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ASSESSMENT OF AERODYNAMIC AND ACOUSTIC CHARACTERISTICS OF COUNTER-ROTATING OPEN ROTORS

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Abstract

Paper contains the results of experimental data assessment for open rotor COMBY2 model developed in CIAM (open rotor COMBY1 model has been developed by CIAM in frame of European project DREAM). Comparison between experimental results and aerodynamic and acoustic calculations executed by means of software developed in CIAM is presented.

Comparison of integral characteristics (absolute values of thrust and torque, thrust coefficients, power coefficient and Open Rotors efficiency) and local parameters of the flow (radial distributions of flow parameters downstream and upstream the rotors, pressure distribution on hub downstream and upstream the rotors) is carried out for aerodynamic performances. The analysis of numerical and experimental results shows good qualitative coincidence.

At the same time it is possible to consider quantitative coincidence only satisfying, especially for integral characteristics (thrust coefficient, power coefficient and efficiency). The reason of notable disagreement between calculation and experiment, probably, is the difficulties in definition of forces and torques acting on hub of each rotor. These values should be taken away from experimental data to get forces and torques acting only on blades for which calculation data is obtained.

Calculation of acoustic characteristics of open rotor models has been performed by means of CIAM software 3DAS. Pulsation fields in near field, directivity diagrams and spectrums in far field have been obtained. Comparison of calculated and experimental data is also presented for acoustic characteristics.

Nomenclature

CRF – Counter-Rotating Fan;
CROR – Counter-Rotating Open Rotor;
GTF – Geared Turbofan;
BPF1 – 1st Blade Passing Frequency;
BPF2 – 2nd Blade Passing Frequency;
V – flight velocity;
n – rotation frequency;
D – outer diameter of the rotor (front row);

$J = \frac{V}{nD}$ – rotor pitch;

$C_T = \frac{F_N}{\rho n^2 D^4}$ – thrust coefficient;

$C_p = \frac{Pw}{\rho n^3 D^5}$ – power coefficient;

$E_f = \frac{F_N * V}{Pw}$ – efficiency;

$\bar{E}_f = E_f / \eta^*_{ad}$, – dimensionless quantity of efficiency;

$\bar{E}_{f1}$, $\bar{E}_{f2}$, $\bar{E}_{f1\&f2}$ – dimensionless quantity of efficiency of first rotor, second rotor and open rotor as a whole;

η^*_{ad} – adiabatic efficiency in specification TOC;
TOC – Top of Climb mode;
M_f – inlet Mach number.

1. Introduction

One of perspective direction in aviation propulsion engineering is the development of turbofans with counter-rotating open rotors. Such engines have high fuel efficiency. Calculations have shown that economy of liquid fuel during cargo transportation by aircraft equipped with such engine can make 20%÷30% in comparison with fuel consumption of modern aircraft powered by turbofan engine. At the same time CRF engines have some peculiar disadvantages, in particular, higher noise levels vs turbofan engines with high and ultrahigh bypass ratio with similar characteristics.

In the given work it is presented the aerodynamic and acoustic optimization for the model of COMBY2 open rotor (fig. 1) on base of CFD and CAA software, developed in CIAM. Version V2.0 of pusher type OR developed in frames of European project DREAM [1-3] was taken as initial prototype of OR.

Aerodynamic optimization was performed both for the purpose of increasing the efficiency, and for improvement of OR acoustic characteristics. For this purpose it was done the smoothing of aerodynamic loading along blade chord by cutting of its peaks near leading edges. Besides, it was performed the redistribution of aerodynamic loading on height of OR blades by unloading blade tip sections and loading of mid sections. Such ideology of aerodynamic and acoustic characteristics improvement has been developed in [4]. Redesign of OR blades by obtained modified loading was done on the basis of 3D inverse problem solution [5].

In order to decrease the intensity of tip vortexes and their interaction it was used rotor clipping (reduction of second rotor diameter by 21.3 %).

When design and optimization works have been finished, model blades of COMBY2 OR have been manufactured and tested at TsAGI: aerodynamic and acoustic characteristics of COMBY2 on takeoff and landing modes have been investigated in subsonic wind-tunnel T-104 at Mach numbers for inlet flow M=0.15÷0.25, and in transonic wind-tunnel T-107 it has been studied aerodynamic and acoustic characteristics for climb and cruise modes.

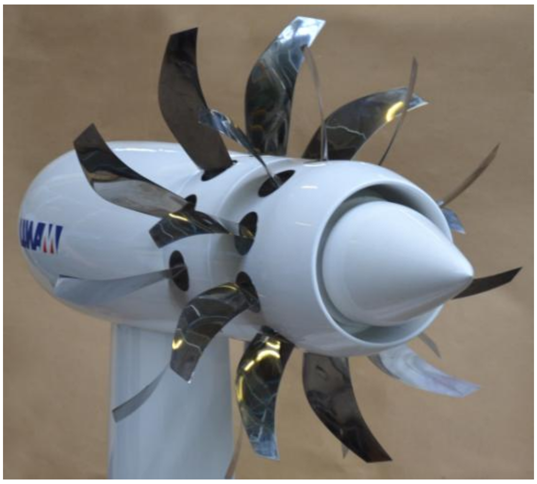
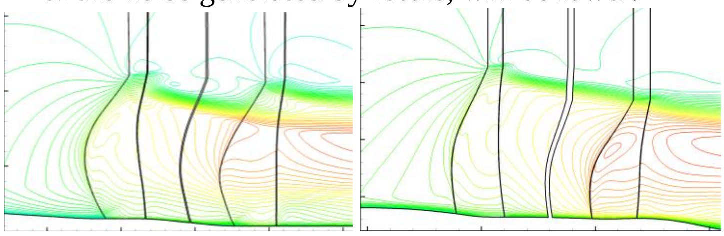


Fig. 1. Research project of pusher type OR

One of concept configuration of CRF is the scheme with the reduced diameter of second rotor (clipping). The main difference between the given scheme and configuration with same diameter of rotors consists in operating conditions of the rear rotor (fig. 2).

