Представлено порівняльну оцінку напірних характеристик і рівня втрат повного тиску дозвукових робочих коліс осьового компресора з однорядними і еквівалентними дворядними лопатковими вінцями. Отримано аероакустичні характеристики дозвукових дворядних робочих коліс. Рівень звукового тиску дозвукових дворядних робочих коліс нижче, ніж рівень звукового тиску однорядних робочих коліс на 0,5...3,2 дБ при густоті лопаткових вінців на середньому радіусі 1...2,5

Ключові слова: аероакустичні характеристики, дворядне робоче колесо, напірність, втрати повного тиску

Представлена сравнительная оценка напорных характеристик и уровня потерь полного давления дозвуковых рабочих колес осевого компрессора с однорядными и эквивалентными двухрядными лопаточными венцами. Получены аэроакустические характеристики дозвуковых двухрядных рабочих колес. Уровень звукового давления дозвуковых двухрядных рабочих колес ниже, чем уровень звукового давления однорядных рабочих колес на 0,5...3,2 дБ при густоте лопаточных венцов на среднем радиусе 1...2,5

Ключевые слова: аэроакустические характеристики, двухрядное рабочее колесо, напорность, потери полного давления

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RESEARCH INTO AERO ACOUSTIC CHARACTERISTICS OF TWO-ROW IMPELLERS OF THE AXIAL COMPRESSOR

E. Doroshenko
PhD*
E-mail: Kiki_ua@ukr.net

Yu. Tereshchenko
Doctor of Technical Sciences, Professor*
E-mail: Terj@nau.edu.ua

I. Lastivka
Doctor of Technical Sciences, Professor,
Head of Department**
E-mail: lola@nau.edu.ua

I. Kudzinovs'ka
PhD, Associate Professor**
E-mail: kudzinovskaya@ukr.net

*Department of aviation engine***
Department of higher mathematics*
***National Aviation University
Kosmonavta Komarova ave., 1, Kyiv, Ukraine, 03058

1. Introduction

Axial compressors are widely used in gas turbine engines. Modern competitive engines must have high-pressure and low-noise compressors with a minimal level of losses (high performance efficiency). These are, however, controversial requirements. When designing compressor blade crowns, engineers have to reach a compromise.

An increase in the degree of pressure rise is ensured by increasing rotation frequency of the rotor, enhancing the aerodynamic loading of stages, as well as by increasing the number of stages. However, increasing the number of stages leads to the enlarged weight-dimension characteristics of the engine. Blade crowns that enable flow control possess improved aerodynamic characteristics. A promising technique to enhance aerodynamic loading of stages is to use the two-row blade crowns [1].

Elements of the axial compressor are one of the main sources of acoustic emission of the engine. To reduce discrete components of the noise, sound-absorbing structures are applied that lead to an increase in the mass characteristics of the engine. A specialized profiling of compressor blades is also employed. However, the use of existing methods of noise reduction is not efficient enough for the engines of advanced aircraft. Thus, we consider it important to undertake the research aimed at solving the task on the improvement of aero acoustic characteristics of compressors.

2. Literature review and problem statement

In paper [2], authors report results of experimental and numerical study into current in the two-row blade crowns. They analyzed influence of geometric parameters of the slit channel on the characteristics of a blade crown. Based on a comparison of the results obtained, recommendations are proposed for the selection of parameters of the slit channel. Article [3] reports results concerning the influence of geometric parameters of a two-row blade crown on its aerodynamic characteristics. In paper [4], authors obtained characteristics for the stage of an axial compressor with a swivel two-row guiding device. Research results indicate that the use of a two-row blade crown makes it possible to increase pressure in the stage.

