ISABE 2013
21st ISABE Conference
September 9-13, 2013 Busan, Korea

29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

Invited lecture ISABE2013-1003

Invited lecture ICAS2014_1026

CHALLENGES IN FAN AND HIGH PRESSURE COMPRESSOR DEVELOPMENT

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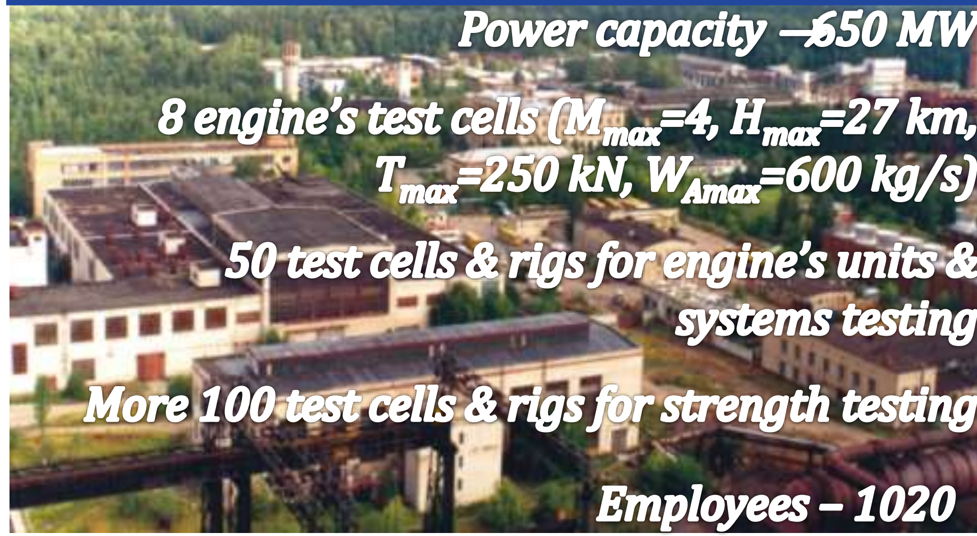


- **BASIC RESEARCHES** *(Gasdynamic, Strength, Heat Transfer, Combustion, Acoustic)*
- **APPLIED RESEARCHES** *(Study of different ABE architecture, ABE's Units & Systems Designing, Maintenance of Reliability and Non-failure operation)*
- **TESTING** *(Testing of ABE's Units & Systems at Real Operational Conditions, Designing of Test Facilities, Test Equipment, and Measuring Tools)*
- **ENGINE'S METHODOLOGY** *(Development & Certification of ABE & GTU, Airworthiness, Authorities Regulation, Authorities Documentation Harmonization, …)*

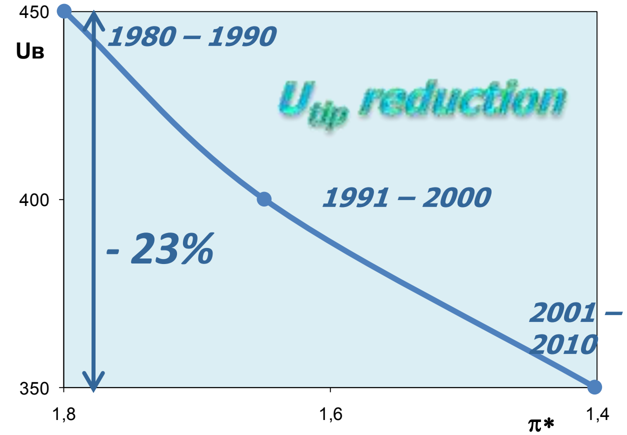
CIAM was founded in 1930

Blades number reduction

1980 – 1990

π^*_f=1.77
U=458 m/s
$G_в/F_{лоб}$=178kg/(s· m²)
Shrouded blades with high aspect ratio

