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DEVELOPMENT OF THE FAN STAGE WITH ULTRA-LOW ROTATIONAL SPEED

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Abstract

This work presents the results of aeromechanical design of a large-scale fan stage model ($\boldsymbol{D}_r = 700$ mm) for a low-noise high-performance single-stage fan prototype for an advanced civil aircraft geared turbofan with an ultra-low tip speed, a high specific flow capacity, and a high bypass ratio ($\boldsymbol{U}_r$ ~310÷330 m/s, $\boldsymbol{m}$~13÷14). The blades are manufactured from titanium alloy or composite material (carbon fiber reinforced polymer or CFRP).

Nomenclature

D	–	blade tip diameter, m
$\bar{\boldsymbol{d}}$	–	relative hub diameter
F	–	cross area, $\pi \cdot D^2 \cdot (1 - \bar{d}^2)$, m^2
P*	–	total pressure, Pa, кPA
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
le	–	leading edge
te	–	trailing edge
ogv	–	outlet guided vane;
st	–	Stage
air	–	Air
ad	–	Adiabatic
cor.	–	corrected, reduced
I	–	core duct value
II	–	bypass duct value

1 Introduction

In 2003-2008, CIAM developed and tested two small-scale single-stage fan models without IGV (*Dr* = 0.4 m) for advanced geared and ungeared turbofans. Both stages were manufactured as a single-flow version (rotor + guide vanes). Rotors in these stages were manufactured as "blisks".

A high specific flow capacity and a high level of efficiency at low rotational speeds of rotor blades caused problems due to lack of experience in developments of these fans. Moreover, a steady tendency towards a decrease in tip speeds was observed in the aircraft engine industry. Tip speeds of ungeared fan rotor blades decreased within the previous 15 years from $U_{r\ cor}$= 450 m/s to $U_{r\ cor}$= 400 m/s to improve fan operating efficiency and acoustics.

Tests at CIAM's UK-3 test facility showed that the first stage at $\boldsymbol{U}_{r\ cor}$=367 m/s design point provided the following values of key aerodynamic parameters: $\boldsymbol{G}_{f\ cor}/\boldsymbol{F}$=200 kg/s/m^2; $\boldsymbol{\pi}^*_f$=1.40; $\boldsymbol{\eta}^*_{ad.f}$=0.91. Tests of the second stage at $\boldsymbol{U}_{r.cor}$ = 415 м/c also showed the target values: $\boldsymbol{G}_{f\ cor}/\boldsymbol{F}$=198 kg/(s·m^2), $\boldsymbol{\pi}^*_f$=1.60 and $\boldsymbol{\eta}^*_{ad.f}$ = 0.91. Additionally, high parameters were provided at low rotational speeds $\bar{\boldsymbol{n}}_{cor.}$>0.5 - $\boldsymbol{\eta}^*_{ad.f.max} \geq 0.92$.

The comparison of experimental and calculated data for small-scale fan stage models showed their coincidence within the total operating range. Acoustic characteristics and properties of various sound-absorbing linings, as well as operation of these stages in conditions of non-uniform total pressure distributions at the inlet have been studying in details up until today.

Parameters of one of these two stages at $U_{r.cor} = 415$ m/s, as well as the comparison of calculated and experimental characteristics are presented in [1].

When specifying the fan parameters for an advanced long-range aircraft turbofan in basic operating conditions, the experience in calculations and tests of these small-scale stage models was taken into account.

As of today, the specified values of parameters are kept unchanged. Positive results of large-scale bypass fan models (Dr = 0.7 m) with four booster stages, as well as a small-scale bypass fan model being identical to a full-scale bypass fan with three booster stages tested at CIAM's C-3A test facility were taken into account. The design goals were identified correctly and specified values of key parameters (π^*_{f}, $\eta^*_{ad\ f}$ and $G_{f.cor}$) were achieved and could be implemented, even if the results of calculations and measurements were over-optimistically construed in the analysis. Rough estimates of surge margins (***SM***) of the bypass duct in calculations and tests of the models were not lower than the required values without casing treatments. The results are presented in details in [2] and [3].

Requirements to thrust and efficiency to be met by competitive advanced engines for short- and medium-range narrow-body as well as long-range wide-body passenger and transport civil aircraft are known. A geared fan at ***U***r = 350÷370 m/s is studied in this work.

A gear drive gives advantages in terms of a possibility of an additional decrease in tip speeds to $U_r < 350$ m/s and even lower, down to $U_r = 300$ m/s.