Qualitative assessment of current in the elementary two-row impeller is presented in [5]. Based on the obtained results of a 2D simulation of current, the authors analyzed a pressure field distribution in the intrablade channel. However, the model applied in the work does not take into consideration the peculiarities of a three-dimensional current. In paper [6], authors proposed a technique for spatial design of the compressor stage with two-row blade crowns. They obtained characteristics of the stage with a single-row impeller and a guiding device, and a two-row impeller with a guiding device. Results of the study indicate that the degree of pressure increase in the stages with two-row blade crowns is higher than that in stages with single-row blade crowns. However, the level of losses in a stage slightly increases. Paper [7] reports results of study into the level of losses of full pressure in a two-row blade crown. It is shown that the gas-dynamic effect on current makes it possible to improve the aerodynamic characteristics of blade crowns. Thus, research results reported in papers [2–7] show that the use of the two-row blade crows makes it possible to increase the pressure of compressor.

Improvement of the aerodynamic characteristics of stages of an axial compressor by using the two-row blade crowns leads to a change of the current in the intrablade channels. This, in turn, affects acoustic characteristics of the axial compressor. When designing modern compressors, a comprehensive approach is required to determine the aero-acoustic characteristics of axial compressor.

Calculation of acoustic characteristics of the compressor is given in paper [8]. The authors investigated acoustic sources in an axial compressor. However, the aerodynamic characteristics were not addressed in the paper. Article [9] investigated aero acoustic characteristics of a centrifugal compressor.

However, there are no data at present concerning the calculation of acoustic characteristics of the two-row impellers of an axial compressor. Therefore, it is a promising task to study aero acoustic characteristics of the two-row impellers. Moreover, there are no data on the impact of mesh density of a two-row blade crown on the aero-acoustic characteristics of two-row impellers.

3. The aim and objectives of the study

The aim of present work is to study aero-acoustic characteristics of the impellers with a two-row blade crown. This would make it possible to obtain scientific results in order to determine parameters of the two-row blade crown, which could solve the task of improving the aero acoustic characteristics of axial compressors.

To accomplish the aim, the following tasks have been set:

– to perform estimation study and to conduct a comparative estimation of pressure characteristics of subsonic impellers of the axial compressor with a single-row and an equivalent two-row blade crowns;

– to perform estimation study and to conduct a comparative estimation of the level of losses in single-row and equivalent two-row blade crowns;

– to perform estimation study into acoustic characteristics of subsonic impellers of the axial compressor with a single-row and an equivalent two-row blade crowns.

4. Method for studying the aero acoustic characteristics of impellers of the axial compressor

In this work, by applying a method of numerical experiment, we calculated parameters of the current in impellers of the axial compressor. Six impellers of the axial compressor were examined. The estimated area of each of the impeller consisted of a blade and an intrablade channel. We constructed unstructured adaptive fine computational grids, which had about 1...1.2 million of cells. A system of the Navier-Stokes equations was closed by the model of turbulent viscosity SST.

Acoustic characteristics were calculated using the Fox Williams-Hawkins equation [10].

The accuracy of the results obtained was ensured by conducting test tasks [11, 12].

5. Results of research into aero acoustic characteristics of two-row impellers of the axial compressor

In this work, we examined 6 impellers (IM) with a different density of the grid at average radius: 3 single-row and 3 two-row (two-row blade crowns are designed to be equivalent to the respective single-row blade crowns). Two-row blade crowns were designed taking into consideration recommendations received in paper [13].

The first pair of impellers consisted of 17 blades with a thickness of the grid at average radius $b/t=1$. The second pair of impellers had 30 blades each and a density of the grid at average radius of $b/t=1.7$. The third pair of impellers consisted of 44 blades with a density of the grid at average radius of $b/t=2.5$. Peripheral radius was equal to 0.2 m, bushing radius – 0.08 m.

Fig. 1 shows 3D models of the investigated impellers of an axial compressor.