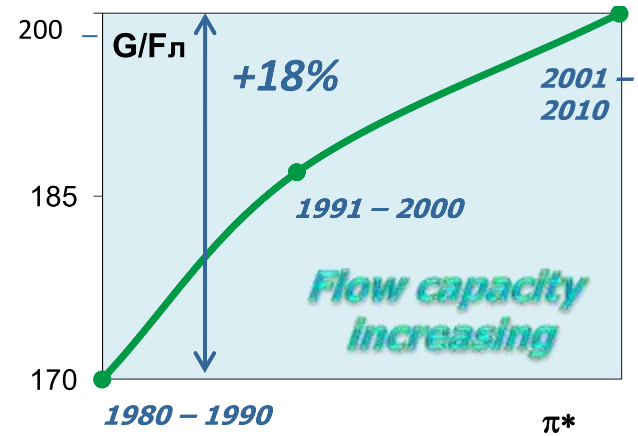
z_{bl}=33



1991 – 2000

π^*_f= 1.68
U=390 m/s
$G_в/F_л$=185.9kg/(s· m²)
Wide chord blades

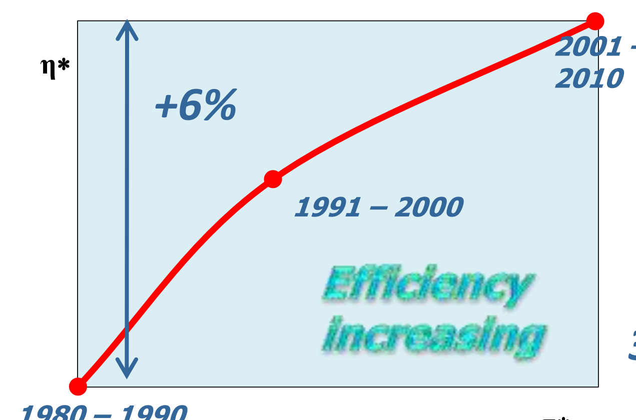
z_{bl}=24



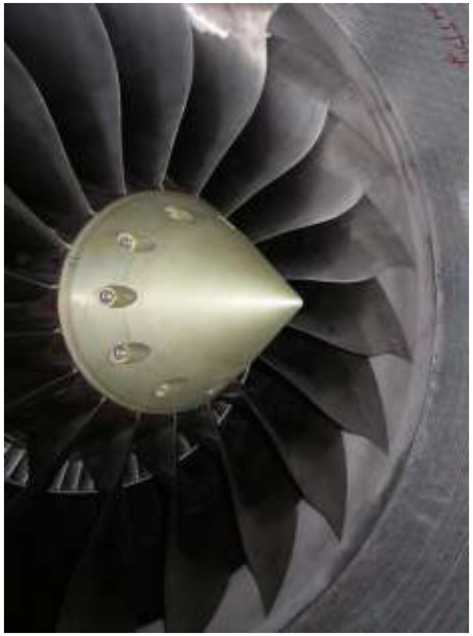
2001 – 2010

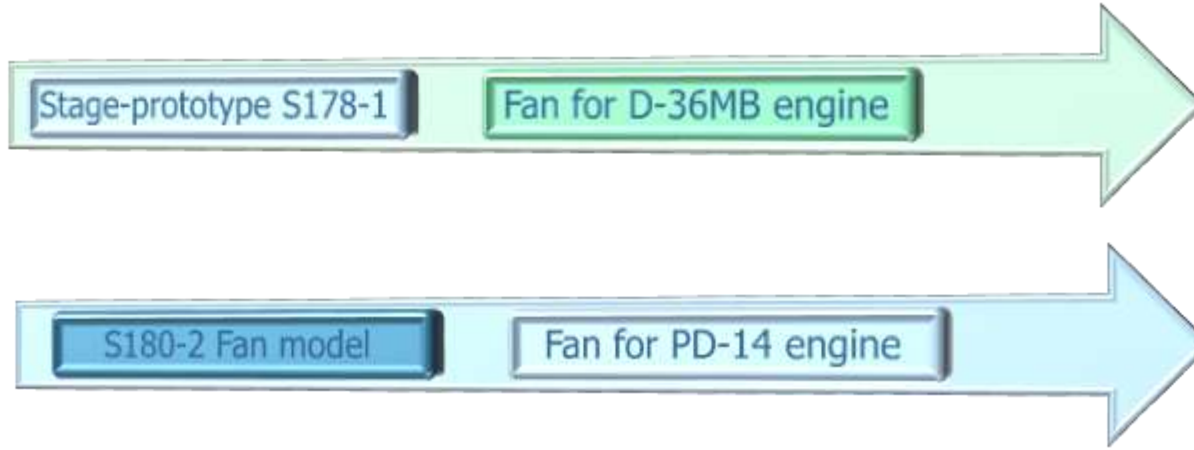
π^*_f=1.48
U=350 m/s
$G_в/F_л$=202kg/(s· m²)
Wide chord blades with variable sweep

z_{bl}=18÷20



Green engine concept. Technologies of advanced engine development. Fan models

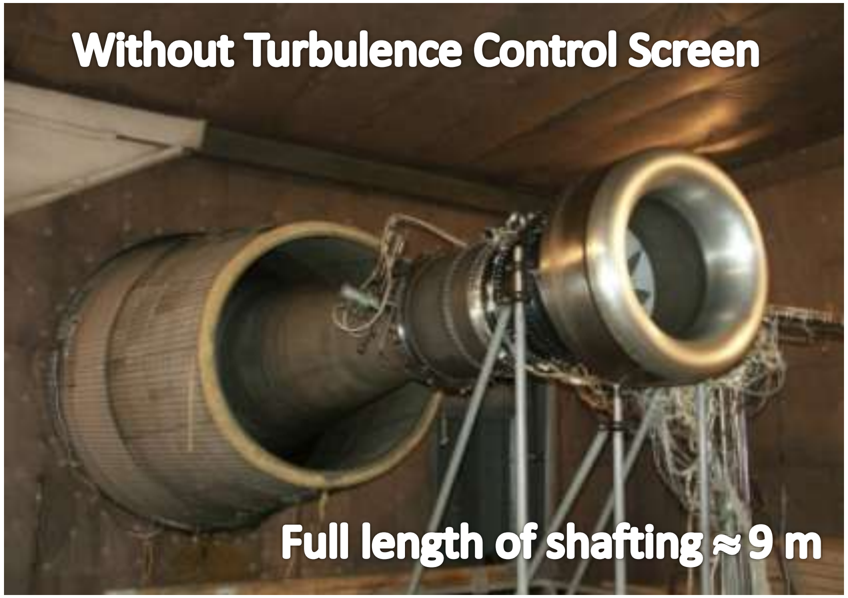




CIAM has developed a family of blades with variable sweep for rotor blades of bypass fan models on different circumferential tip speed:

			Booster	Tests	Engine
C179-2	U_{tip}=390÷400 m/s	$\eta^*_{ad}\approx0.92$	Z=4	2011-2012	PC-12
C180-2	U_{tip}=390÷400 m/s	$\eta^*_{ad}\approx0.92$	Z=3	2011-2012	PD-14
C178-1	U_{tip}=360÷370 m/s	$\eta^*_{ad}=0.91$	Z=0	2007-2011	D-36MB
C190-2	U_{tip}=315÷320 m/s	$\eta^*_{ad}\approx0.92$	Z=4	2014-2015	NEW

Green engine. C-3A test facility. Acoustic, aerodynamic and mechanical performances study



Acoustic test facility with anechoic chamber for development advanced fan of different architecture: ***conventional; counter rotating; geared***

The Advisory Council for Aeronautical Research in Europe (ACARE) identified the new research needs for the aeronautics industry, as described in the new Strategic Research and Innovation Agenda (SRIA – Volume 1), published in September 2012

Noise reduction targets

Goal	**2020** Vision	**2035** SRIA	**2050** SRIA
Aircraft operation	-10 dB (= -50%)	-11 dB	-15 dB (= -65%)

CIAM

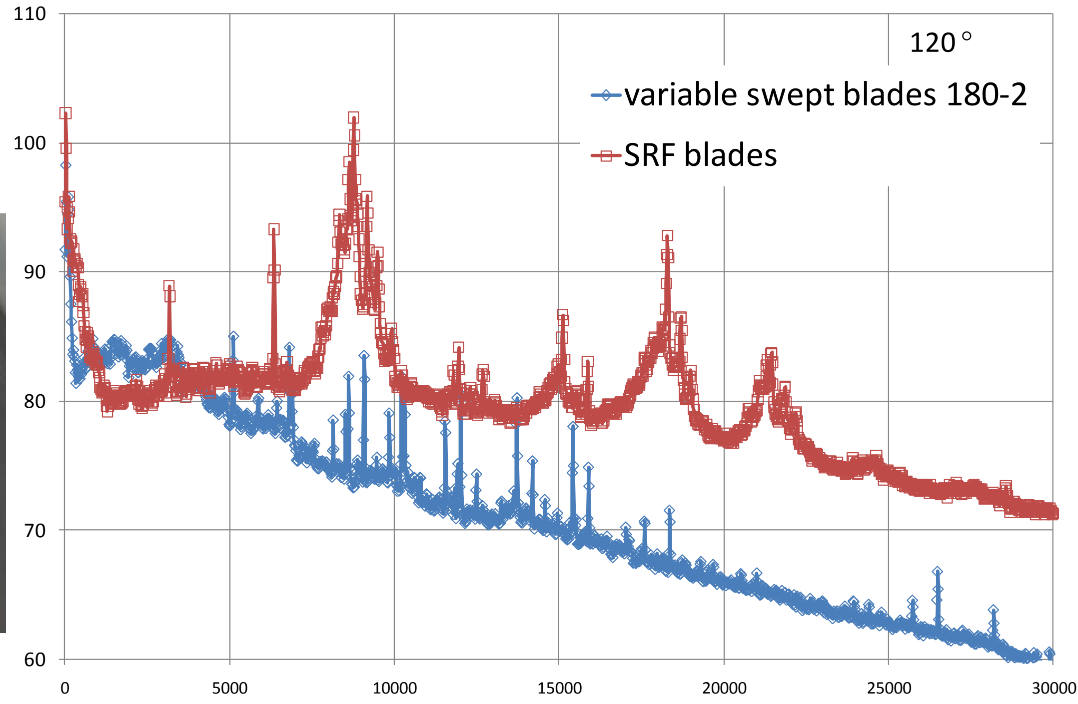
The perceived noise emissions of flying aircraft should be reduced in **2020 by 50%** and in **2050 by 65%**