In case of rotors with the same diameter, the tip vortex from the first rotor passes directly through the second rotor, and for a case with the clipped rear rotor the tip vortex from the first rotor can pass over the rear rotor. As interaction of the second rotor with edge wakes and tip vortexes of the first rotor is considered as key reason of open rotor noise on modes which are important from environmental noise certification point of view, it is assumed that in case of tip vortex passing over the rear rotor, the intensity of the noise generated by rotors, will be lower.



a) same radial dimension　　б) reduced radial dimension

Fig. 2. Principal scheme of the flow at take-off (Mach number contours M_f=0.18)

2 Technique of aerodynamic re-profiling

In order to achieve specified above purposes it was developed the cyclic process of calculation of the analysis and correction of the blade shape which is presented on fig 3 in the form of the block-scheme. Basic elements of iterative process are three software (3DFS, 3D-INVERSE.EXBL, 3DAS). Application of each element is the following:

3D-INVERSE.EXBL – software for profiling (calculation of the blade shape for specified distribution of loading on base of 3D inverse problem, RANS) [5].

3DFS – software for direct numerical simulation of flow field (stationary and non-stationary approach, accounting the interference effects, RANS and URANS) [6].

3DAS – software for direct numerical simulation of noise generation in a source (solution of non-stationary Euler equations for perturbations) [7].

Also the special program for direct correction of the profile in blade random section is used.

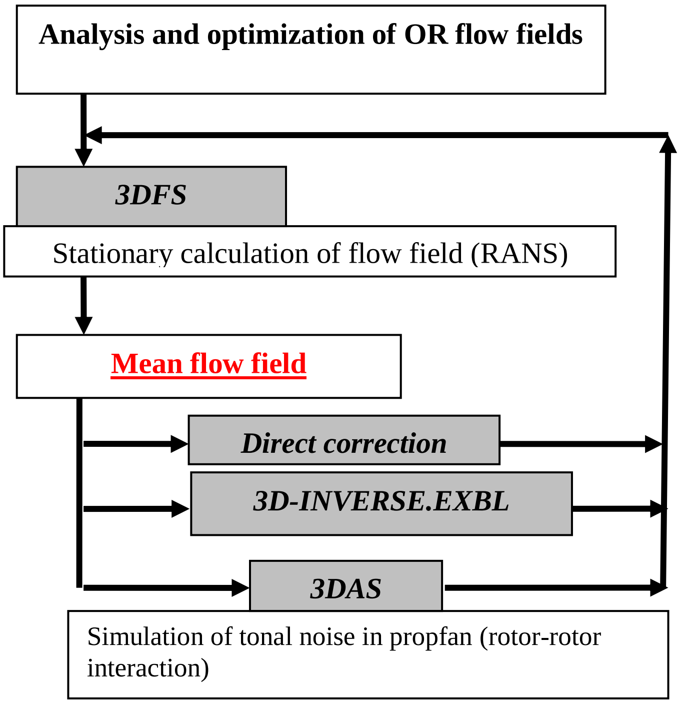


Рис. 3 Block-scheme of iteration process of rotor re-profiling

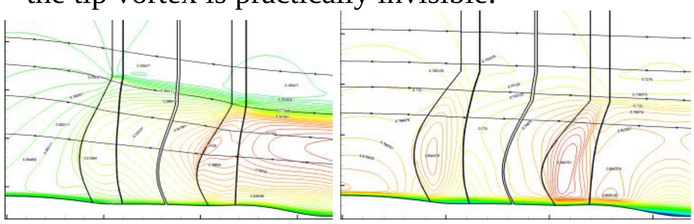
3 Aerodynamic prototype and purposes of re-profiling

At working out the aerodynamic design the basic attention was given to two modes: take-off and top of climb. On both modes it is important to achieve high thrust (for corresponding height and velocity). Thus on the first mode it is important to reach high acoustic characteristics, while on the second mode it is important to provide high efficiency. The main geometrical and aerodynamic characteristics of a prototype for take-off and top of climb are presented in table 1.

Table 1

Geometrical and operation performances		
Rotational speed of the rotors is the same		
Number of blades in 1st rotor – 12		
Number of blades in 2nd rotor – 10		
Outer diameter per first rotor >4 м		
Aerodynamic performances		
	Take off	Top of climb
M_f	0.2	0.73
Thrust % F1 + F2	87.5%	98.2%
Thrust ratio F1 / F2	1.093	1.034
Torque ratio M1 / M2	0.95	1.18
$\bar{E}_{f1}$	*0.692*	*0.914*
$\bar{E}_{f2}$	*0.606*	*1.047*
$\bar{E}f1\&f2$	*0.649*	*0.975*

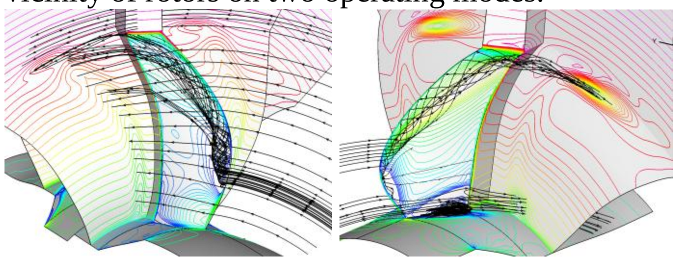
Results of 3D stationary calculation in the form of flow field averaged in circumferential direction for both modes are presented on fig. 4. High intensity of tip vortex in take-off mode is visible. At the same time in top of climb mode the tip vortex is practically invisible.



