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***Представлено результати чисельного моделювання течії в осьовому вентиляторі. Проведено тестовий розрахунок рівня звукової потужності вентилятора. Результати чисельного моделювання показали гарну збіжність. Визначено рівень звукової потужності для перших двох гармонік геометрично еквівалентного дворядного вентилятора. Результати розрахунків показали, що застосування дворядного вентилятора дає можливість зменшити загальний рівень звукової потужності на 6.8...7.4 дБ***

***Ключові слова: моделювання течії, рівень звукової потужності, дворядний вентилятор, тональний шум***

***Представлены результаты численного моделирования течения в осевом вентиляторе. Проведен тестовый расчет уровня звуковой мощности вентилятора. Результаты численного моделирования показали хорошую сходимость. Определен уровень звуковой мощности для первых двух гармоник геометрически эквивалентного вентилятора. Результаты расчетов показали, что использование двухрядного вентилятора дает возможность уменьшить общий уровень звуковой мощности на 6.8...7.4 дБ***

***Ключевые слова: моделирование течения, уровень звуковой мощности, двухрядный вентилятор, тональный шум***

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# CALCULATION OF SOUND POWER LEVEL OF TANDEM AXIAL FAN

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## 1. Introduction

The main trends in the development of aero-engine manufacturing provide for the solution of the main problem – increasing the fuel efficiency of gas turbine engines (GTE). The solution to this problem is ensured by:

– creation of new configurations of engines;
– increase in efficiency of all GTE elements;

– improvement of mixing and combustion in combustion chambers;

– implementation of thermodynamic cycles with high values of the workflow parameters.

The main solutions to these problems are based on:

– aerodynamic improvement of elements in the engine air-gas channel;

– use of new methods of influence on processes in GTE elements;

– use of control systems that provide optimum coordination of the geometric parameters of the engine elements with kinematic and thermodynamic parameters of the flow inside the engine.

A characteristic feature of recent years is the trend towards increasing the requirements of the International Civil Aviation Organization (ICAO) to the noise level of aircrafts. The use of sound-absorbing coatings is an effective means of acoustic emission reduction. But modern coatings adversely affect the weight and aerodynamic characteristics of aircrafts. Therefore, the problem of noise reduction in a source is particularly relevant. The gas turbine engine is the most powerful source of aircraft noise.

In modern aircraft engines, the most significant contribution to the total noise level during take-off and landing is made by the fan noise [1]. The noise of fans and compressors is due to several sources of aerodynamic origin, namely:

– intersection of the flow non-uniformity by impeller blades;

– interaction of non-uniform flows with stator blades;

– vortex shedding from blades.

Rotation of blades even in a uniform flow causes velocity fluctuations in front and behind the impeller, which leads to rotational noise. Rotational noise is amplified at supersonic relative flow rates, when a system of shock waves is formed in front of blades [1].

Flow non-uniformity in the compressor can be caused by various reasons and have different characters. Radial and circular non-uniformity, as well as flow fluctuations, are created in the input device. The compressor elements – previous and subsequent blade rows – also generate significant non-uniformity. Considerable non-uniformity can be created as a result of the flow past elements and structures that are in the air-gas channels of the air-gas path of the engine – racks, pylons, receivers, various devices, and so on.

The methods of fan noise reduction can be divided into active and passive. Active methods influence the process of noise generation in the fan, that is, in the source. Passive methods involve a decrease in the acoustic power of noise on the way of its propagation in the engine air-gas channel from the source to the nozzle or air intake outlet. Among active methods, special attention should be paid to the use of tandem blade rows. The use of tandem blade rows with optimum geometric parameters allows reducing the loss level and non-uniformity of the flow caused by aerodynamic trails. Therefore, a comprehensive research of the flow in the tandem fan is an urgent task in solving the problem of increasing the acoustic perfection of gas-turbine engines.

