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Experimental and numerical characteristics of the rotor rim of axial fan with different tip clearance values

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In this paper the object of research was the rotor rim of axial fan manufactured by MULTWING with the designation 5ZL. Experimental tests of the fan with the above mentioned rotor rim were carried out with factory tip clearance of 5 mm. Next, the geometry of the rotor rim was mapped and numerical simulations were carried out, as a result of which, displacements of the tip of the rotor blade were determined. Based on the results of mechanical simulations and the Traupel formula the possibility was found to reduce the tip clearance to 1 mm. In the next step, numerical flow simulations were performed for both tip clearance values. Obtained results, in the form of basic characteristics of axial fan, were compared with experimental results.

KEYWORDS: CFD, FEM, tip clearance, characteristics of axial fan

Introduction

A distance, called radial clearance or tip clearance [10] must be maintained between blades of the rotor rim and the cover in each flow machine. This clearance prevents from friction of rotating elements against fixed parts.

The clearance value results, among others, from [9]:

- shaft deflections during vibrations,
- thermal elongation of machine elements,
- shaft deflection due to lateral forces,
- blade mounting clearance,
- deviations in machine components,
- elongation of rotor blades under centrifugal forces.

These factors determine the minimum value of radial clearance [9]. At the same time, it should be remembered that too large tip clearance generates flow losses affecting the performance of flow machines [9].

Value of the tip clearance, ensuring safe operation of rotating elements with minimal flow losses, can be determined, among others, based on the value of the rotor blades elongation. One method of assessing the elongation of rotor blades during operation is numerical simulation. Currently, mechanical deformation analyses based on the finite element method (FEM) allow for obtaining results convergent with experimental results. The results of mechanical analyses in combination with flow analyses make it possible to determine the safe value of tip clearance with simultaneous assessment of its impact on the performance of this type of machinery.

Authors of this paper performed numerical mechanical and flow analyses of a 12-blade model of a MULTIWING axial fan rotor with the designation 5ZL. The outer diameter of the rotor rim is 700 mm, thus it is intended for fans with an inside casing diameter of 710 mm (this gives a tip clearance of 5 mm).

Virtual model of the rotor rim

To perform numerical mechanical and flow analyses, a model of the tested object is necessary. Virtual model of the rotor rim blade was obtained with the use of an optical scan performed with an GOM ATOS 2 optical scanner. In this case, basis of the scanning process is the analysis of the bands projected on the scanned surface. These bands are recorded by the camera and processed with the help of appropriate algorithms of the scanner software in order to obtain a point cloud representing the scanned surface [2]. Fig. 1 shows the geometry of the scanned impeller shortly after importing into Siemens NX 8.5 software and the blade model after mapping its geometry. The scanned geometry contains many surface discontinuities and voids, which makes it impossible to perform discretization for the needs of numerical simulations. Therefore, further operations on the model are necessary to obtain the geometry of adequate quality.

The final effect of CAD modeling was discretized and models for numerical analyses were obtained.

Fig. 1. Geometry of the scanned rotor blade rim and its model after the mapping process

The computer fluid mechanics method used

Numerical simulations of a flow through the rotor rim were carried out in the ANSYS Fluent program, based on the so-called averaged Navier-Stokes equations RANS [4]. In order to solve the system of RANS equations, the appropriate turbulence model should be used. In this case, the realizable $k-\varepsilon$ [1] model was used to determine the characteristics of the rotor rim.

Based on the flow simulations carried out, the following characteristics were obtained:

- total pressure increase (fan compression) as a function of volumetric flow rate – $\Delta p_c = f(Q)$,
- total efficiency as a function of volumetric flow rate – $\eta = f(Q)$,
- power as a function of volumetric flow rate – $P = f(Q)$.

Discretization of the computational area and boundary conditions for flow calculations

For the purposes of simulating the airflow through the rotor rim, its discrete model was created. Triangular elements were used on the surfaces of the calculation area. In the area of the boundary layer, five layers of prismatic elements were used, while in the remaining volume of the calculation area – tetrahedral elements. As a result, the so-called hybrid numeric grid, suitable for complex geometries, consisting of 7,410,327 elements, was achieved.

Numerical flow simulations were carried out using the SRF (single reference frame) model [1], designed for flow analysis of single rotating parts of rotor machines and enabling the definition of so-called periodic boundary conditions. Periodic boundary conditions allow for modeling a flow channel for one blade, while software algorithms recalculate flow parameters taking into account the mutual interference of the blades. As a result, the grid generation time and calculation time are reduced. These types of boundary conditions are typical for the simulation of flow through fan blade rims [6, 7].