a) take-off (M_f =0.2) б) TOC (M_f =0.73)

Fig. 4. Field Mach numbers averaged in circumferential direction (absolute coordinates)

Fig. 5 and 6 show field of Mach numbers in relative system of coordinates for the nearest vicinity of rotors on two operating modes.



front row rear row

Fig. 5 Field of Mach numbers and streamlines at take-off mode (M_f =0.2)

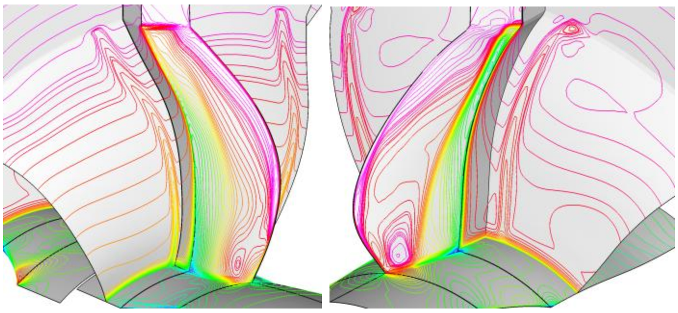


Fig. 6 Field of Mach numbers and streamlines at TOC (M_f=0.73)

From the presented materials it could be seen that take-off mode is extremely heavy. Angles of attack at each rotor are high; therefore the stream is in condition close to stall on all blade height. On periphery of front and rear rotor it is well visible the tip vortexes of significant intensity which considerably exceed edge wakes. The stream with flow separation (area of low speed flow correspond to blue curves) is observed on blade roots. The main problem of a prototype at take-off mode is insufficient thrust which is 12.5 % lower than it is required by technical specification. The increase of blades' angles of attack at take-off mode up to the level of required thrust conducts to efficiency decrease on 4 % (an optimal variant with highest efficiency).

In TOC mode the prototype has more favorable picture of the flow providing thrust close to specified value. Nevertheless, even in this case it does not meet the technical specification. The main disadvantage of a prototype is low thrust efficiency ($\bar{E}_{f1\&f2}$=***0.975*** against required $\bar{E}f_{1\&f2}$=***1.0***) and essential disbalance of the torques between the rotors (M1/M2=1.18), which also is required to be reduced to a minimum (0.95-1.05). Changing the blades angle of attack of the first and second rows before obtaining the required thrust at performance of the specified torque ratio corresponds to thrust efficiency $\bar{E}_{f1\&f2}$< ***0.982***.

Design disadvantage of a prototype is too thin leading and trailing edges of the blades that they could be manufactured from composite materials.

Performed preliminary analysis of prototype's thrust and constructive characteristics has shown that it order to meet specified requirements it is necessary the essential redistribution of loading both on blade height and between front and rear rows, i.e. the re-profiling of blades (the ratio of blade quantity in rows is saved).

Making a start from the listed disadvantages of a prototype, the following tasks for re-profiling are defined:

1. Increase of thickness in vicinity of leading and trailing blade edges up to level necessary to provide possibility of composite materials application in manufacturing.

2. More than 10 % increase of thrust at take-off mode without essential falling of efficiency at saving the torque ratio in a range (0.95÷1.05) and without noise level increase towards a prototype (operated on raised frequency to produce the same thrust).

3. Efficiency increase in TOC mode up to level $\bar{E}f_{1\&f2}$=***1.0*** at reduction of torque ratio on rotors in a range (0.95÷1.05) and keeping thrust level.

4. Optimization of blade shape at take-off mode (3D-INVERSE.EXBL)

The thrust of existing prototype in take-off mode is more than 10 % smaller than required. The required level of thrust can be reached by increasing the angles of attack of each rotor. But, as calculations executed by means of ***3DFS*** and ***3DAS*** software have shown, such approach is unacceptable. Numerical simulation has shown that at meeting the requirements, first of all for torque ratio on rotors, the thrust increase is accompanied by:

1. significant efficiency decrease down to level $\bar{E}f_{1\&f2}$=***0.607*** (at best combination of angles);

2. increasing the area of flow separation on hub of second rotor;

3. growth of level of generated noise, because of significant strengthening of tip vortex generated by front rotor and increase of edge wake (more developed).

Thus, in order to achieve specified target it has appeared to be necessary to perform a re-profiling of rotors by means of ***3D-INVERSE.EXBL*** software. The new shape of blades is found as result of 3D inverse problem solution, providing calculation of blade shape for specified distribution of loading in radial and longitudinal direction (additionally it has been redistributed the loading between rotors). Thus, not only loading on blades has been increased, but also its redistribution along profile chords has been made. In particular, for improvement of acoustic and aerodynamic properties, the loading maximum has been moved from blade leading edge. Fig. 7 represents the specified modification of static pressure distribution at profile for section of the first rotor (50 % of height). On fig. 8 it is shown the new shape of the section corresponding to 53 % of first rotor height which was obtained as a result of calculation. Fig. 9 and 10 contain the initial and obtained (by solving inverse problem) isentropic Mach number distributions along profile for this section.

During the optimization it was widely used the experience accumulated during research works under open rotor of D-27 engine for An-70 aircraft [4,7].

