

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS BYPASS-FLOW FANS FOR AN ADVANCED CIVIL AIRCRAFT ENGINE

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Abstract

When designing fans, it is essential to take into account all specific features of their operation in real conditions. Determination of bypass ratio influence on local flow parameters and integral fan performance is a painstaking problem. Presented is a method of calculating steady flow parameters, as well as turboengine fans performances.

Design, computational and experimental study of bypass scaled down stage model - prototype of a bypass-flow gearless fan including 3-4 booster stages for an advanced civil aircraft engine has been performed.

The calculations show perfect agreement via comparison of numerical results with experimental values at high efficiency level within all operation range. Fan model (scaled down version) meets its design goal of performance, flow capacity and surge margin in its first build. On test results, a decision was accepted to manufacture a full-size fan rotor in the form of scaled model rotor.

The work is organized with the aim of creating a scientific and technological potential for optimal designing and mathematical modeling physical processes, as well as experimental investigations of aerodynamic and acoustic feature of new fans at special test rigs. Calculations of flow parameters and fan performance were carried out for the reason of making a choice of optimal versions at designing as well as expert examination of model stages proposed for manufacturing and testing. All experimental data are obtained at

testing the fan model in the anechoic chamber of C-3A CIAM acoustic test facility.

Nomenclature

D	–	outer diameter, m
P^*	–	total pressure, Pa, kPa
T^*	–	total temperature, K°
G	–	mass flow, kg/s
m	–	bypass ratio
π^*	–	total pressure ratio
$\eta^{*ad.}$	–	adiabatic efficiency
σ	–	total pressure recovery
SM	–	surge margin
n	–	rotational speed, rpm
U	–	tip speed, m/s
M	–	Mach number
H	–	Flight height, m, km

Subscripts

C	–	compressor
IGV	–	inlet guided vane
F	–	fan
R	–	rotor
OGV	–	outlet guided vane;
ST	–	stage
air	–	air
ad	–	adiabatic
cor.	–	corrected, reduced
I	–	core duct value
II	–	bypass duct value

1 Introduction

Last years and hereafter, the aero engine industry (for instance, [1-3, 4, 5]) marks a firm trend to reduction of fan blade circumferential rotational speed. Study of fan work under raised values of circumferential velocity is reasonable from the standpoint of analysis of possible provision of high total pressure ratio values at low stages number [6, 7].

For advanced civil engines of main and regional aircrafts, instead of fans with narrow-banded blades are developed and implemented highefficient low noise fans with widechord blades.

Now it is pressing to find reserves of further reduced level of sound emission, increased efficiency, and stall margin, as well as reduced weight under necessary operation durability and high reliability. Such goals should be achieved at lower blades circumferential rotation speed and greater fan bypass ratio, as well as with technology fabrication development of hollow blades and composite blades.

Last 15-20 years circumferential speed of gearless fan blades in civil turbofans was reduced from $U_C = 450$ m/s to $U_C = 400$ m/s with the aim of significantly better acoustic performance and economy. Gear fans have an advantage in the sense of possible further circumferential speed reduction to $U_C < 350$ m/s and may be even below values $U_C = 300$ m/s.

Becomes firmly established that for each chosen rotor rotation speed exists optimum value π_F^* , at which maximum high adiabatic efficiency level ($\eta_{ad, F}^*$) is reached. Total pressure ratio π_F^* is chosen from condition of possible achievement of these efficiency levels. As well as on the contrary, for given values π_F^* , one can select optimum value U_C . Lower circumferential speed of rotor rotation and reduced π_F^* result in reduced jet velocities in nozzle output and higher flight efficiency, but for ensuring necessary turbofan thrust fan air flow should be increased.

At fan inlet flow speed above $M > 0.7$ shock waves intensity and supersonic flow areas increase, as noted, for instance in [3]. This circumstance brings about limited frontal

capacity $G_{F, cor, \Sigma} / F$ (specific flow) by value $200 \text{ kg}/(\text{c} \cdot \text{m}^2)$ or $220 \text{ kg}/(\text{c} \cdot \text{m}^2)$ depending on whether is taken into account full area F calculated on outer diameter D or only ring duct area at relative hub diameter $\bar{d}_1 \sim 0.3$. Limited specific mass flow rate makes necessary greater fan size and, consequently, its bypass ratio $m = 10 \div 15$ [4]. In case of counter rotating ducted fans [8, 9, 10, 11] or distributed propulsion system (DPS) [1-2, 5] optimum values U_C and π_F^* can be else below, ($m > 20$). Least values U_C and π_F^* at else greater values m are realized in case of opened rotors having greatest flight efficiency [12, 13].

