methods is the navier-stokes equations system describing the flow of gas with minimal assumptions. An important advantage of this approach is that it takes into account the full spatial shape of the blade with all the nuances of form (fillets, grooves, ledges) while offers a wealth of information on all the flow parameters at any point in the computational domain. In fact, the numerical methods in gas dynamics are calculated analogue of experiment, significantly outperforming it in information content, the time of obtaining result and cost (Woollatt *et al*., 2005).

Despite the high potential, CFD is just the solution of the equations that describe reality in the view but of course they are not For this reason, the difference will always be between the calculated results and reality due to lack of knowledge about the physics of the process, calculation and initial data error. Indeed, many the researchers note that the application of numerical methods in gas dynamics make possible to obtain good quality results but quantitatively markedly different from reality (Denton and Dawes, 1999). In this regard, the models that are planned to apply in the optimization must be carefully validated.

In this study, the goal was to develop a reliable numerical model of the workflow in a three-stage transonic

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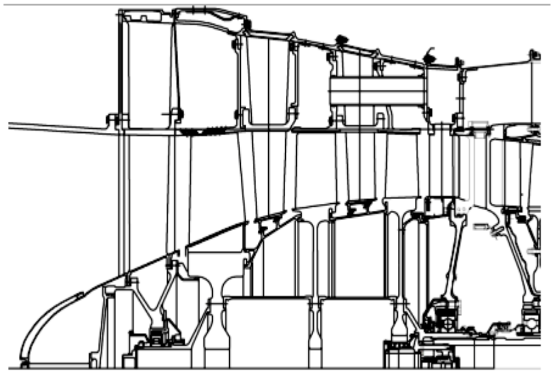

Fig. 1: The investgated compressor

axial compressor of ground power plant (Fig. 1). This compressor has the following parameters: N = 5000 rpm, m = 99 kg sec^{-1}, p_{tr} = 2.25, n = 85%. Its special feature is the permanent working fluid bleed from the first stage for cooling the engine casing at a rate of 2% of the inlet mass flow. This computational model in the future will be used to search via IOSO programs such blade configuration that will provide a noticeable improvement in compressor performance.

DESCRIPTION OF THE COMPUTATIONAL MODEL

Numerical model of the compressor workflow was created in the software package Numeca Auto Grid 5.

Geometric model of the computational domain was based on the design documentation and consisted of domains of inlet guide vanes, rotor blade row and stator blade row (Fig. 2). The geometry of the computational model takes into account the area of the working fluid bleed from the first stage.

The following assumptions were used to create a numerical model of the workflow in the compressor (Popov *et al*., 2014b):

- The flow has the property of cyclic symmetry in each Blade Row (BR). That is the flow is the same in all blade passages within a single BR. Therefore, all the model contained only one blade passage with periodic boundary conditions on the side surfaces
- Calculation was conducted in a stationary statement

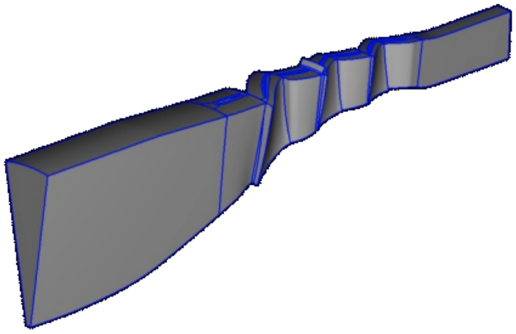

Fig. 2: Geometric model of the Low Pressure Compressor (LPC) computational domain

- Blades geometry accounted for their deformation under the influence of acting loads. Thus, it was considered that the hub is not deformed and the shroud is rotated by some angle γ. In the other study, the rotation angle changing was calculated linearly. The angle γ value was found as a result of the strength calculations
- Ideal gas with the properties of dry air was used as the working fluid
- It was taken into account in the calculation that the viscosity and isobaric heat capacity of the working fluid depend on its temperature
- Turbulence considered isotropic in all directions. For its simulation the Model k-ε (Low Re Yang-Shih) was used
- The heat transfer between the flow passage walls and the flow was not considered due to the rapid speed of the process
- Models take into account the radial gap between the upper blade tip and the stator

The created model was divided into finite elements structural mesh. Its appearance is shown in Fig. 3. Total number of elements is about 2.1 million. On average, one BR had 300,000 elements. The value of the minimum skewness in a three-dimensional mesh was 32 degrees. Average Aspect Ratio value was about 2000.