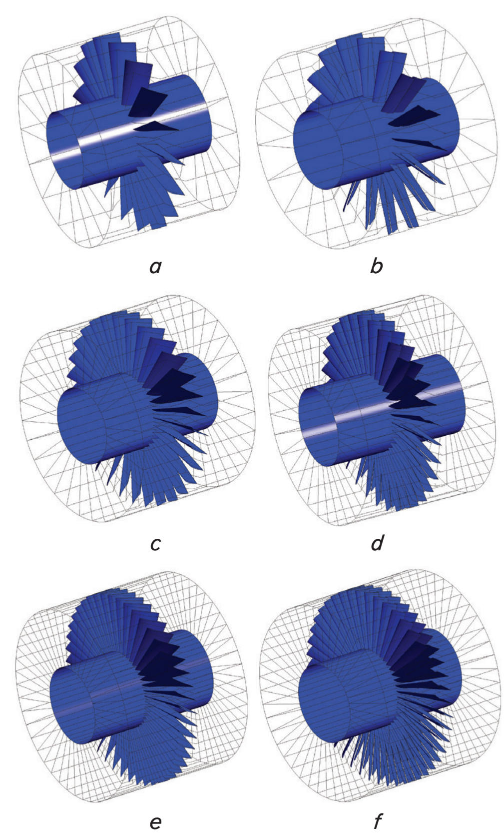

Fig. 1. 3D models of impellers of an axial compressor: *a* — single-row impeller with 17 blades; *b* — two-row impeller with 17 blades; *c* — single-row impeller with 30 blades; *d* — two-row impeller with 30 blades; *e* — single-row impeller with 44 blades; *f* — two-row impeller with 44 blades

Simulation of current in the impeller was held for rotation frequency $n=100\,\%$. In this case, circular speed on the peripheral radius was $u=251.2$ m/s. We calculated each impeller for the values of speed coefficient at input of $\lambda=0.294...0.588$.

At the first stage of research, we calculated pressure characteristics for the examined impellers.

The result of computer simulation of current in the impellers is the dependences obtained for the degree of increase in pressure π on the gas-dynamic function $q(\lambda)$, which are shown in Fig. 2.

The degree of pressure rise was derived from formula:

$$\pi=\frac{p_2^*}{p_1^*},$$

where p_1^* is the average value of total pressure at the inlet to the impeller, p_2^* is the average value of total pressure at the outlet from the impeller. We averaged parameters of the flow in line with the principle of medium-mass averaging over the radius.

Gas-dynamic function $q(\lambda_c)$ was defined by ratio:

$$q(\lambda_c)=\lambda_c\left(1-\frac{k-1}{k+1}\lambda_c^2\right)^{\frac{1}{k-1}}\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}},$$

where $\lambda_c=c/a$ is the coefficient of speed, c is the axial flow speed at the inlet, a is the critical speed of sound, k is the adiabatic index.

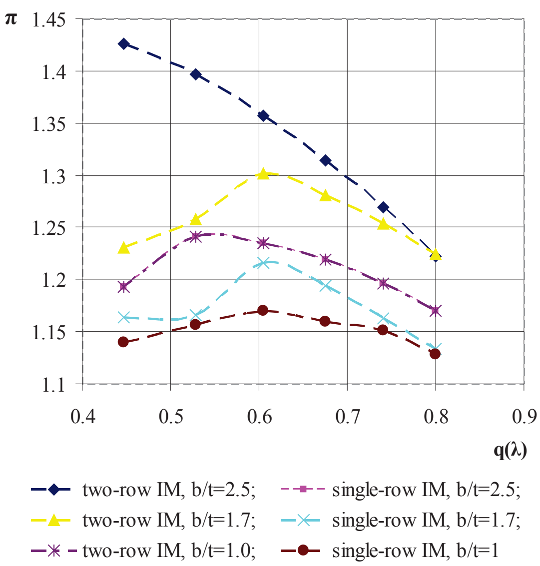

Fig. 2. Characteristic of single-row and equivalent two-row impellers at a different density of the grid at average radius ($n=100$ %)

Analysis of diagrams in Fig. 2 shows that two-row impellers over the entire range of the examined numbers for the coefficient of speed at the inlet have a pressure that is higher than that of impellers with equivalent single-row blade crowns. In the single-row and two-row impellers, an increase in the density of grid leads to a growth in pressure of impeller. Maximum values of the degree of pressure rise in single-row impellers increase from 1.17 to 1.24 when increasing the density of the grid on average radius from 1 to 2.5.