Comparison of spectra of SRF and fan model with variable swept rotor blade

C-3A test facility with anechoic chamber

C180-2 fan model
(variable swept blade and forward swept in tip section blade)

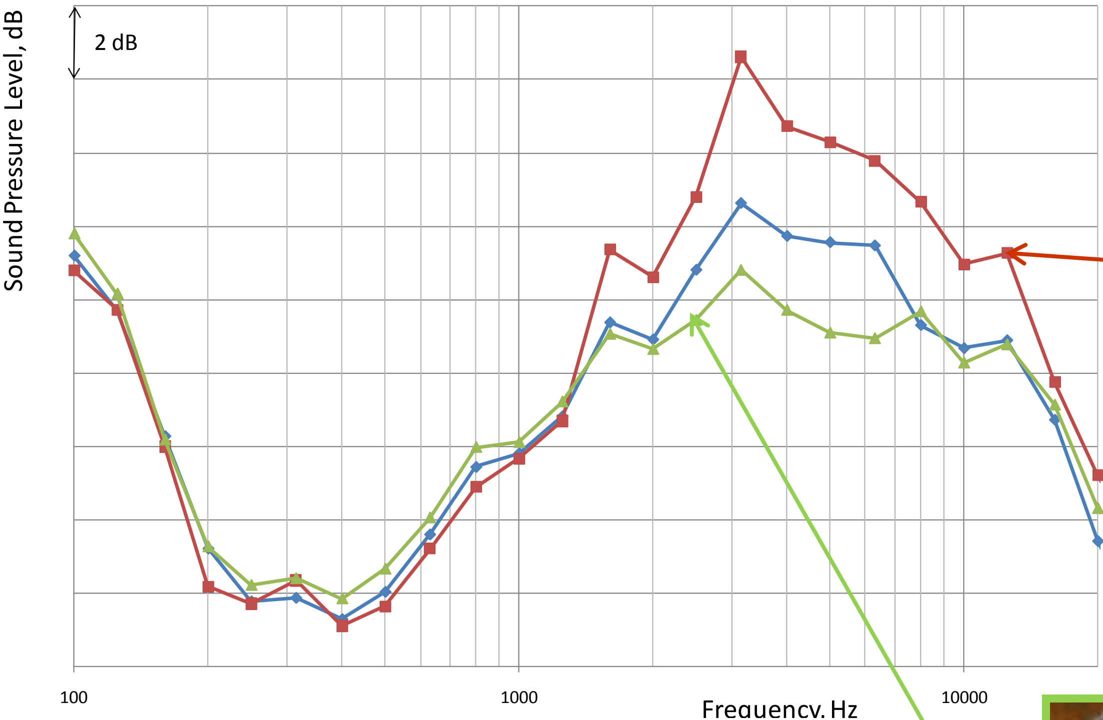
Universal propulsion simulator UPS on base of C180-2 and SRF bypass fan models



SRF model – reference fan 2000 year

Green engine. Fan noise reduction technologies. Swept & Leaned Vanes

C-3A test facility with anechoic chamber



in the opposite direction

in direction of rotor rotation

Approach mode. Rear hemisphere. 120°

It was determined that the tonal noise reduction of the fan model with the scaled factor 1:3 was equal to 1÷3 dB over the wide frequency range

CIAM

European project VITAL. CIAM participated in the project. Fan models, developed and tested in frame of VITAL project

C-3A test facility with anechoic chamber

CRTF1

Project of Snecma, France & CIAM

SRF

Project of Snecma, France

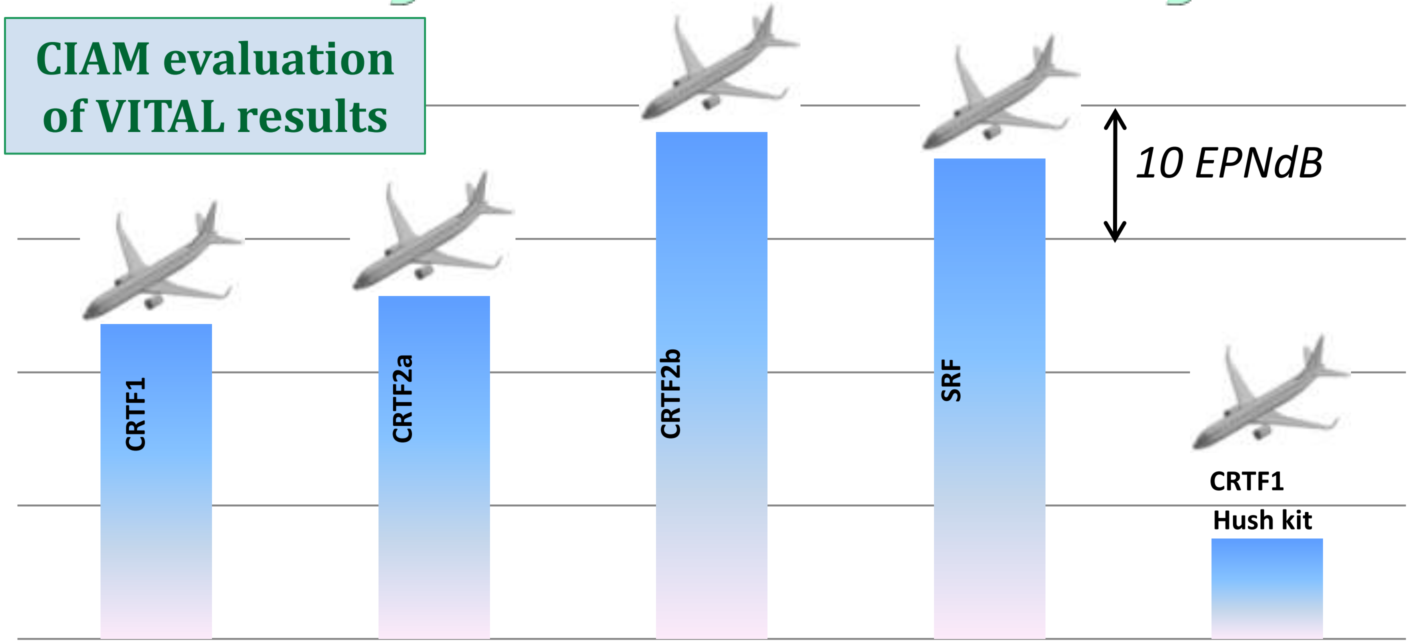
CRTF2b

Project of DLR, Germany

CRTF2a

Project of CIAM

European project VITAL. CIAM participated in the project. Challenges in ducted counter rotating fan development



1. *According to CIAM interpretation of test results the single rotor fan (SRF) model generates noise, higher than of the CRTF1 model on 10 EPNdB.*