The value of the total pressure p_t = 101.325 kPa and total temperature T_t = 288.15 K was specified as the boundary conditions at the LPC inlet, the in let flow direction was set axial.

Spatial regions around the Rotor Blades (RB) and Guide Vanes (GV) were allocated in the computational domain. Region of GV was calculated in the stationary reference frame. Region of RB was

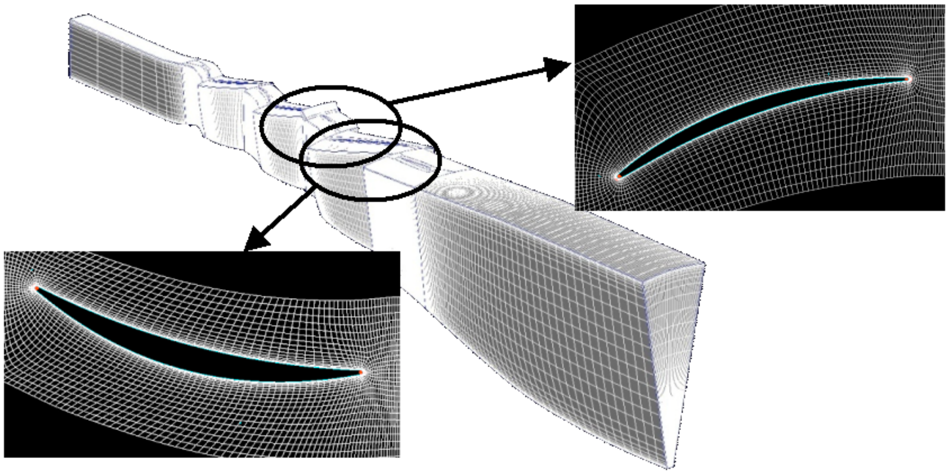

Fig. 3: Finite element mesh of the tested Compressor Numerical Model

calculated in a rotating reference frame, the speed of which coincides with the rotor speed (N = 5000 rpm).

Interface full non matching mixing plane integrated into the software system was used for data transfer between the regions of GV and RB. It averages the flow parameters in the circumferential direction in the upstream domain and passes as a boundary condition to region located downstream.

INVESTIGATION OF THE COMPRESSOR PERFORMANCE

The values of flow parameters, the vectors, the stream line sand values of integral parameters at all points of the calculated area for each of the compressor computational models (Fig. 4 and 5) were the calculation result.

Calculations of the LPC performance at rotor speed of 4200, 4600 and 5000 rpm were conducted to validate the created numerical model. Results of performance calculation were compared with the experimental data provided by the developer of the compressor. Comparison results are shown in Fig. 6.

The graphs show that the calculated performances agree well qualitatively but have a significant quantitative difference. So, the difference reaches 2% (absolute) in the evaluation of efficiency values. The difference is -0.02 (absolute) in the evaluation of pressure ratio.