In respect of obvious advantages of counter rotating ducted fans with fixed blades we shall notice that their regulation is possible by varying rotation frequencies ratio of the first and second rotors n_2/n_1 ($\bar{n}_{cor.}$), may be that will lead to redistribution of works or torques between them. An odd question than arise: may it result in the greatest first rotor work even under some increase in its rotation speed and the least second rotor work up to its full stop, as in usual turbofans consisting of one rotating rotor and still stators in internal and external contours?

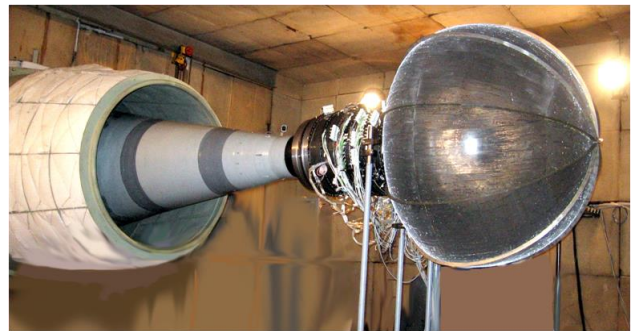


Fig. 1. Fan model with anti-turbulent screen installed in anechoic chamber of the C3-A CIAM acoustic test facility.

2 Bypass fan mathematical model

2.1 Performance calculation method

The computational procedure of integral performances is based on the definition of steady flow field parameters in turbo machine by 3D viscous through-flow calculation of compressible gas using CIAM-developed

software for the numerical solution of Reynolds-Averaged Navier-Stokes equations (RANS). A well-known implicit version of the finite volume S.K. Godunov modified scheme with second order of accuracy for spatial coordinates, semi-empirical models of turbulence with wall functions and "mixing plane" interfaces between rotor and stator vanes are used.

The value of static pressure specified in outlet sections of core and bypass ducts is used as a boundary condition that is very similar to application of two independent throttles in each contour channel during experimental fan study of turbofans. A few of turbulence models applies in calculations for closure the system of equations [14]. Presented are characteristics of fan bypass duct and core contour (including rotor hub part and three-four booster stages) got in calculation with using, for instance, the Bolduin-Lomaks algebraic model and two-equation model "k- ω ".

At present, the method allows calculations of several fan stages in flowpath with contour flow division. In the bypass duct, addition to OGVs, Struts can be taken into account and pylons [15], in core duct, except IGV, AGV, can be transition channel, struts and several stages, booster compressor (such as in [16]), LPC, HPC. The method is successfully used for steady flow calculation and conventional bypass fans performance, open rotors, and ducted counter-rotating fans, for instance, in the framework of VITAL program.

2.2 Object of research

Provision of big specific mass flow rate under high $\eta^*_{ад}$ values above 0.91 of the advanced fans under development is a serious problem and makes pressing experiment-calculated studies.

The creation about a decade ago of two low scale single contour model stages $U_C = 367$ m/s and $U_C = 400$ m/s, which outer diameter is $D = 400$ mm [15] allowed CIAM to develop design approaches for so high-level fans. The stages with their rotors versions were made according to «blisk» technology.

Test results later on the UK-3 CIAM rig showed that the stages provide getting all the main parameters required by the technical assignments on their designing. In comparing, a close convergence is obtained for computed and experimental performances of low scale models at high maximum efficiency level in all operation range ($\bar{n}_{cor.} > 0.5$).

Up to now, detailed studies are conducted of acoustic features of various sound treatment system, as well as these stages operability at non-uniform distribution of inlet total pressure.

Parameters of one of these two stages ($U_C = 400$ m/s), as well as comparison of design and experimental characteristics on results of the first tests are provided in [15].

With the use of this experience for test in anechoic chamber of the C3-A RTC CIAM acoustic rig then were created two large-scale stages ($D = 700$ mm), gearless bypass fan models with four and three booster stages. Wide chord rotor blades of fans models have variable height sweep.

Hereinafter the fan with four booster stages is considered submitted in Fig. 2. As design point for the model developed is accepted maximum cruise regime ($\bar{n}_{cor.} = 1.05$).