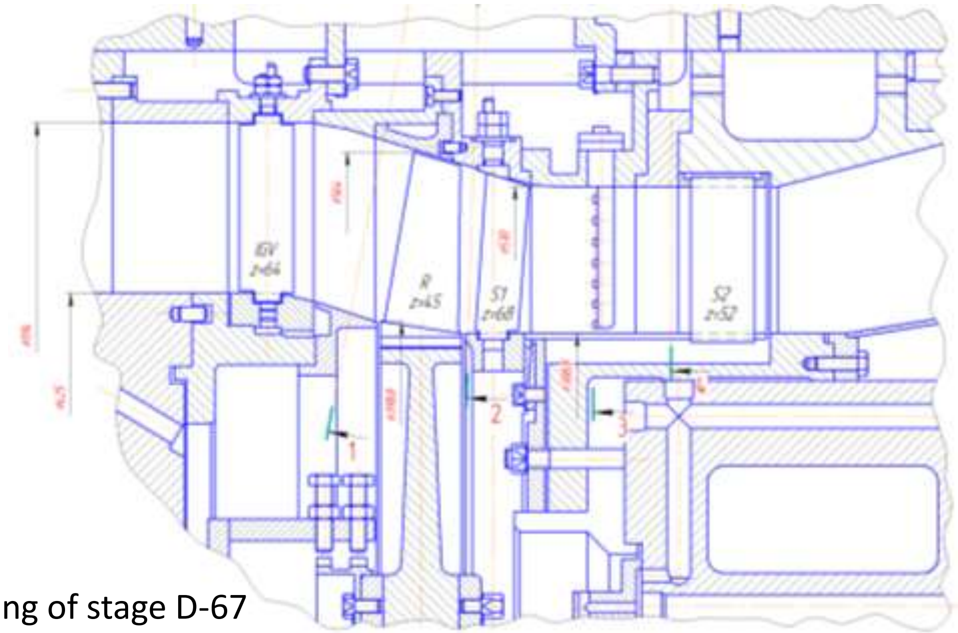
2. *Tests discovered that CRTF2a counter rotating fan model with thickened composite blades generates noise, higher than of the CRTF1 model. Comparison of these fans noise spectra at the same modes showed, that broadband noise of fan model with thickened composite blades was higher than of the model with thin titanium blades on 2…3 dB.*

3. *It is expected that the real estimation of SRF, CRTF1 and CRTF2a fan models noise lies between Snecma and CIAM assessment.*

Tests of different rotor spacing, blade shapes, loading radial distribution and blade number (10x14 and 9x11);
+2.5 point efficiency benefit versus 2000 SoA reference single fan

CIAM UK-3 test rig for investigations of gas dynamic performances of high pressure compressor stage models

Promising test facility and high pressure booster stage for future international projects (MOSCO,…)

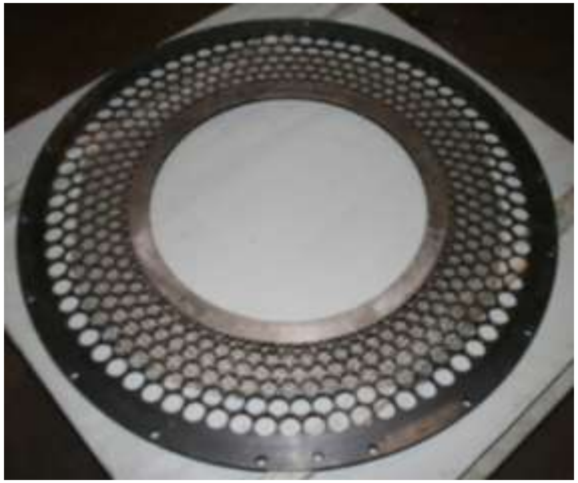


Drawing of stage D-67

Objectives:

1. Study of inlet nonuniformity impact on high pressure compressor stages;
2. Study of casing treatment impact;
3. Investigations of aerodynamic performances of stages with reduced hub diameter

Rotor of stage D-67



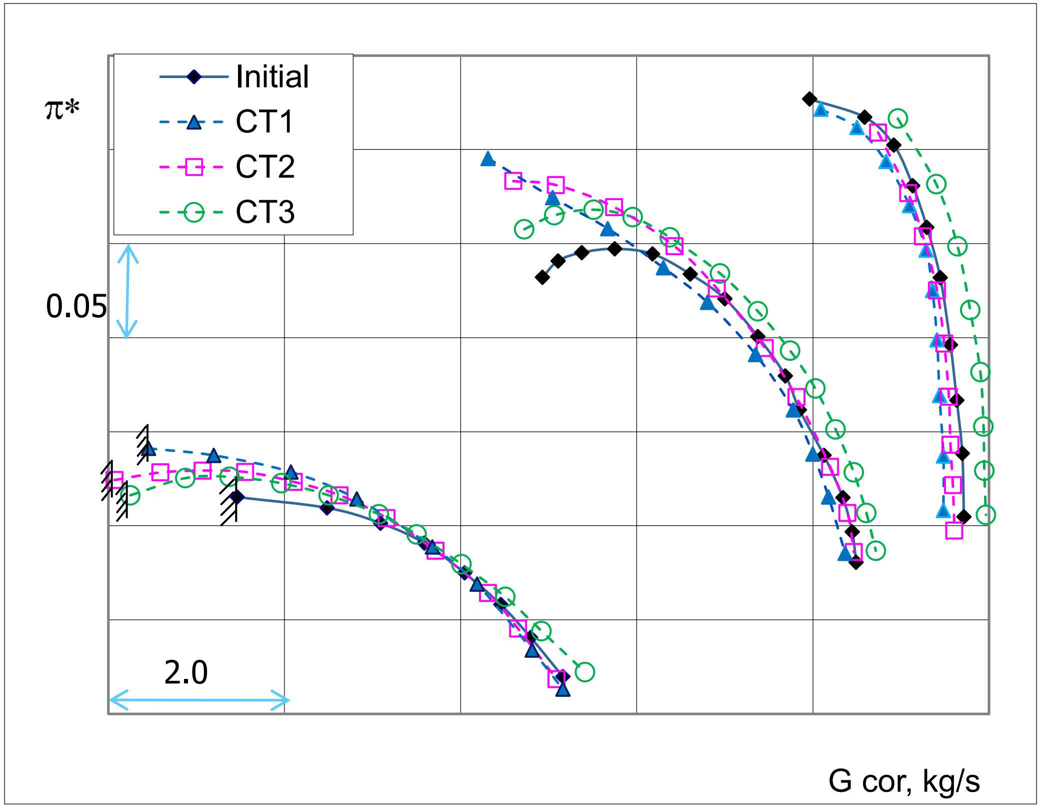
Distortion screen unit for simulation designed radial flow non-uniformity at the stage inlet

CIAM UK-3 test rig for investigations of gas dynamic performances of high pressure compressor stage models

Promising test facility and high pressure booster stage for future international projects (MOSCO,...)