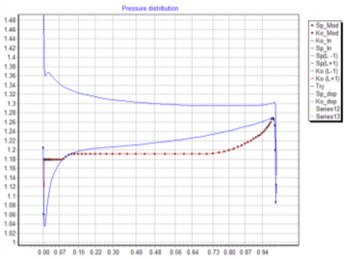


Fig. 7. Specified modification of static pressure distribution along profile (R1 Section - 50% blade height)

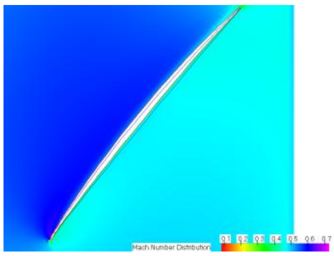


Fig. 8. Initial and optimized blade profile (R1 Section - 53% blade height)

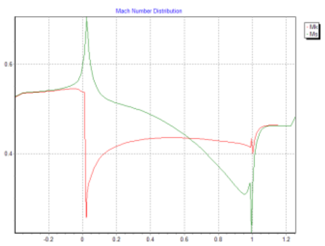


Fig. 9 Mach number distribution for initial profile (R1 Section - 53% blade height)

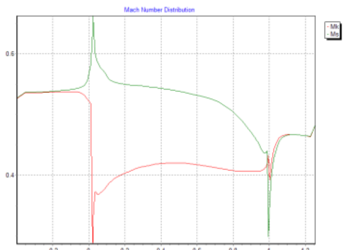


Fig. 10 Mach number distribution for optimized profile (R1 Section - 53% blade height)

The integral characteristics of rotors calculated by means of ***3DFS*** [6] software are presented in table 2. Comparison of pressure distributions on blades of prototype and optimized variant is presented on fig. 10.

Table 2

	prototype	optimization
F1 + F2,%	87.5%	100.8% (+13%)
F1 / F2	1.093	1.086
M1 / M2	0.95	1.02
$\bar{E}_{f1}$	***0.692***	***0.706***
$\bar{E}_{f2}$	***0.606***	***0.663***
$\bar{E}f1\&f2$	***0.649***	***0.685 (+3%)***

prototype optimization

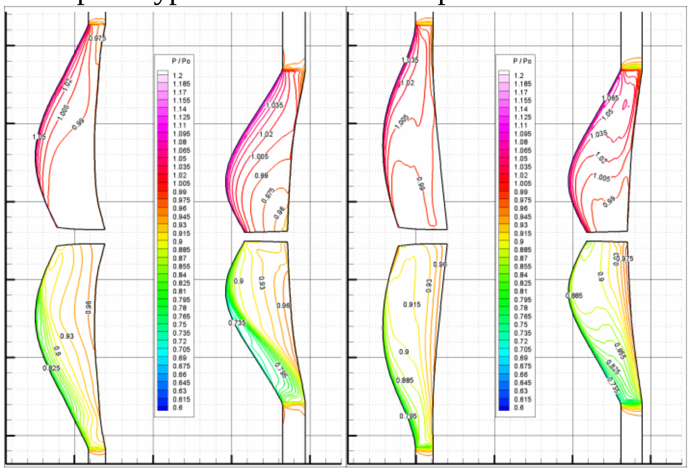


Fig. 10. Distribution of static pressure on blade surfaces of prototype and optimized variant (M_f=0.2)

As a result of rotor re-profiling in take-off mode it is provided the 13 % increase of thrust at 3 % efficiency growth and saving the torque ratio on rotors within the specified range. Besides, flow separation in root section of rear rotor is eliminated at maintenance of more uniform distribution of aerodynamic loading along chord in comparison with prototype.

5. Optimization of blade shape in TOC mode (3D-INVERSE.EXBL)

The relative TOC mode has low level of efficiency ($\bar{E}f1\&f2$=***0.975***) and unacceptable torque ratio on rotors (1.17). Therefore the purpose of re-profiling is work redistribution between rotors and efficiency increase. Rotors' thrust is at desired level and cannot be reduced (thrust growth is allowed). Change of blades' angle of attack (blade sections turn and direct calculation by using ***3DFS***) does not give required result; and the result of this procedure is similar to the results for take-off mode.

As well as in the previous section, for this mode new distributions of loading on blades have been defined and calculations of blade shape by means of ***3D-INVERSE.EXBL*** software have been executed. In order to increase the efficiency, Mach numbers before the shock wave located at trailing edge have been reduced for both blades by means of inverse problem. Besides, negative blade loadings observed near leading edge have been reduced for first rotor blades.

The integral characteristics of rotors obtained by ***3DFS*** software are presented in table 3. Comparison of pressure distributions on blades of a prototype and on blades of optimized variant is presented on fig. 11. Though integral characteristics are close, pressure distributions have noticeable difference. The main source of distinctions is work redistribution between rotors.