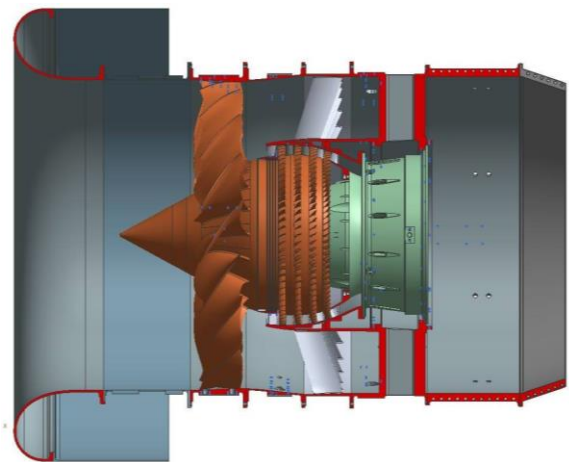


Fig. 2. Object of research C179-2 gearless bypass fan model with four booster stages.

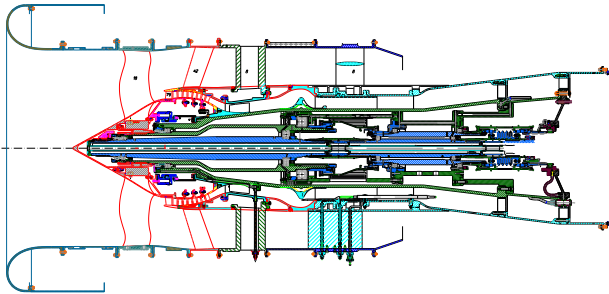
The main parameter values providing fan C179-2 model design point are presented in Table 1.

Table 1

$D_{r,1}$	~ 0.7	m
$\bar{d}_{r,1}$	~ 0.3	—
$G_{F,cor} \Sigma$	75.24	kg/s
m	8.4	—
π^*_I	1.56	—
$\pi^*_{\Sigma LPC}$	2.76	—
$\eta^*_{ad, II}$	≥ 0.910	—
$\eta^*_{ad, I}$	≥ 0.900	—
$n_{cor.}$	11036	rpm
$U_{cor.,}$	404.5	m/s
$G_{F,cor.} \Sigma / F$	195.5	kg/(s·m ²)
Aspect ratio	1.7	

2.3 Aerodynamics mathematical modeling

The scheme of bypass fan model, longitudinal section is shown in Fig. 3. The computational domain covers one blade-to-blade channel of all 11 rows: rotor fan (RF), core guide vanes (IGV), outer duct guide vanes (OGV) and four booster stages.

**Fig. 3. Scheme of the fan model, longitudinal section.**

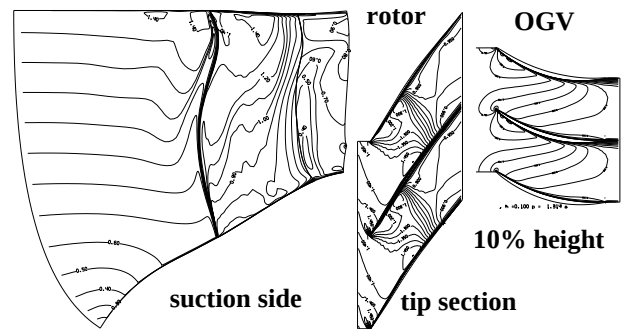
Calculations are performed with approximate account of spinner and radial clearance between rotating rotor blades and still external casing.

In booster stages, we also took into account radial clearances between rotating blades and still casing, as well as between stator vanes NA1, NA2, NA3 console fastening and revolving drum hub. VNA and NA4 vanes are executed twin support, blades have no radial clearance and hub does not rotate.

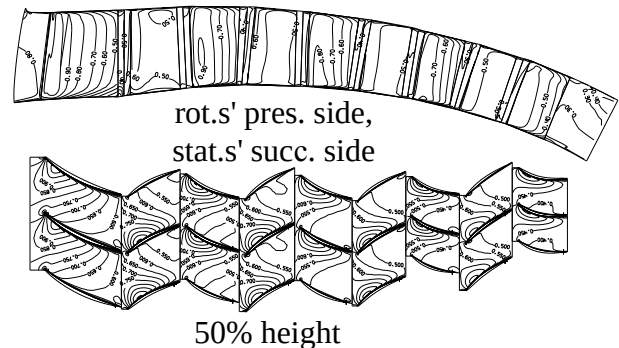
In calculations blades shape corresponds to their deformed condition under the action of gas and centrifugal forces at the design point.