Challenges in development of high loaded high speed booster

Comparison of DC-67 stage total performances with and without casing treatment installation



DC-67 stage

Casing treatment CT – design methodology

For casing treatment design the semi-empirical technique for choice of CT optimal geometrical values and theirs correlations was developed. On base of this technique the following mechanisms of the CT influence on the axial compressor operation were discovered:

– effect of air flow in forward and reverse direction through the space between the rotor tip and the intake duct upstream the rotor;

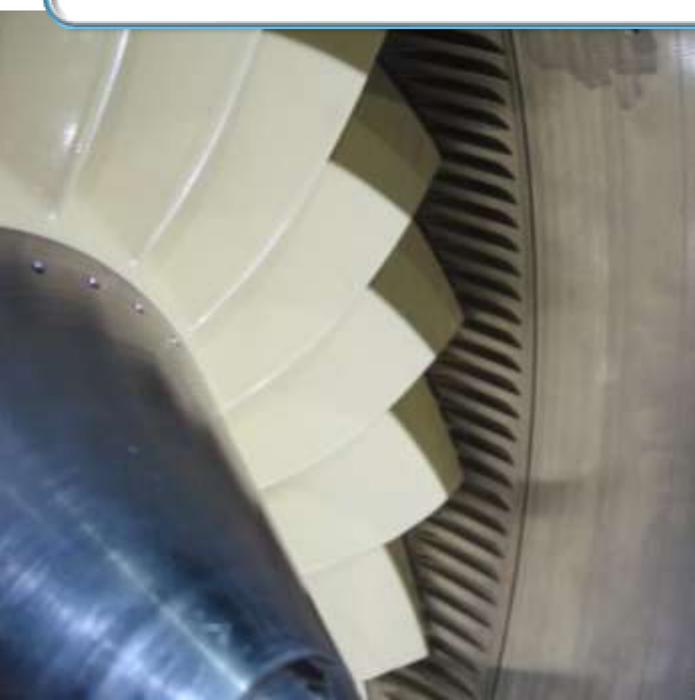
– stall area speed deceleration effect in the stage flow path;

– damping of pulsations on the stage tip at slot type treatment flow

On base of above mentioned methodology the samples of high efficiency CT were developed and tested on different types of one stage and multistage compressors. Owing to CT application significant increase of compressor surge margin was obtained and other design parameters were ensured.

CIAM patents on CT, registered in USSR, USA and RF:

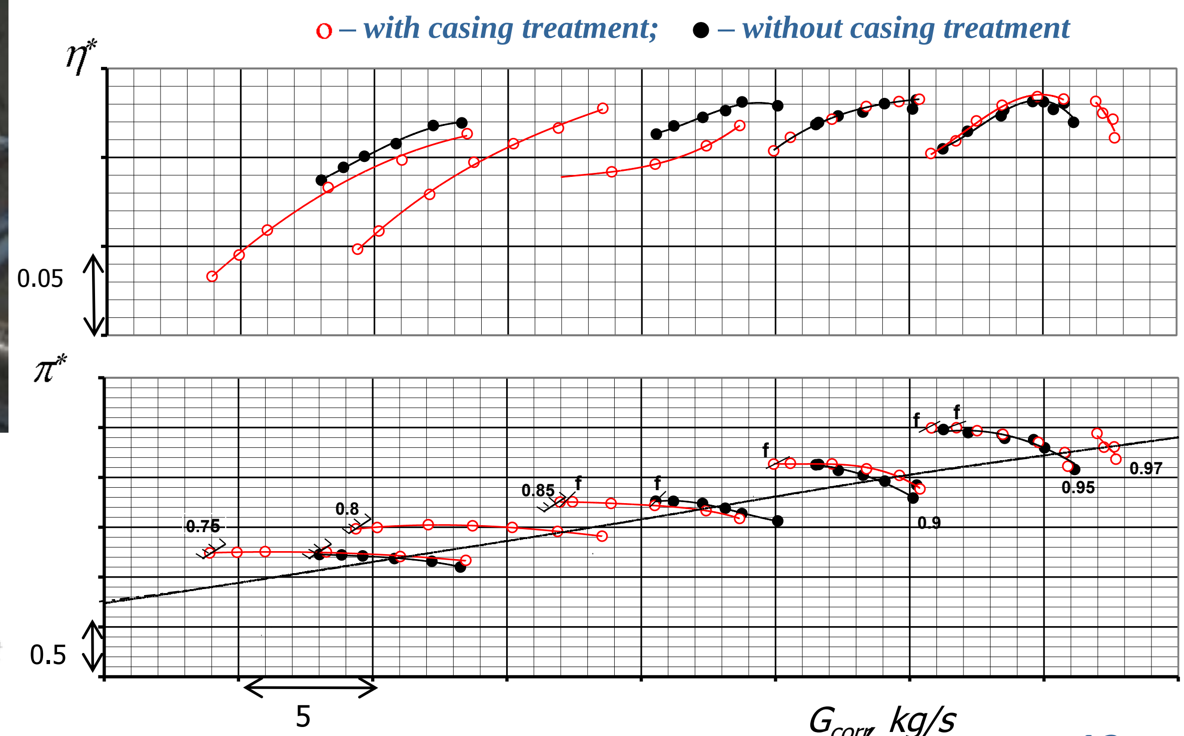
1) **USSR #273364, F 04D 29/47, 1968**
2) **USSR # 757774, F 04D 27/02, 1980**
3) **USA # 4781530, 415-170, 1988**
4) **RF # 2034175, C16F04D 27/02, 1993**



AL-55 (NPO Saturn, Russia) bypass turbofan engine, designed for new generation trainer and light combat aircraft, **MAKS2013** Air show, Zhukovsky, Moscow region

Influence of casing treatment on gas dynamic stability and performances of modified FAN (z=3) of advanced engine

$\bar{n}$		0.6	0.7	0.75	0.80	0.84	0.90	0.95
ΔSM	without	< 0	< 0	7.4	-	6.2	8.6	13.7
	with	18.3	18.5	18.2	16.6	> 12.4	> 11.5	> 14.9