Table 3

	prototype	optimization
F1 + F2	98.2%	99,0% (+1%)
F1 / F2	1.034	0,971
M1 / M2	1.18	1,072
$\bar{E}_{f1}$	***0.913***	***0,945***
$\bar{E}_{f2}$	***1.046***	***1,057***
$\bar{E}f1\&f2$	***0.975***	***0.9988 (+2%)***

prototype optimization

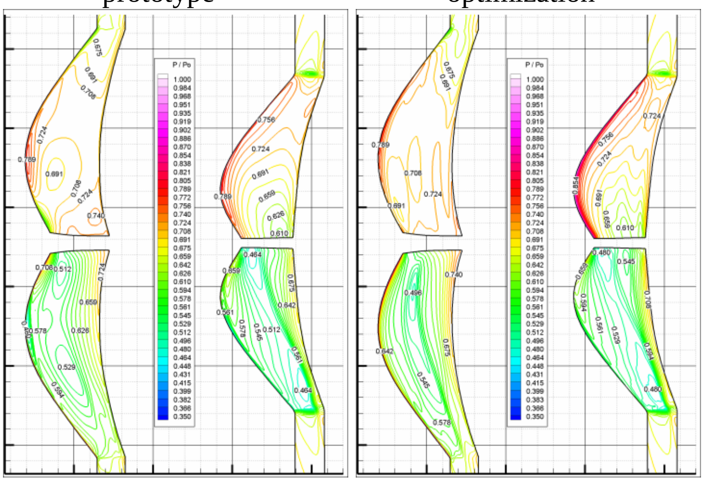


Fig. 11. Distribution of static pressure on blade surfaces of the prototype and optimized variant ($M_{f=}0.73$)

6. Averaged variant of blades (new prototype)

Analysis of two optimized variants at mode change shows the decrease of efficiency with regard to a prototype on this mode. So, the variant optimized for take-off mode, has efficiency reduction in TOC mode more than on 1.5 % in comparison with prototype.

Averaged variant of blades is obtained on base of two optimized variants of blades (for take-off mode and TOC mode). Averaging is executed with various weights for all sections defining blade profile. The optimized variant corresponded to TOC mode has highest weight as the most sensitive to changes of profile shape.

Results of direct numerical analysis of characteristics for rotor averaged variant by means of ***3DFS*** software [6] in comparison with previous variant are presented in table 4 (take-off mode) and in table 5 (TOC mode).

Table 4. Take-off mode (M_f=0.2)

	prototype	optimization	averaging
$\bar{E}_{f1}$	***0.694***	***0.706***	***0.682***
$\bar{E}_{f2}$	***0.607***	***0.696***	***0.6227***
$\bar{E}f1\&f2$	***0.65***	***0.6845 (+3%)***	***0.6526 (+0.2%)***
M1 / M2	0.9556	1.0200	**1.0104**
Fx_1+2 (N)	89783.3	104450 (+14%)	**100310 (+10%)**

Table5. TOC mode (M_f=0.73)

	prototype	optimization	averaging
$\bar{E}_{f1}$	***0.9138***	***0.94***	***0.9125***
$\bar{E}_{f2}$	***1.047***	***1.056***	***1.033***
$\bar{E}f1\&f2$	***0.975***	***0.9965 (+2%)***	***0.971 (-0.3%)***
M1 / M2	1.1786	1.0724	**1.0464**
Fx_1+2 (N)	21134.08	21313.4 (+1%)	**22471 (+6%)**

The resulted averaged variant satisfies the requirements on thrust and torque ratio. However, this variant has low efficiency in TOC mode and small profile thickness in the vicinity of leading and trailing edges. Thus, it is necessary to increase the profile thickness in the vicinity of the edges and further optimization at TOC mode to increase the efficiency from 0.9714 up to 1.0 with saving thrust and torque on rotors.

7. Optimization of new prototype of rotor. Results of aerodynamic design

As mentioned above, new prototype satisfies the requirements for thrust characteristics, but has small thickness of the profile near edges and low efficiency in TOC mode. TOC operation mode is extremely sensitive to changes in the shape and blades angle of attack. For this reason, further optimization has been performed for TOC mode.

As a result of numerous iterations (which will not be detailed discussed) in accordance with block-scheme shown on Fig. 3, it has been achieved the required level of aerodynamic perfection for counter-rotating open rotors of pusher type. Re-profiled blades have significant differences from the original prototype, including the following which should be noted:

1. profile thickness has been significantly increased in the vicinity of the edges;

2. load in sections of the blades and thus the shape and characteristic dimensions of control sections have been redistributed;

3. work between the rotors has been redistributed to keep the torque ratio at (0.95 ÷ 1.05);

4. turning angles of the blades have been reduced at transition from mode to mode.

Comparison of integral characteristics of a prototype with the modified variant is presented in table 6. Fig. 12 shows the pressure distribution on blades' surfaces for initial and re-profiled variant in TOC mode. Fig. 13 represents the pressure distribution on blades' surfaces for initial and re-profiled variant in take-off mode. Flow features of the initial and optimized variant in take-off mode are presented on fig. 14. Some improvement of flow character is visible, in particular, reduction of tip vortex size.

Table 6

	Take-off (M_f=0.2)		TOC (M_f=0.73)	
	prototype	optimized	prototype	optimized
$\bar{E}_{f1}$	***0.694***	***0.676***	***0.914***	***0.944***
$\bar{E}_{f2}$	***0.607***	***0.599***	***1.047***	***1.057***
$\bar{E}f1\&f2$	***0.65***	***0.6377 (-1%)***	***0.975***	***0.9995 (+2%)***
M1 / M2	0.9556	1.008	1.1786	1.046
Fx_1+2 (N)	90812	103630 (+14%)	21134	21666 (+2.5%)