It is known that fight efficiency increases with a decrease in π^*_{f} and $U_{r\ cor}$. The required value of π^*_{f} based on engine parameters determines optimal values of $D_{r\ 1}$ and $U_{r\ cor}$.; and in this case it is necessary to increase air flow rate to provide turbofan thrust, but high air flow rate (***M***> 0.7) at the fan inlet results in high losses in shock waves due to large areas of supersonic flows. This leads to limitations on the specific flow capacity - $G_{f\ cor}/F < 200$ kg/s/m^2, $\bar{d}_{r1} \approx 0.3$, and the need in an increase in fan dimensions, and, consequently, its bypass ratio, «***m***».

Optimal values of ***U***r and π^*_f for counter-rotating ducted fans [4, 5, 6, 7] or distributed propulsion systems [8, 9, 10] can be even lower (***m***> 20). Min. values of ***U***r and π^*_f at higher ***m***-values are achieved by unducted variable-pitch rotors providing the highest flight efficiency [11].

2 Components under study

This paper presents the results of a aeromechanical design of a large-scale fan stage model being a prototype of a highly efficient low-noise single-stage fan designed for an advanced civil aircraft geared turbofan with an ultra-low rotor tip speed, a high specific flow capacity and a high bypass ratio (see Fig.1).

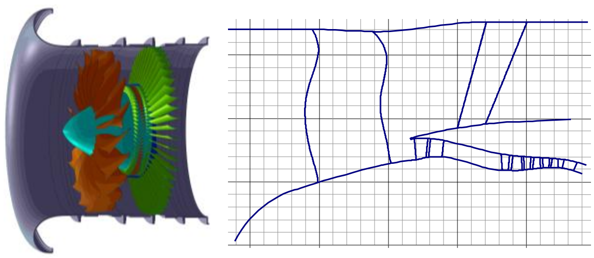

Fig. 1. Stage model (a) - a prototype of a high-performance low-noise geared fan (b)

The stage is designed for tests in the anechoic chamber of CIAM's C-3A specialized acoustic test facility to ensure verification of new methods for optimal design of similar fans with the aim of parameters maximization (Fig. 2).

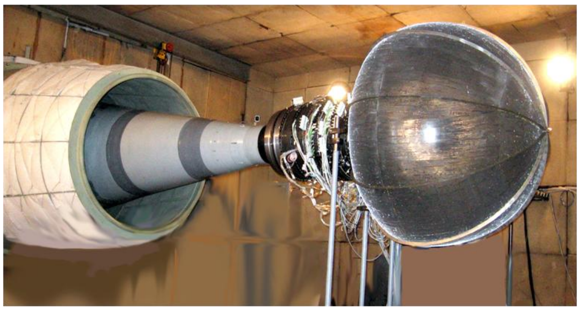

Fig. 2. Fan model with an anti-turbulence device installed in the anechoic chamber of the CIAM's C3-A acoustic test facility.

The tested fan model in max. cruise flight conditions ($\boldsymbol{M}$=0.85, $\boldsymbol{H}$=11 km, $\bar{\boldsymbol{n}}$=1.00, $\boldsymbol{U}_{\text{r cor.}}$=313.4 m/s) should provide the following values of key parameters as listed in Table 1:

Table 1

$\boldsymbol{D}_{\text{r.1}}$, m	0.70
$\bar{\boldsymbol{d}}_{\text{r.1}}$	0.29
$\boldsymbol{G}_{\text{F.cor }\Sigma}$, kg/s	76.36
$\boldsymbol{M}$	13.5
$\boldsymbol{\pi}^{*}_{\text{II}}$	1.379
$\boldsymbol{\eta}^{*}_{\text{ad .II}}$	≥ 0.920
$\boldsymbol{U}_{\text{r cor.}}$,	313.4
$\boldsymbol{G}_{\text{f.cor}}$/F, kg/(s·m^2)	195.5
Aspect ratio	1.905
Sailary	1.467

In climbing ($\boldsymbol{H}$=11 km, $\boldsymbol{M}$=0.85, $\boldsymbol{U}_{\text{f cor.}}$=326.3 m/s), $\boldsymbol{G}_{\text{f cor}}/\boldsymbol{F}$=202 kg/(s·m^2)

2.1 Mathematical modeling of aerodynamics

The bypass fan model (its longitudinal section) is shown in Figure 3.