Over the entire range of values of the gas-dynamic function, a two-row impeller, at the density of the grid on average radius $b/t=1$ has a higher pressure than a single-row impeller. Under the flow-around mode, at $q(\lambda)=0.6$, which corresponds to the maximum pressure, a degree of pressure rise π increases from 1.17 to 1.235 (by 5.5 %).

An equivalent two-row impeller at the density of the grid at average radius $b/t=1.7$ over a range of values $q(\lambda)=0.45...0.8$ has a degree of pressure rise of $\pi=1.23...1.3$. Compared to a single-row blade crown, the degree of pressure rise π increases from 1.22 to 1.3 (by 6.5 %).

An equivalent two-row impeller at the density of the grid at average radius $b/t=2.5$ over the range of values $q(\lambda)=0.45...0.8$ has a degree of pressure rise of $\pi=1.23...1.43$. At a value of the gas-dynamic function of $q(\lambda)=0.55$, a single-row impeller has the maximum degree of pressure rise $\pi=1.24$. In the equivalent two-row impeller, the degree of pressure rise π increases to 1.37, which is 10.5 % higher than that in the single-row impeller.

As shown by results obtained by other authors [2–6], the use of two-row blade crowns leads to an increase in the level of losses of full pressure. However, the problem on determining the influence of density of the grid of two-row impellers on the level of losses of full pressure remains unresolved.

Thus, the next step of present work was to examine the influence of density of the grid over average radius of single-row and equivalent two-row impellers on the coefficient of performance efficiency of the impeller.

Coefficient of performance efficiency of the impeller was derived from formula:

$$\eta=1-\xi.$$

Coefficient of losses of full pressure in the impeller ξ was defined from formula:

$$\xi=\frac{p_1'^*-p_2'^*}{\frac{\rho_o w_m^2}{2}},$$

where $p_1'^*$ and $p_2'^*$ are the mean values of total pressure in the relative motion at inlet and outlet of the impeller, respectively; w_m is the mean relative flow rate in the impeller; ρ_o is the mean value of density.

Fig. 3 shows dependences of coefficient of performance efficiency η on gas-dynamic function $q(\lambda)$.

Analysis of diagrams in Fig. 3 shows that the level of losses depends on the speed coefficient at the inlet and the density of the grid. The biggest losses occur at low speeds at the inlet at values of gas-dynamic function $q(\lambda)=0.45...0.5$. In single-row impellers and equivalent two-row of impellers, the level of losses grows when the value of density of the grid over average radius increases.

In the blade crowns with a thickness of the grid over average radius of $b/t=1$, the level of losses of full pressure changes insignificantly when replacing a single-row impeller with the equivalent two-row impeller. In addition, there is a decrease in the level of losses by almost two times (from $\xi=0.067$ to $\xi=0.036$) under the mode of maximum degree of pressure rise at $q(\lambda)=0.6$. A reduction in the losses of full pressure is also observed in the range of values of gas-dynamic function $q(\lambda)=0.45...0.6$. The level of losses of full pressure in the two-row impeller remains approximately constant at $q(\lambda)=0.6...0.8$. The level of losses of full pressure in the single-row impeller decreases from $\xi=0.067$ to $\xi=0.018$ while increasing the speed at the inlet, which corresponds to the values of gas-dynamic function $q(\lambda)=0.6...0.8$. At $q(\lambda)=0.675$, the level of losses in the single-row impeller and equivalent two-row impeller is the same.