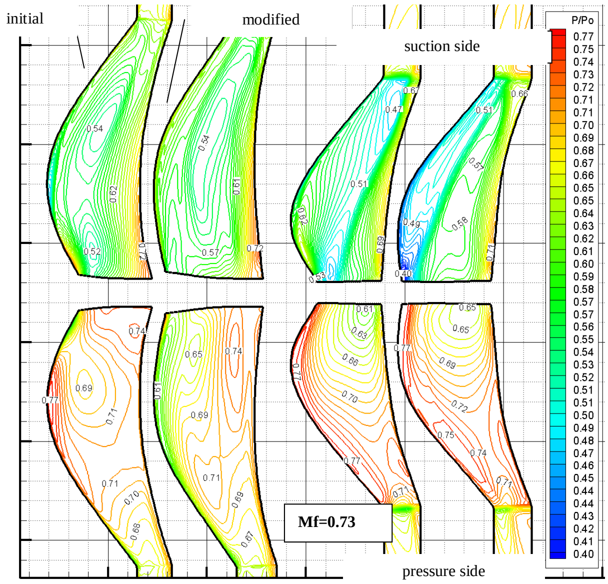


Fig. 12. Pressure distribution on blades' surfaces for initial and re-profiled variant. TOC mode

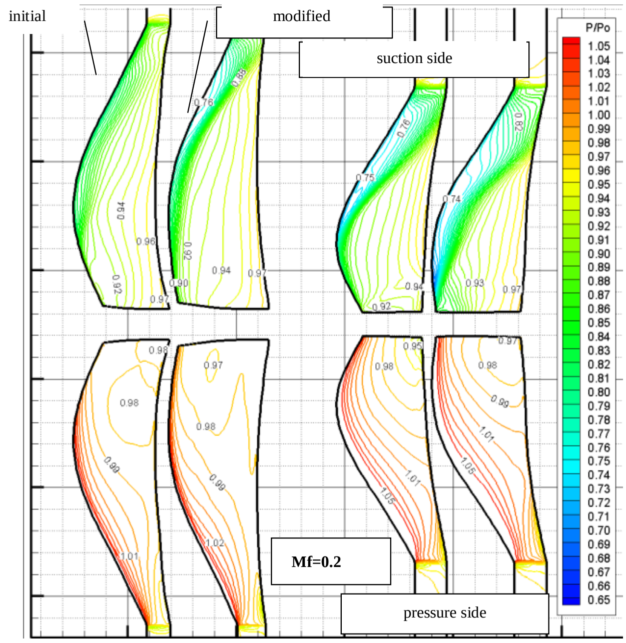
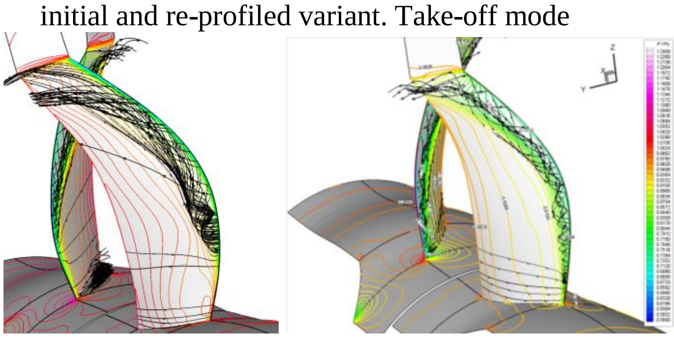


Fig. 13. Pressure distribution on blades' surfaces for initial and re-profiled variant. Take-off mode

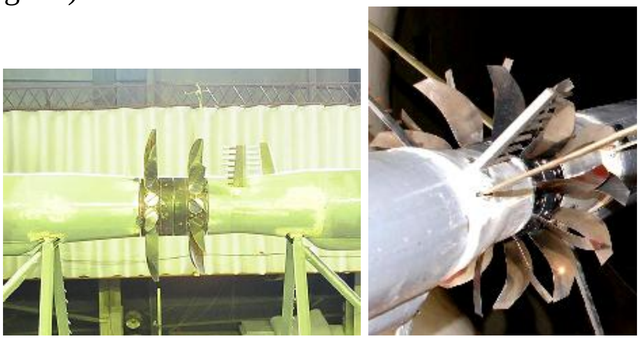


a) b)

Fig. 14. Streamlines and pressure distribution on blades of initial a) and modified b) variants. Take-off mode

8. Results of experimental investigation of characteristics of optimized open rotor model

For experimental investigation of aerodynamic and acoustic characteristics of designed open rotor it has been manufactured a steel model (scale 1/6). Experimental research and manufacturing of OR model have been executed by TsAGI by CIAM order. Tests have been performed at aerodynamic wind-tunnels of TsAGI: T104 (in take-off mode M_f= [0.1-0.3]) and T107 (in TOC mode M_f=[0.6-0.8]) (see fig. 15).