2.4 Parameters distribution in blade-to-blade channels

Fig. 4 shows flow M number distribution at design fan operation condition $n_{cor.}=11036$ rpm, $U_C=404.5$ m/s. In tip sections, fan rotor flow is observed with pressure shocks located inside blade-to-blade channels near blade trailing edges. In tip sections on blades suction sides flow velocity exceeds $M=1.45$. In bottom sections because of positive incidents angles flow at first accelerates in inlet suction waves and then brakes in exit shocks. In fan bypass duct flow velocities, even at the bottom of the bypass duct on the suction sides of OGVs do not reach the sound speed.

**Fig. 4 Distributions of M number in fan rotor and outer contour stator. Design mode, $\bar{n}_{cor}=1.05$, $U_{cor.,}=404.5$ m/s.**

In the fan core contour IGVs suction side flow velocities weakly exceed $M=1$; in blade-to-blade channels of booster stage rotors and stators flow is subsonic, Fig. 5.

**Fig. 5. Distributions of M number in booster stages. Design mode, $\bar{n}_{cor}=1.05$, $U_{cor.,}=404.5$ m/s.**

Under smaller rotation frequency values at take-off condition (throttle mode) $\bar{n}_{cor}=0.92$, $U_{cor.,}=360$ m/s in rotor tip sections are realized

flows with alternating detached shocks and suction waves at the inlet, Fig. 6.

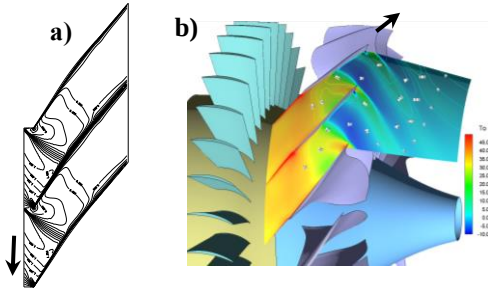


Fig. 6 Fan rotor.

Take-off mode, $\bar{n}_{cor}=0.92$, $U_{cor,}=360$ m/s.

- a) Distribution of relative M_{rel} number.,
b) Distribution of absolute T^*

Maximum Mach number in tip sections at blade suction sides before shocks equals to $M=1.35$, Fig. 6a. Fig. 6b also presents T^* value distribution in tip rotor blade-to-blade channels. The periodic system of detached shocks and suction waves results in a high static pressure disturbance at the inlet that is the primary source of noise radiated in the forward hemisphere in these operating conditions.

Herewith in moving (rotating with rotor) shocks increases and in suction waves diminishes total temperature T^* (enthalpy h^* in absolute motion), as follows from the energy conservation law

$$Dh^*/Dt = (1/\rho) \cdot \partial p / \partial t, \quad (1)$$

pressure waves propagation leads to temperature variation in moving gas particles [17]. So at stage inlet revolve with rotor periodically alternating areas of raised and lower total temperature T^* values (Fig. 7a).

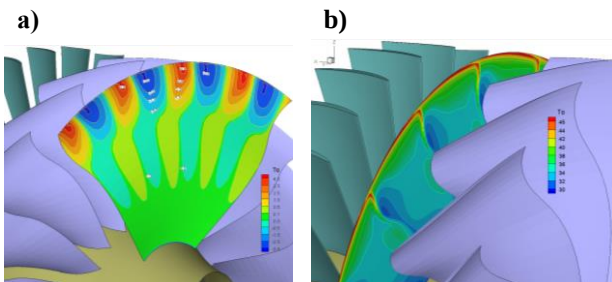


Fig. 7. Absolute T^*

Take-off mode, $\bar{n}_{cor}=0.92$, $U_{cor,}=360$ m/s.

- a) Inlet stage T^* ,
b) T^* between rotor and stator.

Obviously, temperature pulsation frequency equals to blade repetition rate and their intensity decreases with blade distance and is height wise. Inlet section total temperature distribution presented give the evidence that at about blade chord distance from leading edges T^* deflection from average tip value makes up $\sim \pm 5^\circ\text{C}$.

