NLH calculation of the influence the inlet nonuniformity on the fan parameters

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Abstract. The paper presents the results of numerical simulation of the effect of flow nonuniformities at the engine inlet on the working process of the engine fan. Flow nonuniformities is created by pushing the interceptor into the flow part of inlet device like as it is often done during field tests. The authors have created a numerical model capable of considering non-stationary pro-cesses in the fan using nonlinear harmonic analysis. As a result, qualitative and quantitative estimates were obtained of the influence of overlapping of the inlet duct by the interceptor on the main parameters of the fan workflow. It is shown that the more the duct is blocked, the more its parameters are deteriorated. Moreover, the deterioration is not linear, but according to.

1. Introduction

Inlet devices of bypass turbofan engines (characterized by a high degree of bypass ratio) of modern passenger aircraft have a large flow area and are relatively short (their length is less than the diameter). It would seem that losses in such conditions should be minimal in all typical flight conditions. However, in some cases (for example, with a strong side wind, flying sideways, etc.) a separation flow occurs at the inlet edge of the air intake, which causes the flow at the fan inlet to become uneven. This, in turn, causes a significant reduction in the efficiency of the low-pressure compressor and the engine. In addition, the inlet nonuniformity causes oscillations of the fan blades, which can lead to their destruction.

In this paper, the authors aim to test the possibility of conducting a computational study of the influence of the inlet nonuniformity on the working process (efficiency) of a fan of turbofan engine, reproducing tests with an input simulator. There will also be given a qualitative and quantitative assessment of the influence of the inlet nonuniformity on the main parameters of the working process of the engine fan.

The object of the study was the fan of the NK-56 turbo-jet engine (Figure 1), developed at Kuznetsov, PJSC (Samara, Russia) [1] for civil aviation aircraft in the early 1980s, but not commercialized.
2. Description of the basic computational model of the workflow of the low-pressure compressor of the NK-56 engine

To conduct the research, a computational model of the LPC of the NK-56 engine was created using the Numeca FineTurbo software [2], which includes a fan with an add stage.

At the first stage of the study, the adequacy assessment and validation of the created computational model was carried out [3-7]. For this, the calculated characteristics obtained using various stationary models differing in the turbulence model and density of the finite volume mesh were compared with the test results on the engine test bench provided by Kuznetsov, PJSC. Comparison of the results obtained as a result of stationary calculation with experimental data is shown in Figures 3, 4 and in Table 1.

Table 1. Comparison of the results of calculations obtained using the considered numerical models with the data by PJSC "KUZNETSOV".

| Model No. | Mesh   | Turbulence model | Internal circuit efficiency | External circuit efficiency | Mass flow rate of the internal circuit | Mass flow rate of the external circuit | $\pi_c^*$ of the internal circuit | $\pi_c^*$ of the external circuit |
|-----------|--------|------------------|-----------------------------|-----------------------------|----------------------------------------|----------------------------------------|----------------------------------|----------------------------------|
| 1         | 2.36 mln | Spalart – Allmaras | 0.5...2% more               | 3...6% more                 | 6% less                                | $\pm$2%                                | Higher by 0.05                   | Higher by 0.07...0.13             |
| 2         | 2.36 mln | k – epsilon      | 0...1% more                 | 3...6% more                 | 4% less                                | $\pm$2%                                | Higher by 0.03                   | Higher by 0.05...0.12             |
| 3         | 7.06 mln | Spalart – Allmaras | 1.5% more                   | 2% more                     | $\pm$2%                                | $\pm$2%                                | Coincides                       | Higher by 0.02                   |
| 4         | 7.06 mln | k – epsilon      | 1...3% more                 | 1.5...5% more               | 3% less                                | $\pm$2%                                | Higher by 0.02                   | Higher by 0.03...0.1              |

Figure 1. Low pressure spool of the NK-56 engine.

Figure 2. Comparison of pressure characteristics obtained using the created computational models with experimental data.
Of all the models considered, the best match with the data of the design calculation is shown by model No. 3 (fine mesh and Spalart-Allmaras turbulence model). It is accepted as the final for further research of the workflow in the fan blade passages.