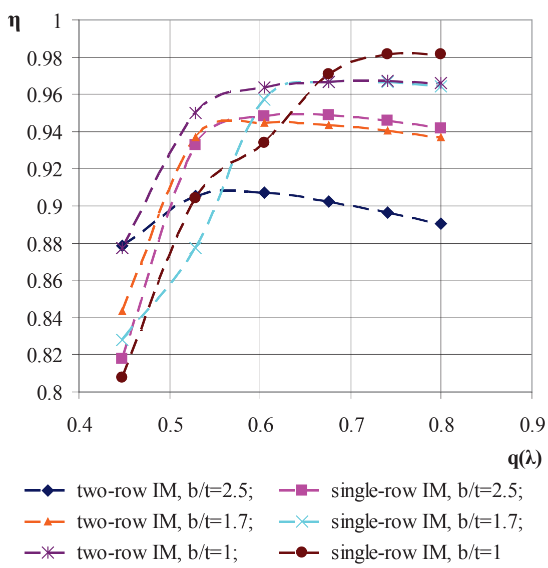

Fig. 3. Dependence of coefficient of performance efficiency η on gas-dynamic function $q(\lambda)$ for single-row and equivalent two-row impellers at a different density of the grid over average radius ($n=100$ %)

The level of losses of full pressure in the two-row impeller with a thickness over average radius of $b/t=1.7$ at $q(\lambda)=0.45...0.59$ is lower than that in the single-row impeller with an equivalent blade crow. At $q(\lambda)=0.53...0.8$, coefficient of losses of full pressure in the two-row impeller is $\xi=0.061...0.056$. In this case, the minimum value of $\xi=0.056$ corresponds to the maximum value of the degree of pressure rise in the single-row impeller. Over the range of values of gas-dynamic function $q(\lambda)=0.6...0.8$, coefficient of losses of full pressure in the two-row impeller increases by 0.013...0.03 (or by 1.3...3 %).

The level of losses in the two-row impeller with a density of the grid over average radius of $b/t=2.5$ at $q(\lambda)=0.5...0.8$ increases in comparison with the single-row impeller with an equivalent blade crown. For the flow-around mode, at $q(\lambda)=0.45$, the losses of full pressure in the two-row impeller are 0.06 less (by 6 %). At values $q(\lambda)=0.52...0.8$, coefficient of losses increases by 0.027...0.05 (by 2.7...5 %).

At the next stage of present study, we calculated the levels of acoustic pressure for the single-row and equivalent two-row impellers. Fig. 4 shows dependence of change in the levels of acoustic pressure for impeller ΔL on gas-dynamic function $q(\lambda)$.

The level of acoustic pressure in the two-row impellers is lower than that of the single-row impellers. At a density of the grid over average radius of $b/t=1...2.5$ in the range of values of gas-dynamic function $q(\lambda)=0.45...0.8$, the level of acoustic pressure decreases by 0.5...3.2 dB.

The density of the grid over average radius affects a change in the level of acoustic pressure in the two-row impeller. Under operational modes over a range of $q(\lambda)=0.67...0.8$, an increase in the density of the grid leads to an increase in the level of acoustic pressure. For example, at $q(\lambda)=0.7$ for the impeller with $b/t=1$, a change in the level of acoustic pressure of a given impeller is $\Delta L=2.8$; for the impeller with $b/t=1.7$ – $\Delta L=1.95$; for the impeller with $b/t=2.5$ – $\Delta L=1.1$. Under the mode on the left branch of a pressure line that corresponds to $q(\lambda)=0.45$, one observes a reverse pattern – the two-row impeller with $b/t=2.5$ demonstrates the greatest noise reduction – up to 3 dB. Over the range of $q(\lambda)=0.5...0.65$, the level of acoustic pressure decreases by 3.2...1.5 dB.

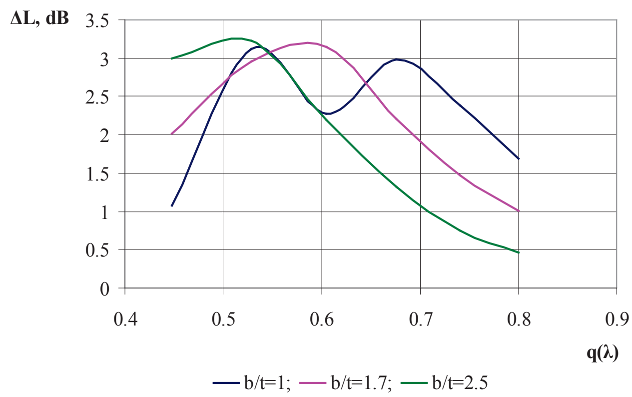

Fig. 4. Dependence of change in the level of acoustic pressure for impeller ΔL on gas-dynamic function $q(\lambda)$