## 2. Literature review and problem statement

In the paper [2], noise sources in the near field of modern aircrafts have been analyzed. A critical review of various methods of calculating acoustic characteristics in the near field has been made. It has been shown that in engines with the high by-pass ratio, the greatest contribution to the total noise level during take-off is made by the fan.

Many theoretical and experimental works deal with the understanding of the noise formation mechanism in turbomachine elements. In [3], the obtained results allow understanding the nature of acoustic radiation sources in the flow past an isolated fixed profile. Experiments were carried out in the Mach number range of $M$=0...0.3. The paper [4] deals with the study of noise generation in the turbulent flow past the blade row. It has been shown that the acoustic radiation level increases with increasing flow turbulence level. As turbomachines rotate, there are additional acoustic sources. In [5], various factors affecting the noise level in the axial fan have been investigated. Generation of tonal components of acoustic radiation of the axial fan at low subsonic speeds has been analyzed based on experimental data. In [6], the phenomenon of non-harmonic acoustic resonance has been considered. The results on noise generation of the four-stage axial compressor at high subsonic flow rates have been obtained. Empirical relationships to improve the calculation of acoustic characteristics taking into account non-harmonic acoustic resonance have been proposed. In [7], the results of the computational studies of acoustic characteristics of the compressor, taking into account the effect of interaction between the rotor and the stator have been presented. Also, the authors have found the dependence of the tonal noise on the shape of the leading edge of the impeller blade.

As shown in [2–7], the mechanism of noise formation in turbomachines is rather complex. Its components change in different operating conditions, gas-dynamic interaction of the rotor-stator system, turbulence and many other factors.

Based on the results of research on the generation of acoustic radiation, methods for reducing the noise of blade machines are developed. In [8–10], it has been shown that radial overflows affect acoustic characteristics of the fan. The use of special plates in the peripheral part of the compressor can reduce the acoustic emission of the fan [8–10]. In [8], modifications of specially profiled plates in the radial gap have been considered. The influence of height, shape, density of plates on acoustic characteristics has been investigated. It has been proven that at optimum parameters of plates, the noise level of the fan decreases. In [9], it has been shown that when installing plates in the radial gap, as well as changing the shape of the compressor blades, acoustic emission decreases. In addition, re-profiling of blades has improved aerodynamic characteristics. The paper [10] deals with the study of acoustic characteristics in the fan at low subsonic speeds. It has been shown that the use of a set of plates in the peripheral part of the fan reduces the noise level in the near and far fields.

The results of [8 –10] show that acoustic emission in the near and far fields can be reduced by influencing the vortex formation in the radial gap. But the use of plates will complicate the design and may worsen the compressor characteristics in the designed operation mode.

Aerodynamic and acoustic characteristics of blade machines are inextricably linked. One of the effective methods for extending the range of attached flow past the compressor is the use of tandem blade rows. Problems related to the acoustic characteristics of tandem blade rows remain unresolved. Thus, research aimed at solving the problem of noise reduction in the fan is promising.

## 3. The aim and objectives of the study

The aim of the paper is to evaluate the efficiency of using the tandem blade row for reducing the axial fan noise.

To achieve the aim of the research, the following objectives were set:

– to perform a test calculation of acoustic characteristics of the fan;

– to perform a computational study of acoustic characteristics of the stages of axial fans with geometrically equivalent single and tandem blade rows.

## 4. Method of research of acoustic characteristics of the axial fan

The research was performed using the numerical experiment. The parameters of the flow in the fan were calculated by solving the non-stationary system of Navier-Stokes equations. The equations were closed by the SST turbulent viscosity model. A 3D model of the axial fan was constructed. An unstructured adaptive grid consisting of 800 thousand cells was used for the calculation. In accordance with the periodicity condition, the estimated range of the blade row consisted of a single blade and an inter-blade channel.

The sound power level was calculated by the formula [1]

$$L=10\lg W/W_0, \quad (1)$$

where $W$ is the sound power, $W_0=10^{-12}$ W is the magnitude of the sound power corresponding to the sound energy flow with an intensity of $I_0=10^{-12}$ W/m$^2$ through an area of 1 m$^2$.