Total temperature distribution in rotor output section before stator, Fig.7b, indicates that maximum total temperature increases near outer casing and in blade wakes. Rotor rotation results in pressure waves propagation, and total temperature in particles passing from entry through blade-to-blade channels increases in front of OGVs at average by more $\Delta T^*=34^\circ\text{C}$, formula (1). Total pressure ratio and rotor efficiency at this operation mode with detached shocks waves equal to values $\pi_{r,}^*=1.436$, $\eta_{ad,r}^*=0.915$.

At present such total temperature pulsation values at stage inlet and also spectrums and static pressure pulsation values are considered to be well measured [18].

3 Experimental estimations of fan model aerodynamics

The C-3A rig is designed for mechanical, aerodynamic and acoustic tests of bypass single rotor and counter-rotating rotors fan models. The test rig, different fan models, as well as experiment-calculated studies of their aerodynamics and acoustics are presented earlier, for instance, in [11,19,20-21], Fig. 1.

The model of fan under investigation is located in acoustic (anechoic) room modeling condition of free acoustic field and having volume beside 1300 m^3 at a distance about 6 m from chamber back wall [20]. This condition allows getting acoustic characteristics of test fans in forward and backward semi spheres simultaneously. Air enters the chamber from the front part; but is pumped away through cone-shaped intake located beside the back wall. Air from inner fan duct is taken off through a flow meter device. For airflow control through inner contour, the rig is equipped with hydraulic drive throttle. The models are in detail prepared by

numerous instruments. At inlet and in different sections, as well as at exit there are installed total pressure and temperature sensors in the manner of pitch and radial rakes. In interrow axial clearance, parameters are measured also with the help of traverse rotating probe.

Total fan airflow is defined on inlet measured values of total pressure P^* , temperature T^* (about 24 sensors) and static pressure P . When inlet rakes absence is supposed, under acoustic test for instance, total pressure and temperature are taken equal averaged pressure and temperature in acoustic room.

Adiabatic efficiency is defined as relationship of ideal adiabatic compression work

$$L_{ad} = G_F \cdot C_p \cdot T_{inl}^* \cdot (\pi^{*(k-1)/k} - 1),$$

C_p - specific heat at constant pressure,
 k - ratio of specific heats

to actual spent work value

$$L = G_F \cdot C_p \cdot T_{inl}^* (\theta^* - 1),$$

$$\eta_{ad}^* = (\pi^{*(k-1)/k} - 1) / (\theta^* - 1),$$

$$\pi^* = P^*/P_{inl}^*, \quad \theta^* = T^*/T_{inl}^*.$$

Accuracy of efficiency determination at low pressure ratio values π^* is small and depends on accuracy of measuring flow total pressures and temperature. So spent work value is defined also by measuring shaft torsion moment M

$$L = \omega \cdot M, \quad \omega - \text{rotational speed, rad/sec,}$$

and efficiency is calculated on the formula

$$\eta_{ad}^* = G_B \cdot (\pi^{*(k-1)/k} - 1) / (\omega \cdot M_e).$$

Shaft torsion moment M is usually calculated on high accuracy planimeter recordings for deduction of friction losses in booster (gearbox) and running part. These losses are approximate defined by two ways: on pumped oil heat balance and else on measurements of idle moment at all operation rpm.

Average values P^* , T^* are calculated as average arithmetical remained after rejecting time average recordings by sensors located on circumferences in given section.

Duct height wise average parameters are defined on conservation equations, i.e. equality of air flow values, entropy and total enthalpy for initial non-uniform flow to correspondent values of provisionally average uniform flow as follows. First define flow average entropy values

$$S = R \cdot \ln(\sigma) + S_0, \quad R - \text{gas constant,}$$

$$\sigma = \pi^* / \theta^{*k/(k-1)}$$

and total enthalpy (temperature T^*), then on state equation is calculated average total pressure and efficiency values.