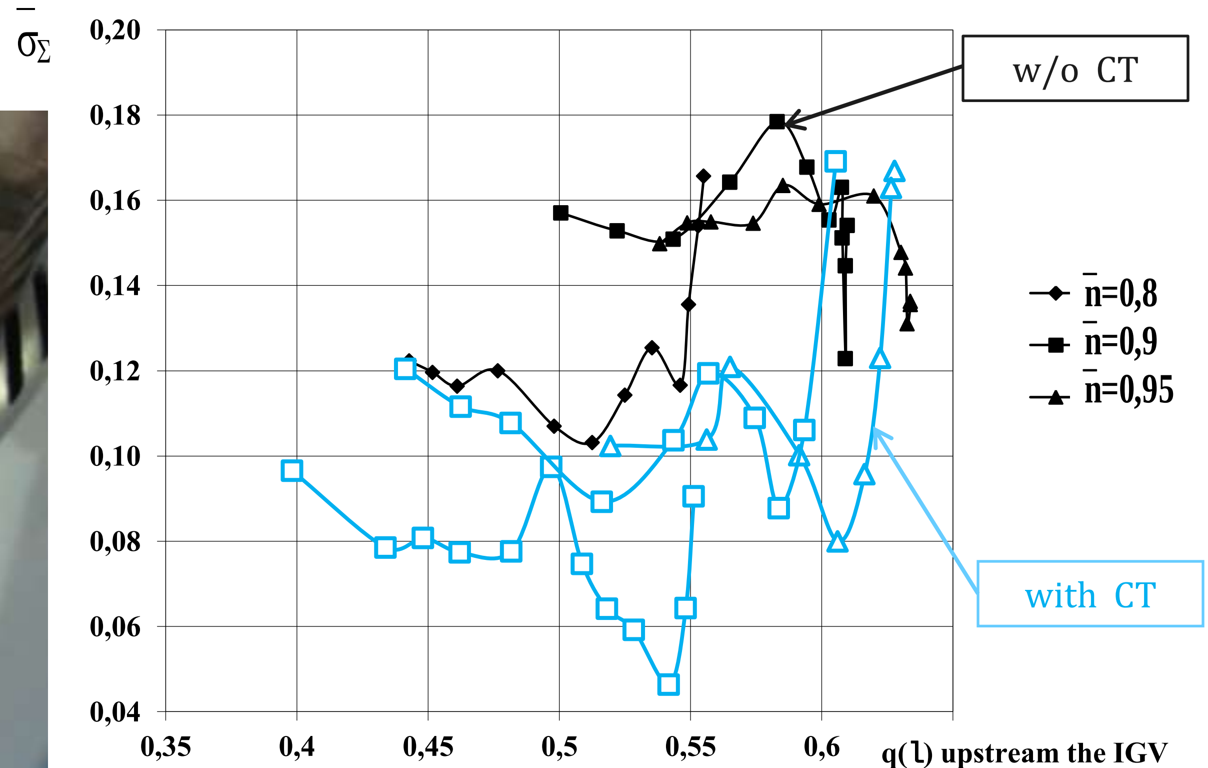


Owing to casing treatment implementation:

The danger of flow separation at operating modes is completely eliminated and sufficient gas dynamic stability margins are provided

Investigations of flow pulsations in wide-chord high pressure fan stage and CT application for compensation goals

MD-120 (NPO Salut, Russia) gas-turbine engine,
MAKS2013 Air show,
Zhukovsky, Moscow region

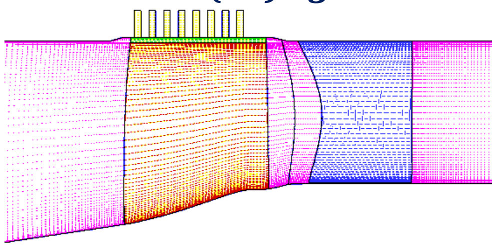


Chord averaged intensity of pressure pulsations measured on casing over the stage rotor: dark markers – stage without CT; light markers – stage with CT

CT is an effective tool for flow pulsations reduction in fan and compressor stages

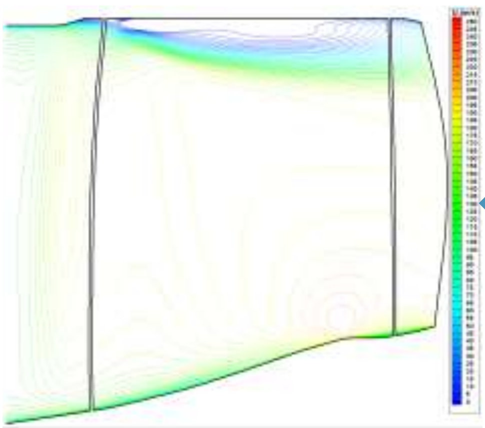
Experimental and numerical study of CT type 1, performed in CIAM

TYPE 1 OF CASING TREATMENT (CT) - grooves

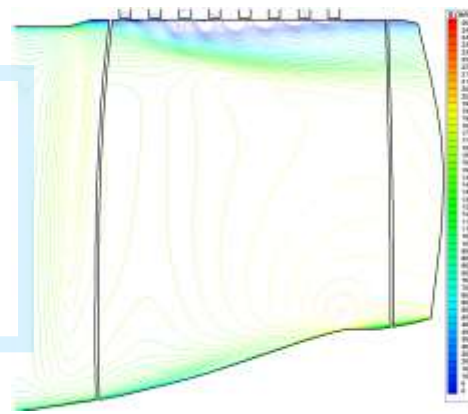


Goal: to compensation the negative influence of increased radial clearance on surge margin and efficiency

4D URANS – 3DFS CIAM in-house software

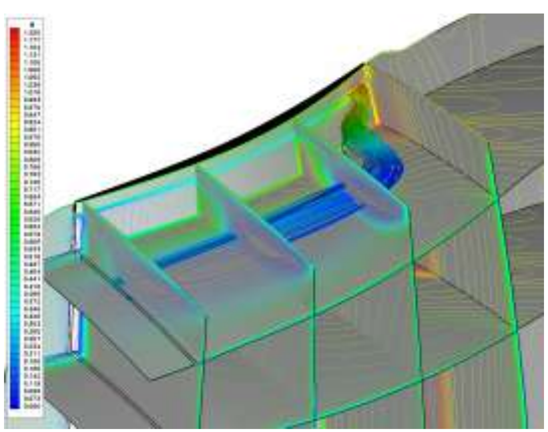


*Large tip clearance.
Near-surge point of characteristic.
Axial velocity level lines.
Mid-pitch of rotor blade-to-blade channel*



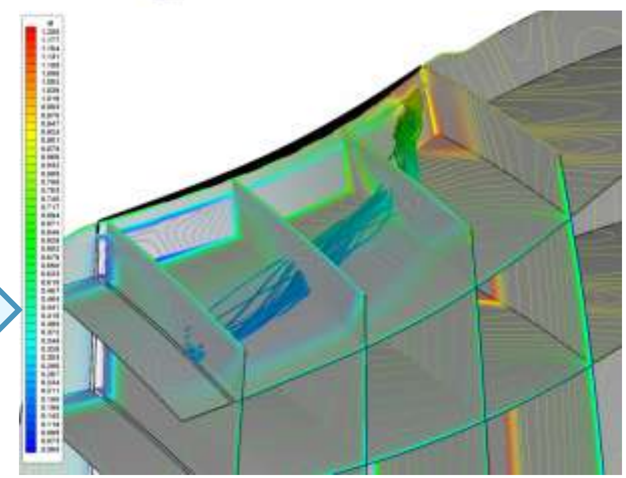
*Large tip clearance +casing treatment.
Near-surge point of characteristic.
Axial velocity level lines.
Mid-pitch of rotor blade-to-blade channel*

4D URANS



Large tip clearance

Large tip clearance equipped with 8 circumferential grooves (casing treatment)

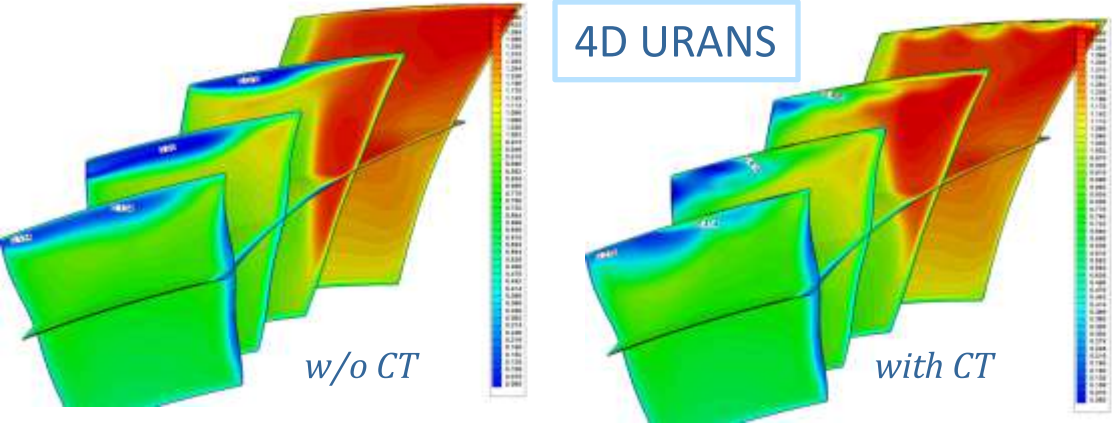


Rotor at near surge conditions. Tip clearance vortex and level lines of Mach number in relative motion