The reliability of the results was provided by conducting a test problem and confirmed by comparing the data of numerical and physical experiments.

## 5. Results of the research of acoustic characteristics of the tandem axial fan

At the first stage of the research, the acoustic characteristics of the single fan were calculated. The obtained results were compared with the results of the physical experiment [11]. The studied fan consisted of one blade row with 16 blades. The outer radius R is 350 mm.

Fig. 1 shows the 3D model of the axial fan. Key parameters of the fan are presented in Table 1: $\overline{r}$ – relative radius; Θ° – blade angle (the angle between the chord and the front of the grid); $\overline{b}=b/R$ – relative chord; $t/b$ – grid density.

Table 1

Key parameters of the fan

| $\overline{r}$ | Θ° | $\overline{b}=b/R$ | $t/b$ |
|---|---|---|---|
| 0.62 | 53° | 0.302 | 1.24 |
| 0.825 | 35° | 0.302 | 0.94 |
| 0.97 | 25°45’ | 0.302 | 0.793 |

The low-frequency maximum of the one-third octave-band spectrum corresponds to broadband emission with a continuous frequency spectrum [1]. This is evidenced by the joint consideration of the one-third octave-band and narrow-band radiation spectra of the axial fan. High-frequency maxima of the one-third octave-band spectrum represent a combination of the continuous radiation frequency and individual tonal components. The tonal components correspond to the fan engine radiation on the first and second harmonics of the frequency of the impeller blades. Therefore, the sound power level was calculated for the first two harmonics. The calculation of the fan parameters was made for the rotational speed of $n$=900 rpm.

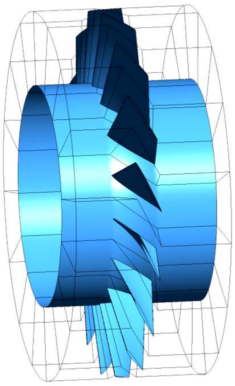

Fig. 1. 3D model of the single axial fan

Fig. 2 shows the results of the calculation.

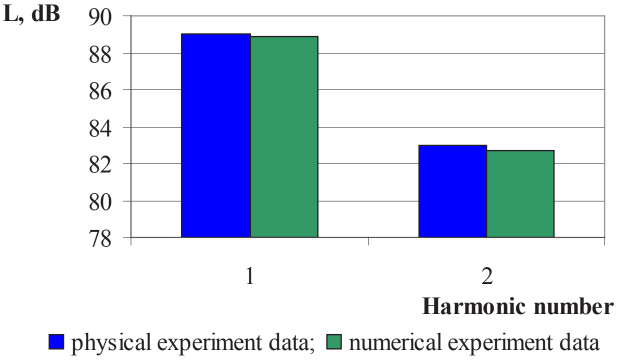

Fig. 2. Sound power level of the axial fan for the first two harmonics

The divergence between the results of the physical [11] and numerical experiments on the sound power level for the first harmonic is 0.08 %, for the second harmonic – 0.35 %.

The fan noise spectrum consists of two main components: discrete and broadband.

The total acoustic radiation of the fan is divided into rotation noise and vortex noise.

The discrete component is characterized by rotation noise. Rotation noise includes noise from an aerodynamic load and displacement noise.

Noise from the aerodynamic load is due to the force impact of the blades on the medium.

Displacement noise is associated with periodic displacement of the medium by the fan blades. However, noise generation by this mechanism is more typical for propellers, whose blades have a large thickness. Fans have rather thin blades. Therefore, for fans, the rotation noise is mainly associated with the force impact on the medium.

The broadband component of the total acoustic radiation is characterized by vortex noise. Similar to discrete, this noise is associated with fluctuations of the aerodynamic forces acting on fan blades. But the fluctuations that cause broadband noise are random, rather than periodic. There are three main reasons for random fluctuations:

1. Turbulence in the oncoming flow. Turbulent flow around blades leads to a chaotic change in the forces acting on the blades. This, in turn, generates broadband noise.