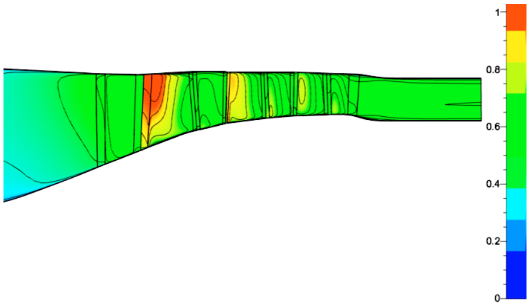

Fig. 4: Mach number field averaged in the circumferential direction for the point of maximum efficiency

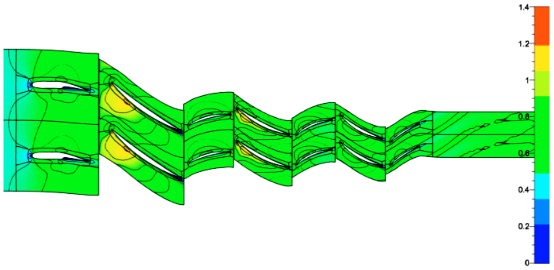

Fig. 5: Mach number field in blade passages at 50% relative height of the flow passage for the point of maximum efficiency

The results of compressor calculation with the working fluid bleed for cooling the GTE casing are also shown in Fig. 6. As can be seen accounting of the bleed led to that the compressor curves at total-to-total pressure ratio performance at modes over than the design shifted to the area of higher pressure ratio values. This is due to the fact that the same power is supplied to the lower working fluid mass in the stages located downstream of the bleed, thereby increasing the specific stage work. This also shows that the efficiency curves are shifted toward higher mass flow and about 0.1 and 0.2% down. The overall efficiency decline is due to the fact that the energy expended in compression is lost along with the discharged air. The maximum efficiency shift is because

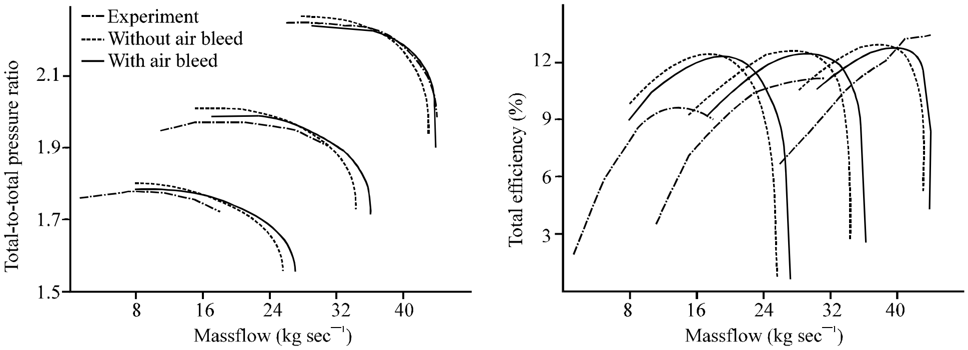

Fig. 6: Comparison of calculated performances without air bleed and with air bleed from the first stage with the experimental data

the optimal in cadence angle on the blades is achieved at high mass flow of working fluid. Comparing the total-to-total pressure ratio and total efficiency performances it should be noted that a greater efficiency decrease at low mass flow also leads to lower compression ratio there, despite the increase in the specific work (Kulagin, 2003). Thus, the obtained results are in good agreement with the existing physical concepts that confirms the adequacy of created computational model.

CONCLUSION

Summing up it can conclude that created computational model of the compressor workflow in good qualitative agreement with experimental data in the whole range of changes of operating condition. The difference in quantity of efficiency and pressure ratio may be up to 2%.

High quality of computational model is supported by the fact that it correctly describes the behavior of the compressor in terms of the working fluid bleed from the first stage of the compressor. Moreover, the created model with the bleed is in better agreement with experiment.

Thus, the model without bleed can be used in the optimization process where the qualitative coincidence is important. The model with bleed should be used for final checking calculation where accuracy is important to quantify the results.

ACKNOWLEDGEMENTS

The research was financially supported by the Ministry of Education and Science of Russia in the framework of basic part of government assignment and in the framework of the implementation of the Program of increasing the competitiveness of SSAU among the world's leading scientific and educational centers for 2013-2020 years.

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