3. Computational model for the study of the influence of the inlet nonuniformity on the characteristics of the fan of the NK-56

At the second stage of the study, based on the created and verified computational model of the workflow of the LPC of the NK-56 engine, a computational model was created to study the influence of the inlet nonuniformity on the working process of its fan [8-13].

The modified model was created in such a way as to meet the conditions of testing a fan with a simulator of the inlet nonuniformity on the test benches of PJSC Kuznetsov. There, the nonuniformity is modelled by extending the interceptor into the duct between the lemniscate and the inlet to the fan (Figure 4). During the tests, the intensity of the inlet nonuniformity was regulated by the depth of the interceptor extension to the flow part of the duct.

Due to the highly variable nature of the flow at the fan inlet, the task should be solved in a transient statement [14-16]. In this case, since the nonuniformity generated by the interceptor has a different intensity of direction of the velocity vectors around the circumference of the RW, the assumption about the periodicity of the flow cannot be accepted, and the computational model must contain all the blade passages.

It was assumed to conduct the research using the method of nonlinear harmonic analysis (NLH) [17], which allows to obtain nonstationary flow patterns several times faster than using transient simulation. The geometry of the LPC was significantly simplified [18-21]: the separator of the contours was eliminated (the task became single-circuit). The computational domain contained only a RW and a model GV (“lengthened up” GV of the fan of the internal circuit) (Figure 5) simulating the effect of downstream elements on the rotor.
Figure 5. Simplified geometry of the NK-56 engine fan for conducting research on the effect of inlet nonuniformity on its workflow.

An input section imitating the engine inlet channel with an interceptor was attached to the inlet boundary of the fan domain (Figure 6).

Figure 6. Computational model for studying the influence of inlet nonuniformity on the fan workflow.

4. The results of the study of the influence of the interceptor extension on the working process of the fan of a turbofan engine

In the course of the research, series of quasi-steady state calculations was performed using the NLH method, differing by the distance at which the interceptor was extended. Analysis of the obtained results showed that the overlapping of the flow part of the inlet duct by the interceptor causes the appearance of a separation zone at the fan inlet, which has a significant impact on its working process.

Figure 7 shows, as an example, the contours of Mach numbers in relative motion when the interceptor extends into the flow part so that it covers 6.8% of the flow part of the duct, in two mutually perpendicular planes passing through the engine axis. It shows that in front of the interceptor a zone of flow deceleration is formed, and behind it a developed separation zone reaches the inlet of the engine, located at a distance more than the size of its outer diameter (i.e. by more than one calibre). In this case, part of the flow entering the duct opposite the interceptor is redirected to the axis of the engine, causing local flow acceleration, and changing the flow structure there. That is, the injecting the interceptor affects not only the structure immediately near it, but the rest of the duct to a depth of more than half the diameter of the engine.

Figure 7. The calculated contours of the change in the Mach number in relative motion in the “inlet duct + fan” system when the interceptor is extended so that it blocks 6.8% of the flow-part of the duct.
These circumstances lead to the emergence of significant inhomogeneity over the cross section of the pressure field at the fan inlet (Figure 8). It can be seen that it is formed behind the interceptor, and, with an increase of the interceptor extension, an area of reduced total pressure grows behind it. In this case, Figure 8 confirms that with an increase in the overlapping area of the duct, the uniformity of the pressure field is disturbed over the entire cross section. And the higher the extension, the greater the level of unevenness. The flow nonuniformity with increasing overlap of the flow path by the interceptor increases linearly. More-over, when 13% overlap, the nonuniformity reaches 50%.

The above-described phenomena lead to the fact that the conditions at the inlet to each blade passage and, correspondingly, the flow structure there are unique, disrupting the interaction of adjacent passages and reducing the pressure ratio, efficiency, stability margins and air flow through the fan.

With the increase in the part of the duct blocked by the interceptor, all compressor parameters deteriorate: the working fluid mass flow rate, the pressure ratio, and the efficiency decrease. In addition, the range of mass flow rate between the modes of surge and choke is also reduced, pressure lines become more vertical. This signals a decrease in the stability of the compressor.