6. Discussion of results of examining the aero acoustic characteristics of two-row impellers of the axial compressor

We have obtained results of examining the aero acoustic characteristics of subsonic two-row impellers of the axial compressor. The research results showed that the use of the two-row blade crowns in the impeller makes it possible to reduce the level of acoustic pressure in the range of operation $q(\lambda)=0.45...0.5$ by 0.8 dB to 3.2 dB. When calculating the aero acoustic characteristics of impellers of the axial compressor, we did not take into consideration the effects of acoustic interaction between elements of the rotor and the stator.

The pressure characteristics of impellers obtained at $q(\lambda)=0.45...0.8$ show that using the two-row impellers can improve pressure of the stage over the entire range of operation. The density of the grid over average radius of the blade crown affects the pressure. Under modes that correspond to the maximum pressure, the degree of pressure rise for the impeller with $b/t=1...1.7$ increases by 5.5...6.5 %; at $b/t=2.5$, the degree of pressure rise increases by 10.5 %.

Comparison of the efficiency of single-row and equivalent two-row impellers showed that the coefficient of performance efficiency for the two-row impellers is lower than that for the single-row impellers. An increase in the density of the grid leads to an increase in the level of losses. The level of losses for the two-row impeller with a density of the grid of $b/t=2.5$ is approximately 2.5 times higher than the level of losses of the two-row impeller with a thickness of the grid of $b/t=1$. Under the flow-around modes that correspond to the maximum values of pressure for the equivalent single-row impellers, for the two-row impellers with a density of $b/t=1...2.5$, the coefficient of losses of full pressure varies in the range of $\xi=0.038...0.095$, respectively.

Thus, the replacement of a single-row blade crown in the impeller of a stage of the axial compressor with the equivalent two-row can ensure enhancement of the aerodynamic loading of the stage and reduce acoustic emission of the compressor.

In this study, when modeling the current, we disregarded circular irregularity at the inlet, which affects the level of losses in the impeller, pressure, and acoustic emission. To assess the influence of circular irregularity on aero acoustic characteristics of a stage of the axial compressor, it is necessary to conduct a comprehensive experimental and numerical study of current in blade crowns that implies consideration of many factors. We regard the limitations of the conducted research to be the fact that we did not take into consideration the patterns of current in the inlet channel, and we ignored the impact of sound-absorbing structures on acoustic radiation.

The task for further theoretical and experimental research is to determine the aero acoustic interaction between elements of the rotor and the stator of the axial compressor.

7. Conclusions

1. We have obtained results of research into the influence of density of the grid over average radius of the two-row impeller on pressure. Over a range of operational modes that correspond to the values of gas-dynamic function $q(\lambda)=0.45...0.8$, the degree of pressure increase for the equivalent two-row impellers is higher than that for the single-row impellers. Under the flow-around modes that correspond to the maximum pressure for a single-row impeller, for the blade crowns with $b/t=1...2.5$, the degree of pressure rise increases by 10.5 %.

2. The research results showed that the two-row impellers demonstrate the higher level of losses compared with the level of losses in the equivalent single-row impellers. Under the flow-around modes that correspond to the maximum values of pressure for the equivalent single-row impellers, for the two-row impellers with a density of $b/t=1...2.5$, the coefficient of losses of full pressure varies in the range of $\xi=0.038...0.095$, respectively.

3. We have examined the aero acoustic characteristics of subsonic two-row impellers. The level of acoustic pressure of the subsonic two-row impellers is lower than the level of acoustic pressure of the single-row impellers by 0.5...3.2 dB at a density of blade crowns over average radius of $b/t=1...2.5$.

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