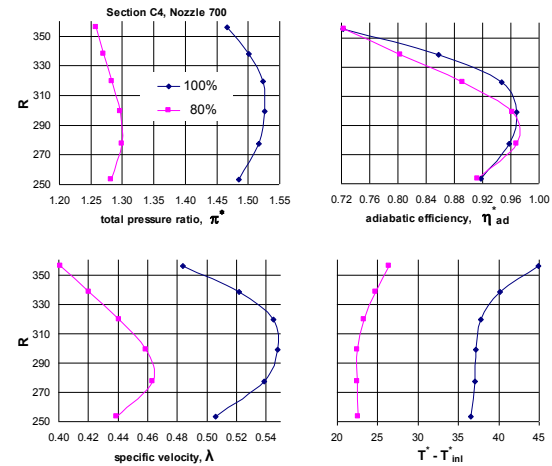


Fig. 8. Distribution $\pi^*(R)$, $\eta_{ad}^*(R)$, $\lambda(R)$, $\Delta T^*(R)$ on radius for OGVs, $\bar{n}_{cor}=1.0, 0.8$, nozzle 700 mm.

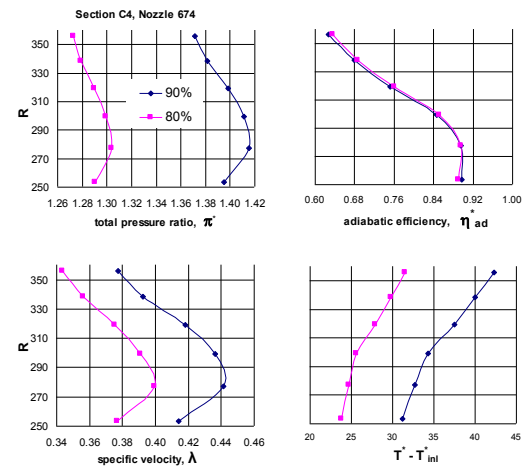


Fig. 9. Distribution $\pi^*(R)$, $\eta_{ad}^*(R)$, $\lambda(R)$ on radius for OGVs, $\bar{n}_{cor}=0.9, 0.8$, nozzle 674 mm.

Fig. 8,9 show main parameters distribution of pressure ratio $\pi^*(R)$, adiabatic efficiency $\eta_{ad}^*(R)$, specific velocity $\lambda(R)$, and total temperature rise $\Delta T^*(R)$ height wise with two duct nozzles in OGV section and two rotor rotation frequency values.

4 Comparison of numerical results with experimental data

Calculated performances are obtained by separate throttling core and bypass contours. Static pressure values, i.e. boundary conditions at external and internal contour exits are originally determined for each mode so that main parameter values in calculations are close to desired values on corresponding operating lines. When calculating characteristics only one contour is throttled, the static pressure value in another duct was kept constant. Fan bypass ratio $m = G_{B II} / G_{B I}$ is changing in accordance with values changing $G_{F I cor.}$ or $G_{F II cor.}$ along characteristics.

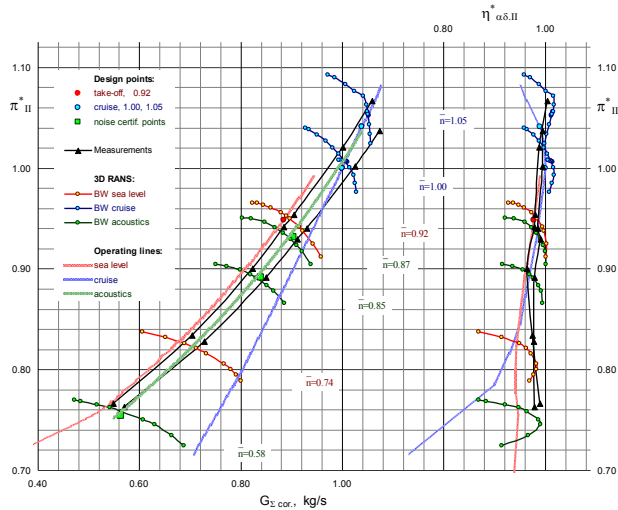
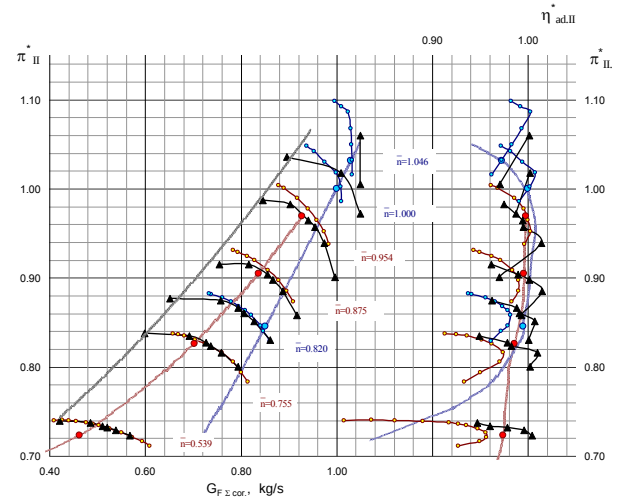


Fig. 10. Calculation of external contour characteristics of bypass fan prototype model of the C179-2 stage.