A quantitative assessment of the influence of the overlap of the flow part of the input duct on the parameters of the compressor workflow, obtained from the analysis of Figure 9, is shown in Figure 8. As can be seen, the increase in the level of the interceptor extension degrades the parameters not linearly, but by parabolic dependence. The least change is in the mass flow rate of the working fluid (with a decrease in the area of the inlet duct by 10%, it is reduced by 3%). The difference between the values of mass flow rate at surge and choke changes most of all (with a decrease in the duct area by 10%, it is reduced by 40%). If the duct area is reduced by 10%, the efficiency of the compressor decreases by 11% (rel.), and the pressure ratio - by 9%.

![Figure 8. Transformation of the total pressure fields at the fan inlet flange at different levels of extension of the interceptor (at the top) to the flow part of the supply duct.](image-url)
5. Conclusion
To solve the investigated problem, the authors developed and verified a numerical computational model of the workflow of an inlet device, retractable interceptor (an inlet nonuniformity generator) and a turbofan fan stage using NLH approach. Analysis of the results of calculations carried out using the created computational model showed that while reducing the duct area by 10%, the air flow through the compressor decreased by 3%, efficiency by 11% (rel.), the pressure ratio increases by 9%, the difference between surge and choke mass flow rates by 40%.

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References
[1] Zrelov V A 2002 Otechestvennye GTD. Osnovnye Parametry i Konstruktivnye Skhemy. CHast' 2 (SGAU Samara 250 2002)
[2] NUMECA https://www.numeca.com/home
[3] Pasquale D, Persico G and Rebay S 2012 ASME Turbo Expo 2012: Turbine Technical Conference and Exposition, Copenhagen GT2012 69884
[4] Safari A, Lemu H G and Assadi M 2013 ASME Turbo Expo 2013: Turbine Technical Conference and Exposition GT2013 94093
[5] Yan C, Yin Z, Guo F, Shen X, Fan J and Luo J 2017 ASME Turbo Expo 2017: Turbine Technical Conference and Exposition GT2017 64177
[6] Zhang P, Lu J, Wang Z, Song L and Feng Z 2015 ASME Turbo Expo 2015: Turbine Technical Conference and Exposition GT2015 42582
[7] Walther B and Nadarajah S 2015 ASME Turbo Expo 2015: Turbine Technical Conference and Exposition GT2015 44142
[8] Tang X, Luo J and Liu F 2016 ASME Turbo Expo 2016: Turbine Technical Conference and Exposition GT2016 56170
[9] Vasilopoulos I, Flassig P and Meyer M 2017 ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition GT2017
[10] Astrua P, Piola S, Silingardi A and Bonzani F 2012 ASME Turbo Expo 2012: Turbine Technical Conference and Exposition GT2012 68993
[11] Kang Y-S, Park T-Ch, Yang S-S, Lee S-II and Lee D-H 2012 ASME Turbo Expo 2012: Turbine Technical Conference and Exposition, openagen GT2012 69252
[12] Safari A, Hajikolaei KH, Lemu HG and Wang GG 2016 ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition GT2016 56741
[13] Komarov OV, Sedunin VA and Blinov VL 2014 ASME Turbo Expo 2014: Turbomachinery Technical Conference and Exposition GT2014 25379
[14] Sonoda T, Endicott G, Arima T and Olhofer M 2014 ASME Turbo Expo 2014: Turbomachinery Technical Conference and Exposition GT2014 25857

Figure 9. Changing in the main parameters of the compressor process at different levels of overlapping the inlet section.
[15] Deng X, Guo F, Liu Y and Han P 2013 ASME Turbo Expo 2013: Turbine Technical Conference and Exposition GT2013 95357
[16] Egorov I N, Kretinin G V and Fedechkin K S 2010 Workshop CEAS VUB
[17] The Nonlinear Harmonic module https://www.numeca.com/product/nlhmethod
[18] Kang Y-S 2012 ASME Turbo Expo 2012: Turbine Technical Conference and Exposition GT2012 69252
[19] Ellbrant L, Eriksson L-E and Mårtensson H 2012 ASME Turbo Expo 2012: Turbine Technical Conference and Exposition GT2012 69272
[20] Yu J, Ji L, Li W and Yi W 2015 ASME Turbo Expo 2015: Turbine Technical Conference and Exposition GT2015 42234
[21] Yanhui D, Wenhua W, Zhaolin F and Ti C 2016 ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition GT2016 56861