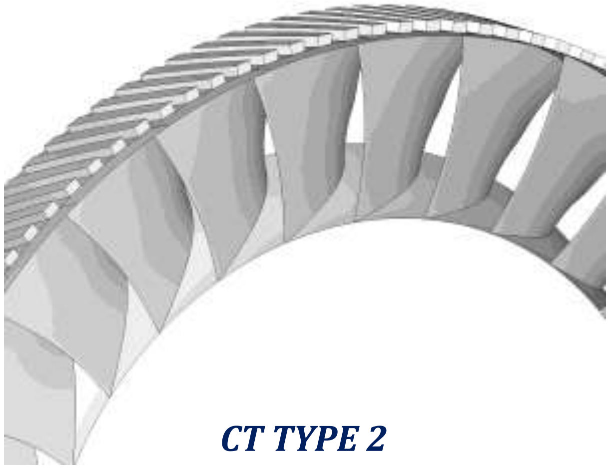
Experimental and numerical study of CT type 2 and 3, performed in CIAM

CT type 2: the size of the low-speed area (blue color) is decreasing

Axial component of velocity in blade-to-blade rotor channel

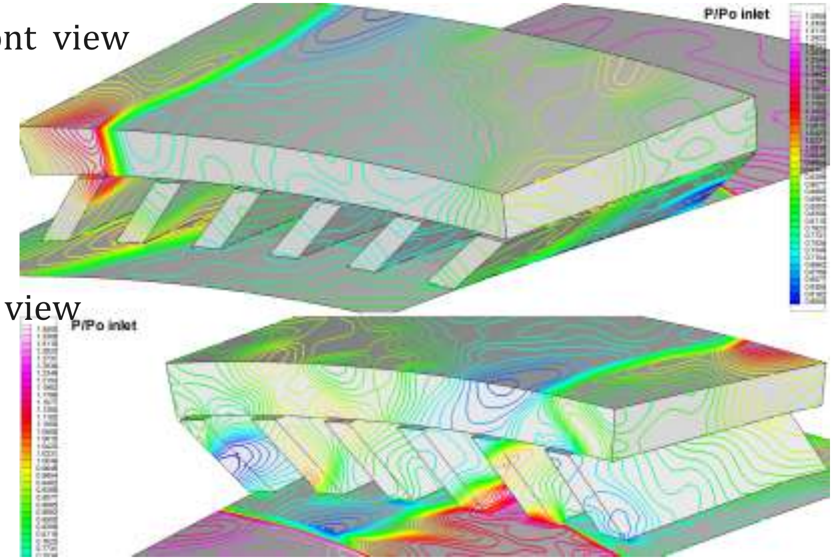


4D URANS



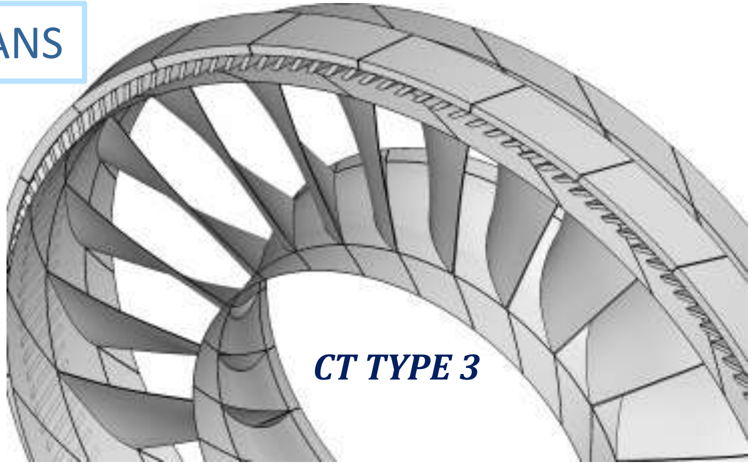
Front view

Aft view



CT type 3: Movement of unsteady shock wave along with the rotor is clearly seen inside the CT cavity

4D URANS

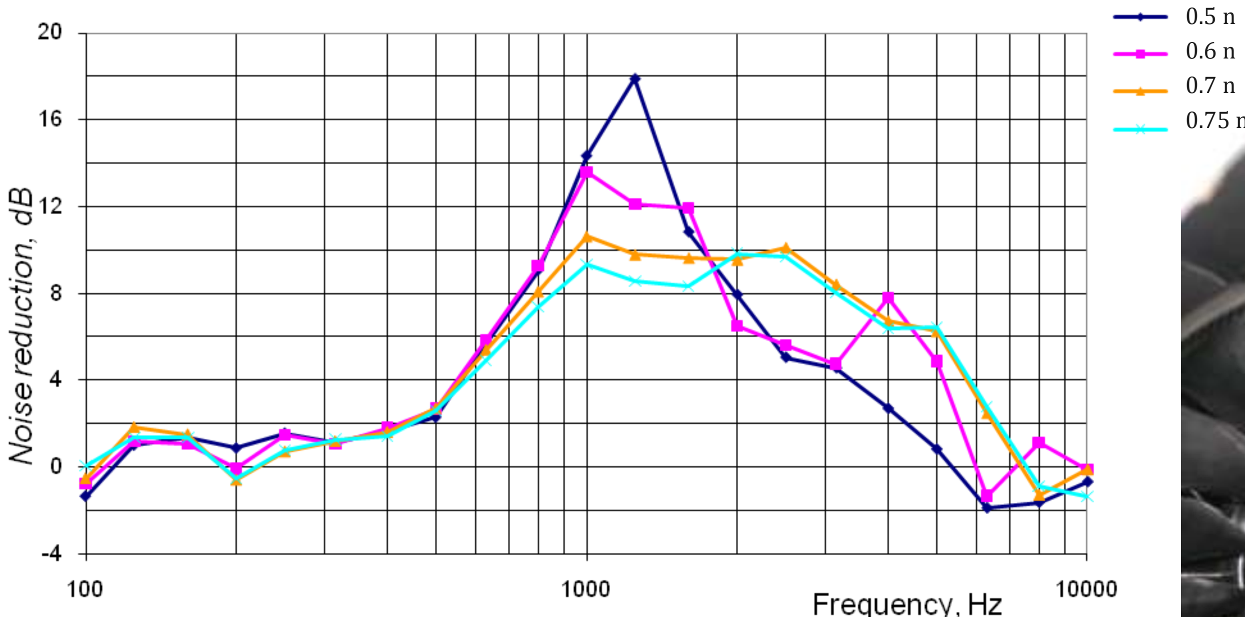


Instant distributions of static pressure in casing treatment (front and aft view)