All data referred to its values in "Cruise Design Point", $\eta_{cor.} = 1.00$

The results obtained are submitted in Fig. 10. Red lines correspond to land operation state ($M=0$, $H=0$, ISA). Blue lines are chosen to represent cruising flight mode in high-altitude condition. Green color meets acoustics certification modes. Black lines and black triangles are drawn in fan tests with removable nozzles. The figure also shows two such lines got as lines of joint work of fan and two replaceable nozzles of different area installed in external contour exit. We need these lines to determine desired nominal nozzle area for testing acoustics. The experimental characteristics of external contour can be received in tests with special designed blade throttle in external contour. But fig 11 shows experimental performances of bypass fan

model, obtained by using of different area replaceable nozzles system.



The Rice. 11. Comparison of computed and experimental external contour characteristics of an advanced fan prototype model.

Calculations of external contour characteristics are executed with the use of Bolduin-Lomaks algebraic model, other models application leads to similar results.

As it is seen, calculations of external contour performances have shown good convergence by comparing numerical results with the experiment at high efficiency level within all operation range. Fan model (scaled down version) meets its design goal of performance, flow capacity and adequate surge margin in its first build. On test results, a decision is taken to manufacture a full-size fan rotor in the form of scaled model rotor.

At present, we realize aerodynamic upgrading blades thickened versions with the aim of natural frequencies tune-out from dangerous resonance. Further studies else are pressing since some divergences have been obtained at comparison of design data and of these blades test, which reasons have not yet wholly revealed.

Fig.12 presents core contour characteristics (rotor hub part and booster stages). Color lines mark performance got in calculation with the use of Baldwin-Lomax algebraic model, black lines – two-equation model "k- ω ". As it is seen, the calculation results of inner contour can noticeably depend on turbulence models.

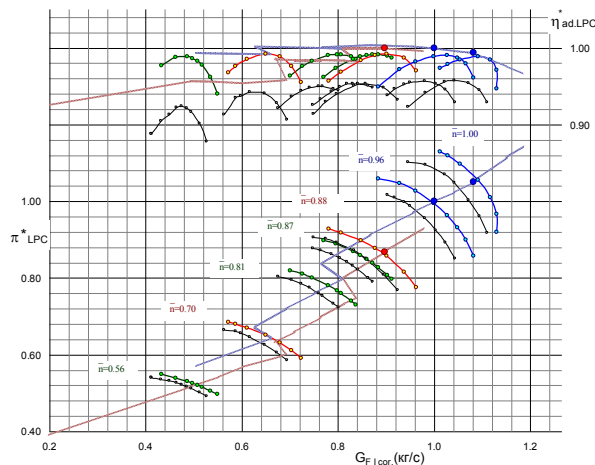


Fig. 12. Comparison fan inner contour characteristics got in calculations using two turbulence models

Conclusion

1. Presented is a method of calculating steady flow parameters, as well as bypass fan performances.
2. Design, computational and experimental study of bypass scaled down stage model - prototype of a bypass-flow gearless fan including 3-4 booster stages for an advanced civil aircraft engine has been performed. Tip model diameter is $D=700$ mm.
3. The calculations of bypass contour performances have shown a good agreement in comparing numerical results with experimental values at high efficiency level within all operation range from choke up to near-surge regime $n_{cor} = 0.6-1.05$ with the use of Baldwin-Lomax algebraic turbulence model and two-equation differential model "k- ω ".
4. Fan model meets its design goal of performance, flow capacity and surge margin in its first build. On tests results, a decision was accepted to manufacture a full-size fan rotor in the form of scaled model rotor
5. Presented is a collation of fan inner contour design characteristics got with the use of two turbulence models. The calculation results depend noticeably on turbulence models selection.
6. The calculations of core contour performances with the use of Baldwin-Lomax algebraic turbulence model and two-equation

differential model "k- ω " show that the results can noticeably depend on turbulence models.

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