Two versions of the fan stage are designed. The first version with a decreased hub diameter at the blade trailing edge entails planned activities aiming at improvements of the test facility, including an increase in flow capacity of the core duct. This stage version more accurately simulates the full-scale fan under designing with a transition channel and a high-speed three-stage compressor in the core duct.

It is worth noting that the second fan stage version has an increased total pressure ratio in the core duct to increase its through-flow capacity due to an increase in the hub diameter.

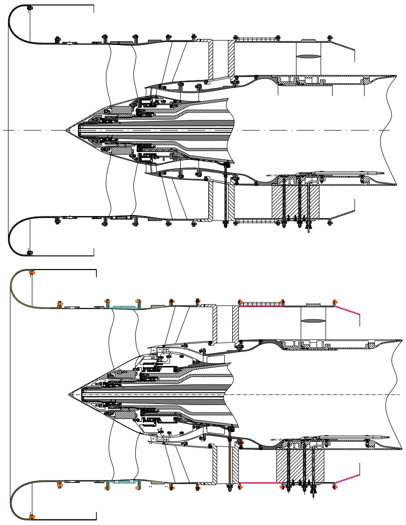

Fig. 3. Two fan stage versions (longitudinal sections).

An auxiliary booster stage in the core duct of the second model is used for the same purpose. The computational domain covers one blade channel for each of 4 blade rows: the fan rotor (r), the double-row guide vanes at the core duct inlet (igv), and outlet guide vanes in the bypass duct (ogv). In the second case the computational domain also includes the booster stage.

The booster stage near the operating mode provides a high loading coefficient ($\psi=C_P\cdot\Delta T/U^2$), high theoretical flow coefficient, low efficiency and low total pressure ratio due to low rotational speed of its rotor blades: ~ 172 m/s.

Calculations are performed with approximate consideration of a spinner and a tip clearance between rotating rotor blades and a fixed outer casing. The shape of blades corresponding to their strained state under action of gas and centrifugal forces at the design point is used in calculations.

A transition duct and a LPC installed in the core duct of a full-scale fan are not simulated at the test facility, but the simplified mathematical modeling takes these components into account by multiple 1-D and 2-D calculations in direct and inverse problem definitions with pre-profiling of all blade rows. It is widely thought that potentialities of these methods have been exhausted, but they can be very useful in the foreseeable future. They include simple phenomenal approaches with empirically estimated parameters; an improvement of predictability and solutions reliability results in step-by-step replacement of these methods by more intricate mathematical models (RANS, URANS) [12].

2.2 Method for calculations of characteristics

Fan designing and calculations presented below are made using methods and algorithms implemented in software developed by CIAM.

The mathematical model is based on the numerical solution of Reynolds-averaged Navier-Stokes equations by through-flow calculations using a modified high accuracy implicit version of S.K. Godunov's scheme, semi-empirical models of turbulence with wall functions as a boundary conditions on solid surfaces and «mixing plane» interfaces between rotor and stator vanes To close the system of Navier-Stokes equations, a two-parameter differential turbulence model («k-ω») was used.

The bypass ratio effect on local and integral flow characteristics is taken into account in the fan model designing by specifying the values of static pressure at outlets of core and bypass ducts in the same manner as two independent throttles in these ducts are used in experimental studies of fans for by-pass engines.

The fan model performances are calculated from choking to the surge line within a wide range of rotational speeds - $\bar{n}$ = 0.50, 0.70, 0.90 1.00, 1.05, 1.10. The target key aerodynamic parameters are achieved in calculations with required surge margins and with a certain efficiency margin in the bypass duct (see Fig. 4). All values are compared with their design values at $\bar{n}$ = 1.00.

The calculations indicate a potential for high fan efficiency; for example, maximum efficiency of the fan rotor in these calculations exceeds $\eta^*_{max} > 0.95$ without account of an exhaust system and guide vanes installed in core and bypass ducts.

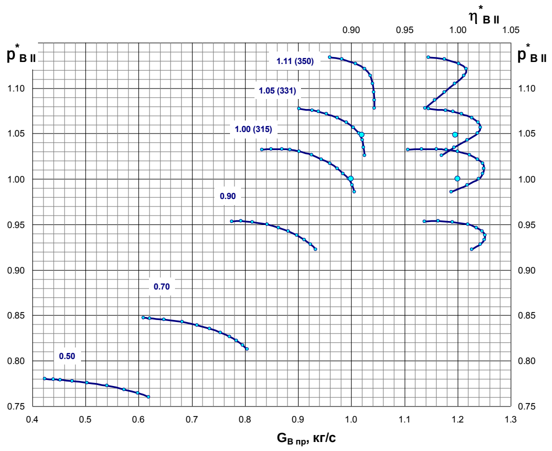

Fig. 4. Performances of the fan model bypass duct (calculations, 3D-RANS).