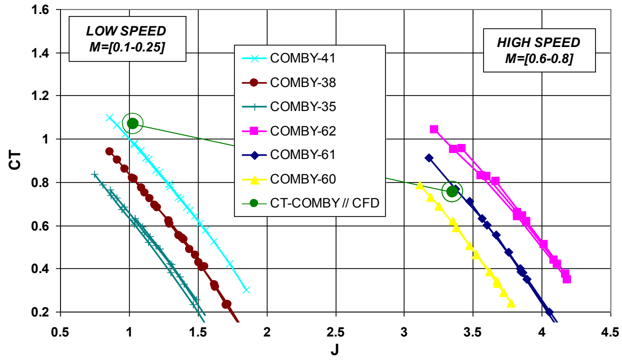
T104 wind- tunnel T107 wind- tunnel

Fig. 15. Model of open rotor in aerodynamic wind-tunnels of TsAGI

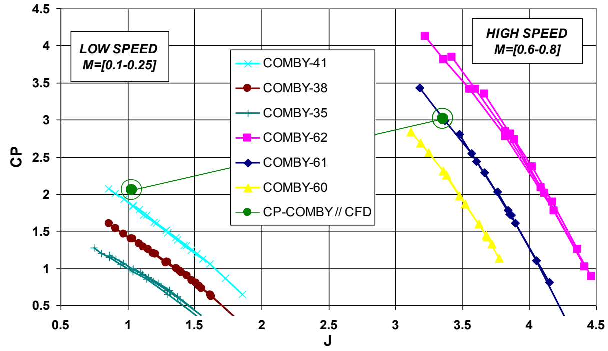
As a result of tests, the aerodynamic and acoustic characteristics are defined and flow fields averaged in circumferential direction downstream the open rotor are measured (static pressure, Mach number, flow direction and total parameters of the flow). Aerodynamic characteristics of the single rotor of front row are additionally investigated, and also influence of the size of axial clearance between rows on aerodynamic and acoustic characteristics has been investigated. Fig. 16 shows the results of aerodynamic tests in comparison with design point on two modes (data is presented in dimensionless parameters accepted for rotors). On each mode three incidence angles of the blade for front and rear rows are considered (difference in incidence angles in take-off mode is ±3°; in TOC mode the difference is ±1°). Comparison of the measured and calculated data shows good coincidence in TOC mode. In take-off mode the experiment shows that open rotor provides required thrust at specified power; but these parameters are reached at higher angle of attack on blades. Two circumstances are the reasons of such mismatch:

1. inadequate description of the flow in radial clearance between the hub and blades (on this mode it is the highest, and during calculations it has been neglected);
2. inadequate account of blades turning for this mode (during model manufacturing the cold shape of blades was defined only by TOC mode as major mode).

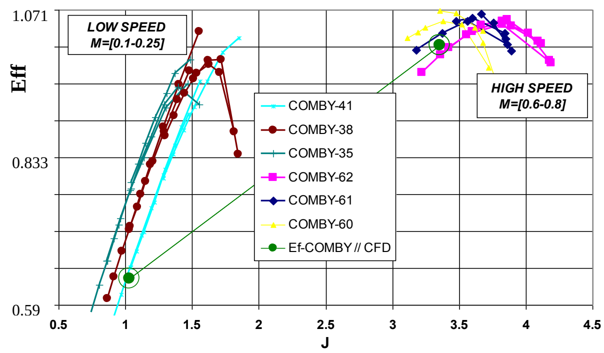
Taking into account these remarks, the coincidence of experimental and calculation data can be considered as good, and the used technique of prototype optimization as suitable for practical application.



a) open rotor thrust coefficient vs rotor pitch (for first row)



б) open rotor power coefficient



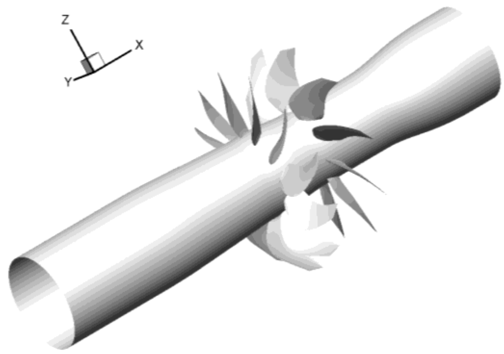
в) open rotor thrust efficiency

Fig. 16. Comparison of calculation and experimental results on two operation modes (for each mode experiment has been performed for three blade angles of front and rear rows)

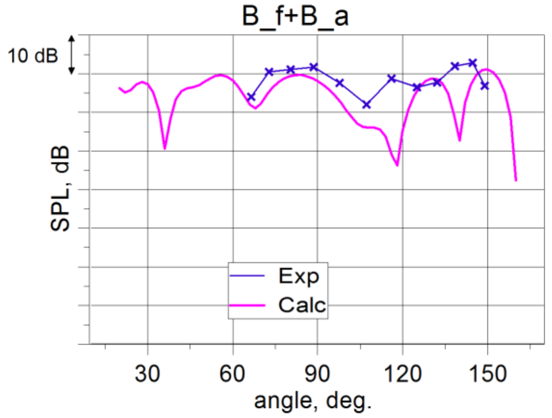
9. The analysis of OR acoustic properties

For investigation of acoustic properties of an open rotor in this work it has been applied ***3DAS*** software developed in CIAM (3 Dimensional Acoustics Solver) [7-10].

3DAS software was used for investigation of acoustic characteristics of open rotors in DREAM project of 7th European Frame Program. In frames of the project for several variants of open rotors it was performed the comparison between the calculation directive diagrams obtained by means of ***3DAS*** software and directive diagrams obtained by experiment. Comparison between results of calculation and experiment has shown that results of comparison are satisfactory for noise on frequencies which are the combinations of BPF1 and BPF2 harmonics. It is observed the qualitative and quantitative (in some microphone positions) coincidence between calculation and experiment. The difference between noise levels on harmonics of blade passing frequencies for separate rotors in calculation and experiment is significant. It, apparently, can be explained by interactions of rotors during experiment with inlet distortion of incident flow created by design of the rig [11]. The example of calculation and experimental directive diagrams for open rotor is presented on fig. 17. More detailed results of software in frames of DREAM project are presented in work [12].



Open rotor V0



Comparison

Fig. 17 Open rotor V0 and comparison between calculation and experiment for first combinational harmonic $f=B_f+B_a$, where B_f – BPF1, B_a – BPF2.

Investigation of acoustic characteristics of developed open rotor COMBY2 has been performed for take-off mode. Calculation directive diagrams are presented on fig. 18 (separately total diagram and directive diagram for noise on combinational harmonics and for noise on BPF harmonics). It is visible, that noise on combinational harmonics is dominated in calculation.