Numerical flow simulations were carried out under the following boundary conditions:

- fan inlet – relative pressure 0 Pa,
- fan outlet – variable pressure (throttling),
- rotational speed – 1486 rpm (hub),
- reference pressure – 101,325 Pa.

Analysis of rim blade extension

Numerical calculations of the blade extension of the rotor rim were made in the ANSYS R17.2 program [3, 5]. The analysis was carried out for blade loads caused by mass forces in rotational motion at a rotational speed of $n = 1486$ rpm. The CAD model of the tested blade and method of its loading and restraint in the lock are shown in fig. 2.

Fig. 2. CAD model of a blade stretched by mass forces in rotational motion and fixed in a lock

It was assumed that the tested element was made of aluminum alloy with Young's modulus $E = 7.1 \cdot 10^{10}$ Pa and Poisson's ratio $\nu = 0.33$. As a result of numerical calculations, the maximum value of blade tip displacement in radial direction was obtained, $u = 0.016$ mm. Based on the analysis of blade rim elongation during its operation, it was determined that it is possible to reduce the value of the tip clearance of the tested fan. Based on the Traupel formula [10]:

$$s_r = \frac{0.6 \cdot D_z}{1000} + 0.25 \text{ mm}$$

where: s_r is the tip clearance value, and D_z – external diameter of the fan, a 1 mm tip clearance value was used in the virtual rotor rim model and numerical simulations of the air flow through the fan were carried out to verify the impact of the clearance reduction on the fan performance.

Results of flow simulation through the rotor rim

Fig. 3 shows the characteristics of total pressure increase as a function of volumetric flow rate of the rotor rim. Based on these characteristics, it can be concluded that the compliance of the experimental and numerical results for a rotor rim with an apical clearance of $s_r = 5$ mm is satisfactory. The average relative difference of results in the entire range of volumetric flow rates obtained in the experiment was 10.75%.

The largest difference in results was observed for expenses from about 1.65 to about 3.54 m³/s, and its average relative value was 17%. The smallest difference in characteristics was obtained for the expenditure range from about 3.80 to about 5.17 m³/s, and its average relative value was 4.96%.

Analysis of the characteristics confirmed that the reduction of tip clearance to 1 mm caused an increase in the total pressure with a shift in its maximum value towards lower flow expenditure. The average relative

increase in total pressure in relation to the characteristic for $s_r = 5$ mm was 20.23% in the expenditure range from approximately 2.33 to about 5.69 m³/s. The highest increase in fan compression was obtained for flow rates from about 2.86 to about 4.87 m³/s, and its relative average value was 34.32%.

Fig. 3. Pressure increase characteristics of the total rotor rim of an axial fan, obtained by two test methods

Fig. 4 shows the characteristics of total efficiency as a function of volumetric flow rate of the rotor rim. As it can be seen, the numerically obtained characteristics differ significantly from the experimental characteristics. This was mainly due to the fact that the simulations did not take into account the drive of the rotor rim by an electric motor. According to the standard [8], the efficiency calculated on the basis of experimental results is the ratio of the air stream power to the fan motor power. At the same time, it should be noted that the roughness of surfaces in question was not taken into account during numerical simulations. Relative average difference in numerical efficiency was 29.08%.

The consequence of the tip clearance reduction to 1 mm was an average relative efficiency increase of 8% for expenses from about 2.33 to about 5.69 m³/s, in relation to results of numerical simulations for $s_r = 5$ mm. This increase is due to a decrease in flow losses due to the presence of the tip clearance. It can therefore be concluded that just such a level should be achieved by an increase in the efficiency of the actual rim while reducing the tip clearance.

Fig. 4. Total efficiency characteristics of the axial fan rotor rim, obtained by two test methods

Fig. 5. Fan power characteristics, obtained using two test methods

Fig. 5 shows the power characteristics as a function of the axial fan volumetric flow rate, determined by two test methods. In this case, satisfactory compliance of the experimental and numerical results was obtained. The average relative power difference over the entire range of volumetric flow rates in experimental studies was 4.82%. After reducing the tip clearance to 1 mm, the fan power increased, which is due to the increased blade surface.

Conclusions

The paper presents comparison of basic characteristics of an axial fan. These characteristics were obtained on the basis of experimental and numerical studies. In the case of the characteristics of the total pressure increase and power as a function of the volumetric flow rate, satisfactory compliance of the experimental and numerical results was obtained.

Numerical mechanical analyses confirmed the possibility of reducing the tip clearance from 5 mm to 1 mm (due to the slight elongation of the rotor blade during its operation).

Results for two values of the tip clearance were discussed and its significant effect on the performance of axial fans was demonstrated. After the tip clearance was reduced, the increase in total pressure and efficiency increased.

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