Distribution of M-number in blade channels for the fan rotor and stator is shown in Figure 5.

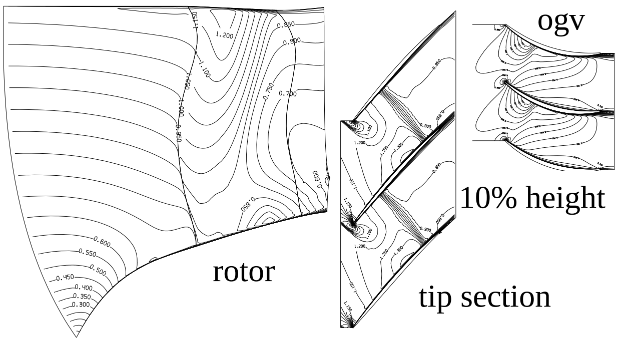

Figure 5. Distribution of M-number in the fan rotor and stator in the bypass duct. Design point, $\bar{n}_{cor}$=1.0

3. Strength calculations for rotor blades made of titanium alloy or polymer composite materials

Shroudless wide-chord blades of the fan model have an complicated 3D shape; their sailary is 1.467, aspect ratio is 1.905 and they are manufactured with a variable sweep along the blade height; all features of their manufacturing from composite materials are taken into account in the designing process. Profiles in cross-sections of rotor blades have a specific shape in order to reach necessary static and dynamic strength and decrease wave and viscous losses.

Two sets of blades made of titanium alloy and a polymeric composite material are to be manufactured and tested. Metal and composite blades should have the same shape in hot state at the design point.

Resistance to bending and torsional flutter on the basis of Strouhal numbers is estimated - $\boldsymbol{Sh}=2\pi f\, b_{0.9}/w_{0.9}$ (f – vibration frequency, $b_{0.9}$ – blade chord at $\bar{h}$=0.9 height, $w_{0.9}$ – relative flow rate at the blade inlet at the same height).

Critical values of Strouhal number separating the reliable flutterless area have been already found statistically by processing reported flutter events in rotors of aircraft GTE axial fans and compressors.

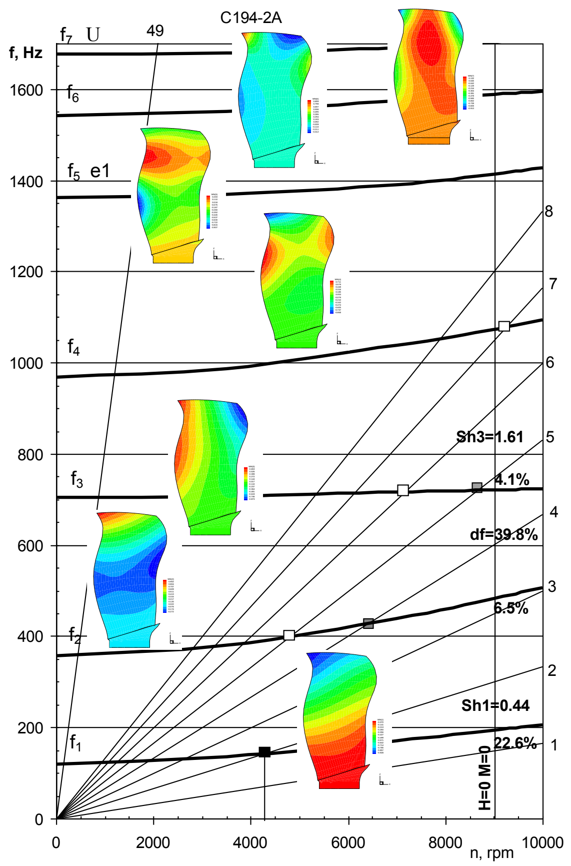

Fig. 6. Campbell resonance diagram for a rotor blade with a decreased hub diameter