2. Vortex shedding from the trailing edge of the blades. As the vortex sheds, there is an instant change in circulation and, consequently, the force acting on the blade.

3. The presence of a boundary layer on the blade surface. The local forces occurring in such a layer are chaotic in nature and can be considered as acoustic sources.

Thus, by influencing the fan noise excitation factors, it is possible to change the values of the discrete and broadband components of acoustic radiation. By changing the parameters of the boundary layer using passive and active control methods, it is possible to improve the compressor aerodynamics. One of the promising methods for improving aerodynamic characteristics is the use of tandem blades.

At the second stage, the research on acoustic characteristics of the axial fan with the geometrically equivalent tandem blade row was performed.

Taking into account recommendations on the chord ratio [12], a 3D model of the axial fan with the tandem blade row was constructed (Fig. 3).

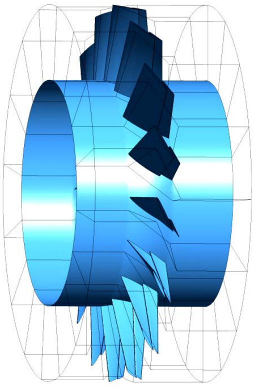

Fig. 3. 3D model of the axial fan with the tandem blade row

Estimation of the acoustic efficiency of the geometrically equivalent tandem fan was performed at a rotation frequency of $n$=900 rpm.

The results of the calculation of the sound power level for the first two harmonics are shown in Fig. 4.

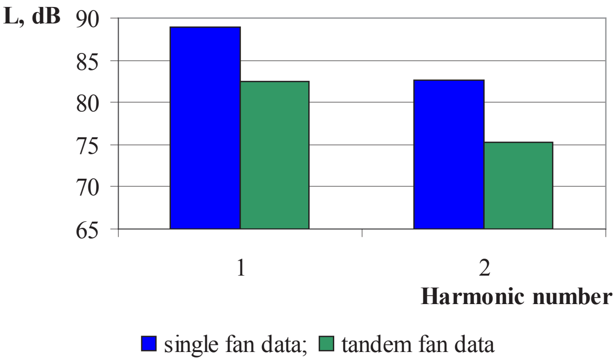

Fig. 4. Sound power level for the first two harmonics of the output single fan and tandem fan

The calculation results showed that the decrease in the sound power level of the tandem fan by more than 7 dB is provided for the first and second harmonics.

Fig. 5 shows a change in the total sound power level for fans with geometrically equivalent single and tandem blades. The calculations were made in the rotation frequency range of $n$=900...1,500 rpm. The total sound power level was calculated by the logarithmic summation of the power of acoustic radiation of the first six harmonics.

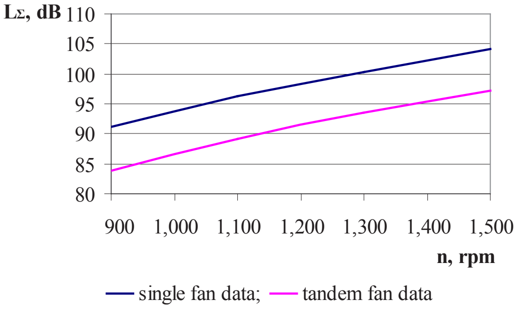

Fig. 5. Dependence of the total sound power level on rotation frequency

The use of the fan with the geometrically equivalent tandem blade row can provide a reduction in the total sound power level by 6.9...7.4 dB at a rotation frequency of $n$=900...1,500 rpm.

## 6. Discussion of the results of the research on acoustic characteristics of the tandem axial fan

The results on acoustic characteristics of the fan with the tandem blade row are obtained. The acoustic power level is estimated for subsonic fans in the near field without taking into account the phenomena of interference and diffraction of acoustic waves.

Comparison of the results of solving the test problem with the data of physical research [11] showed that the divergence between the results of numerical simulation and physical experiment is 0.08...0.35 %.