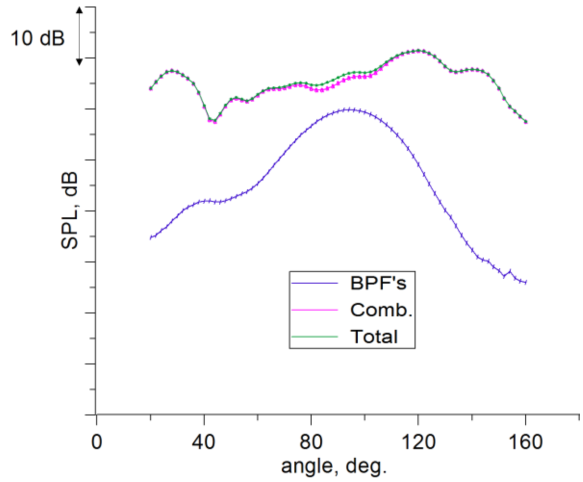
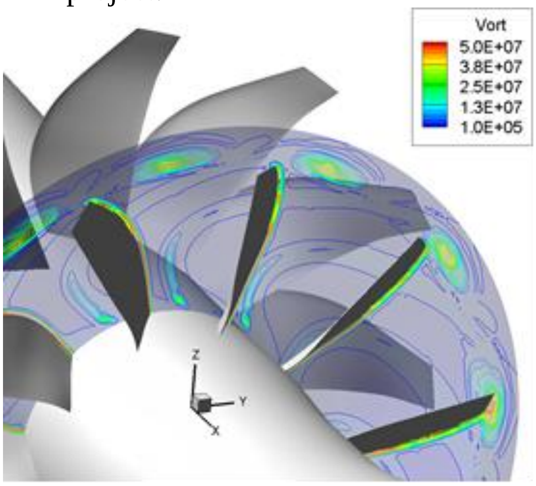
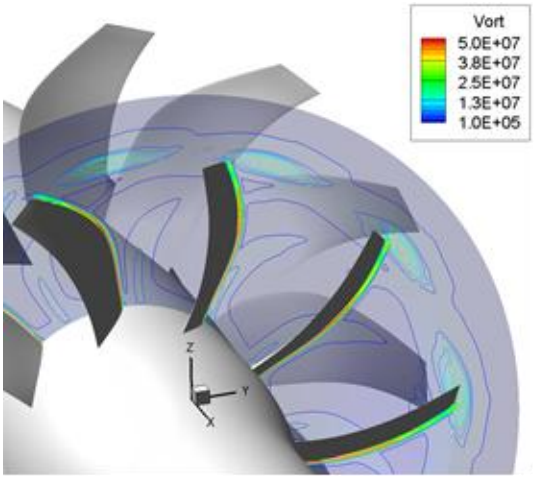


Fig. 18 Total directive diagram of tonal noise and diagrams for noise at combinational harmonics and for noise at COMBY2 BPF's.

The results of calculation have been compared with calculation results of acoustic characteristics for one of the open rotors, developed and tested within the final stage of DREAM project V2.0 [3]. The given variant differed by rather low noise levels. As for the considered variant of the blade of rear rotor it had smaller height of the blades relative to the blades of front rotor. Fig. 19 shows the comparison between intensity of tip vortex downstream the first rotor blades for both variants of open rotors (absolute value of vorticity rot **V** is shown). It is visible that tip vortex intensity of CIAM variant is lower, that should, basically, conduce to noise decrease. Fig. 20 shows the comparison between total directive diagrams for first four combinational harmonics of two open rotors. Corresponding experimental data for the fan developed in DREAM project are resulted on fig. 20. It is possible to assume that OR designed in CIAM essentially does not concede by acoustic characteristics, and, probably, surpasses the OR developed in DREAM project.



DREAM



COMBY2

Fig. 19 Comparison of trace intensity downstream the rotors

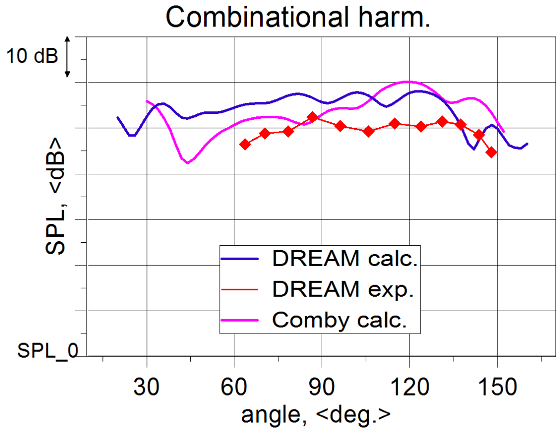


Fig. 20 Comparison of calculation results for DREAM V2.0 and COMBY2 open rotors

Conclusion

In the given work some results of aerodynamic design of blades for CROR first and second stages are presented. The development has been made on the basis of initial prototype. The aim of this development was the creation of a new variant of open rotor with better aerodynamic characteristics in comparison with initial one and with preservation of acoustic characteristics. The optimized variant of open rotor with following characteristics has been developed as a result of the work:

- increased thickness of blade profiles in a vicinity of edges, that allows to use composite materials for manufacturing;
- increased thrust in take-off (+14 %) and TOC (+2.5 %);
- torque ratio on rotors is close to 1 (1.008 – take-off, 1.046 - TOC);
- 2 % higher efficiency in TOC mode (increased up to $\bar{E}_{f1\&f2}=1.0$);
- calculated acoustic characteristics (for tonal noise in take-off), which at least are not worse than in initial variant.

Comparison of calculation and experimental results is performed and it has shown their satisfactory coincidence.

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