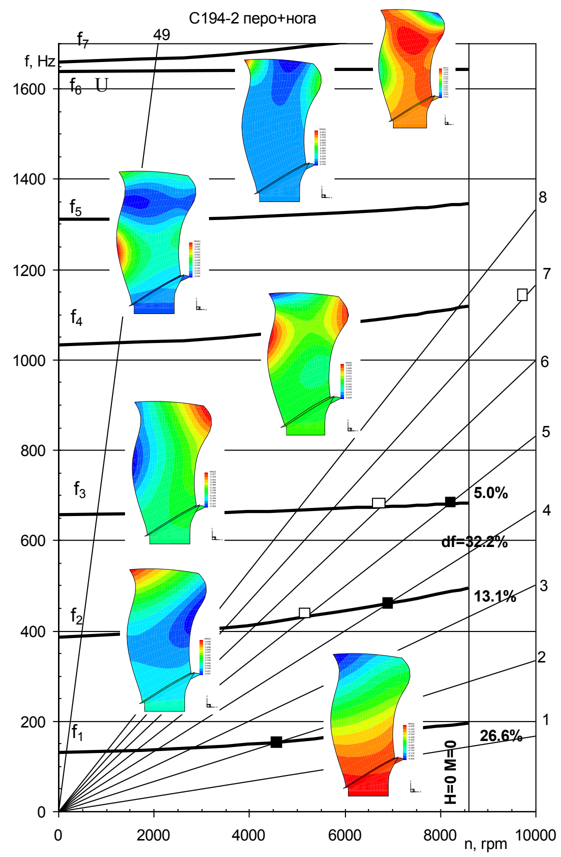

Fig. 7. Campbell resonance diagram for a rotor blade with an increased hub diameter.

Static strength of a blade with a foot, a root, and a shroud is provided. Resonant vibrations of blades for first three waveforms in maximum operating conditions are tuned out. Campbell diagrams for rotor blades with decreased and increased hub diameters are drawn.

As a rule, in statistical data processing there is an area of uncertainty between areas of positive and negative diagnoses. In other words, the critical value in any case is calculated with a considerable margin.

Table 2 shows Strouhal numbers for fan blades at the design point.

Table 2. Strouhal numbers at the design point

Shape No.	f, Hz	b, mm	w, m/s	Sh	Sh_{min}
With a decreased hub diameter					
1	193.9	138	380	0.44	0.50
3	721	138	380	1.61	1.50
With an increased hub diameter					
1	195.2	141	370	0.467	0.50
3	682	141	370	1.63	1.50

Conclusions

1. Calculation procedure for bypass fan performances is presented.
2. Aeromechanical design of a large-scale fan stage model for a low-noise high-performance single-stage fan prototype for an advanced civil aircraft geared turbofan with an ultra-low tip speed, a high specific output, and a high bypass ratio ($\boldsymbol{U}_r$ ~310÷330 m/s, $\boldsymbol{m}$~13÷14) is completed.
3. Outer diameter of the model is $\boldsymbol{D}$ = 700 mm. Two versions of the fan stage are designed. The stage is designed for tests in the anechoic chamber of CIAM's C3-A specialized acoustic test facility.
4. The first version with a decreased hub diameter at the blade trailing edge more accurately simulates a full-scale fan developed with a transition channel and a high-speed three-stage compressor in the core duct, but it entails planned activities aimed at improvement of the test facility, including an increase in flow capacity of the core duct.
5. The second version provides higher total pressure ratio in the core duct to increase its flow capacity by increasing the hub diameter. An auxiliary booster stage in the core duct of the second model is used for the same purpose.
6. Two sets of blades made of a titanium alloy and a polymeric composite material are to be manufactured. Metal and composite blades have a similar shape in hot state at the design point.
7. Flow parameters and characteristics of the core and bypass ducts are calculated within a wide range of operating modes - from choking to the surge line (n_{cor} = 0.5 … 1.1), using the Bolduin - Lomax algebraic turbulence model and the two-parameter differential ««k-ω»» model for closing the system of equations.
8. Calculations of performances show that the fan model can provide a high frontal specific flow capacity, a high efficiency, and a sufficient surge margin.
9. Strength calculations for rotor blades of the fan stage under designing ensure static strength in max. operating conditions. Max. equivalent stresses in rotor blades in these most stressed conditions are ≤30 kg/mm^2, and in guide vanes - ≤11 kg/mm^2.
10. Distribution of blade thickness is optimized with the aim of tuning out dangerous resonances and providing dynamic strength of the rotor in all max. operating conditions.
11. There is a low probability of pure-bending and torsional flutter. The probability of occurrence of bending-torsional flutter is low due to a relatively high difference (~40% for blades with a decreased hub diameter and ~32% for blades with an increased hub diameter) between values of second and third bending-torsional frequencies and low bending -torsional coupling of blades.

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