The computational study of acoustic emission of two fans with equivalents geometric parameters of single and tandem blade rows was performed. The results of the research show that changes in the blade row can lead to a decrease in the sound power level of the fan.

When increasing the frequency of rotation, the sound power level increases. When changing the frequency of rotation from $n$=900 rpm to 1,500 rpm, the total sound power level of the single fan increases from 91.14 dB to 104.19 dB. The axial fan with the geometrically equivalent tandem blade row in the rotation frequency range of $n$=900...1,500 rpm has the total sound power level of 83.77...97.26 dB. That is, under the same operating conditions, the tandem fan has the best acoustic characteristics. First of all, this is due to a change of the flow in the blade row.

Fig. 6, 7 show the velocity fields for single and tandem blade rows of the fan.

As can be seen from Fig. 6, 7, under the same operating conditions, the velocity in the flow core in the tandem fan is lower than in the single fan. In the tandem fan, there was a change in the velocity field along the radius and in a circular direction. In the circular direction, the reduced velocity zone has decreased by about 30 %. Along the radius, the size of the zone has practically not changed. However, the flow velocity in the reduced velocity zone has decreased.

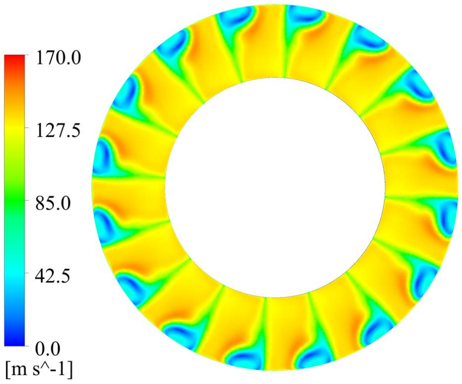

Fig. 6. Velocity field for the single fan

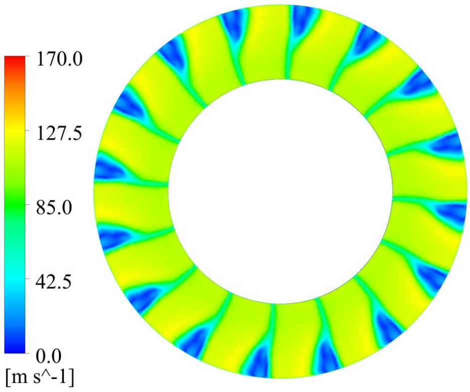

Fig. 7. Velocity field for the tandem fan

In the flow past the single fan, in separate zones of inter-blade channels, there are zones with a velocity higher than in the flow core. Also, there is a non-uniformity in the flow core. In the tandem fan, on the contrary – the velocity field is uniform in the flow core.

According to the research results, it was found that the use of the tandem fan ensures the alignment of the velocity field in flow core and reduction of the reduced velocity zone.

Therefore, the use of the tandem fan in terms of acoustic emission reduction is appropriate.

The problem of further theoretical and experimental studies in this direction is to obtain generalized results for the solution of practical problems for improving the aeroacoustic characteristics of turbomachines with multiple blade rows. These studies include an assessment of the mutual influence of the aeroelastic, strength and acoustic characteristics of blade rows. The complexity of solving these problems lies in the lack of approved models for calculating aeroacoustic characteristics in the near and far fields.

## 7. Conclusions

1. The results of solving the test problem of calculating the acoustic characteristics of the fan showed a good convergence with the results of the physical experiment. The error in the results of the numerical experiment on determining the sound power level is 0.08...0.35 %.

2. Comparison of the sound power level for geometrically equivalent single and tandem fans showed that for the first two harmonics, the sound power level in the tandem fan is lower by 7 dB at a rotation frequency of 900 rpm.

The use of the tandem blade row makes it possible to improve acoustic characteristics of the axial fan. The results of the research showed that in the geometrically equivalent tandem axial fan at a rotation frequency of 900...1,500 rpm, the total sound power level can be reduced by 6.9...7.4 dB.

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