CT type 3 has provided: - increased efficiency and surge margin at low speed mode;
- impact on performances is insignificant at designed point

Casing treatment applications for fan noise reduction and surge margin increasing

Fan model C178-1 with combined hush kit – (CT + double layer honeycomb liner)



Reduction of broadband noise in C178-1 stage by means of double layer honeycomb liner, installed in the fan intake. The length of the liner is equal to 1 caliber

High efficiency fan parameters
(confirmed experimentally)

Geared version

U_F = 367 m/s; π_F =1.4; η^*_{ad} = 0.91;

Flow capacity:

G_f/F=200 kg/s· m^2

CIAM

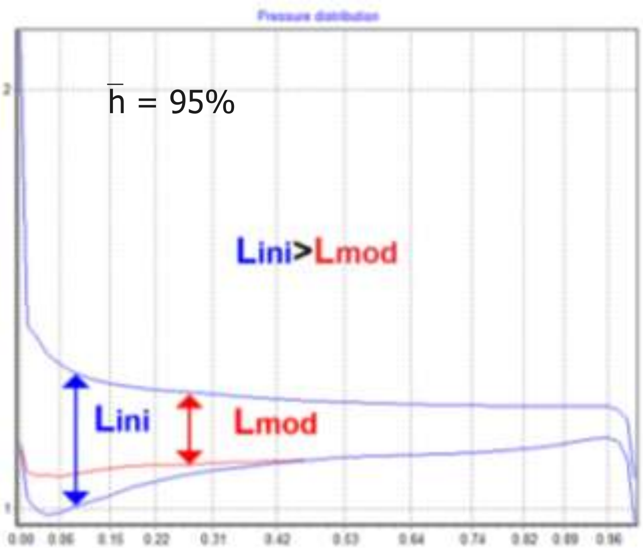
Open rotor. Background

USA
UDF project – GE 1980

Ukraine-Russia
aircraft powered by open rotor – AN-70

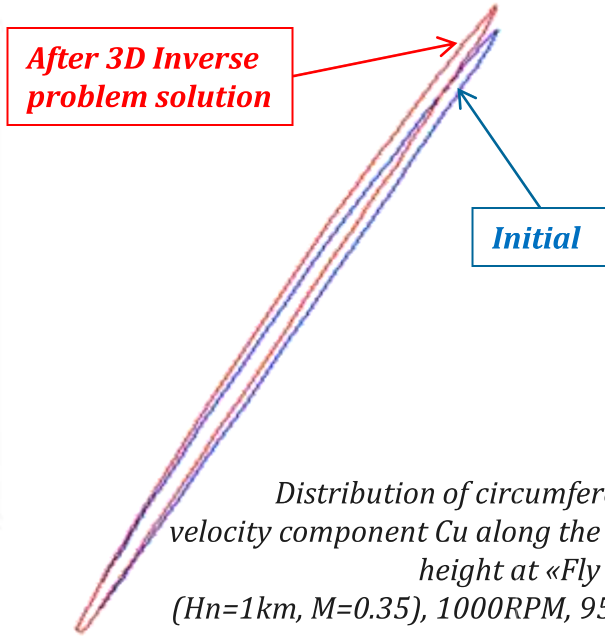
USSR
aircraft powered by open rotor – AN-22

Open rotor. CIAM design concepts of OR on base of 3D inverse problem solution (ASME Turbo Expo CIAM paper GT2008-51173)

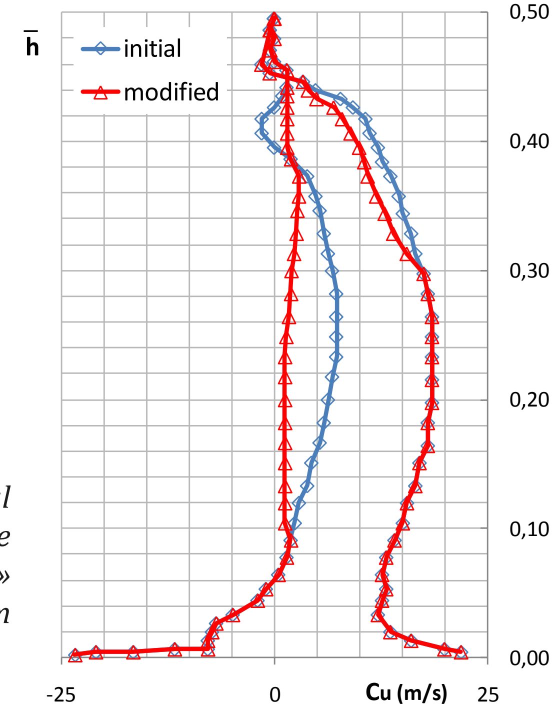


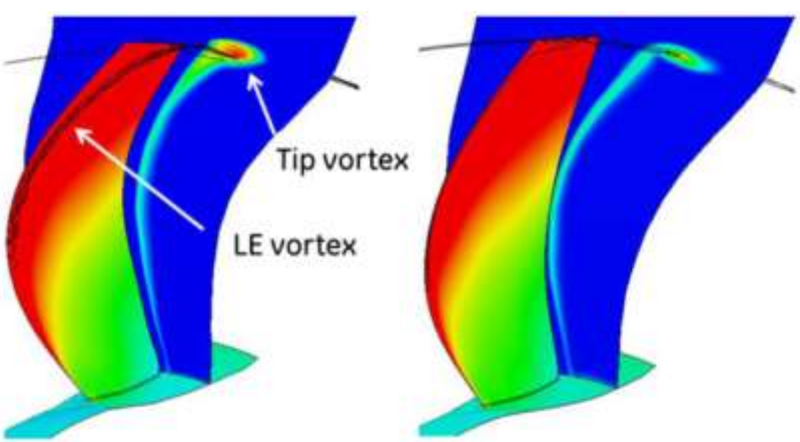
initial load

modified load



Distribution of circumferential velocity component Cu along the blade height at «Fly over» (Hn=1km, M=0.35), 1000RPM, 950mm





(a) (b)

Gradient of aerodynamic loading on open rotor blade is a dominant contributor to open rotor noise.

For noise reduction it is necessary to:

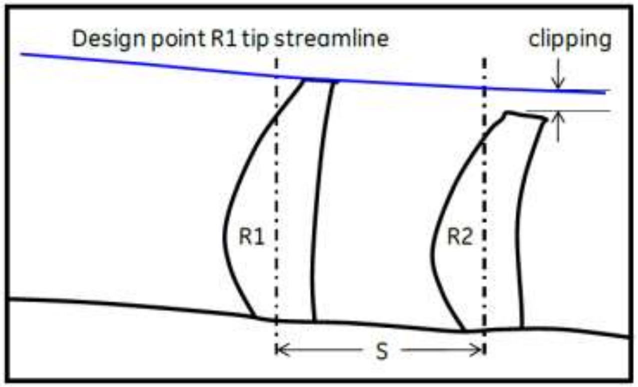
- *decrease the leading edge load peak in order to eliminate the vortex on the leading edge;*
- *reduce the aerodynamic loading in tip sections and redistribute it in the lower sections keeping the same thrust in order to decrease the tip vortex intensity on the rotor blade*

Open rotor. Open rotor designs for low noise and high efficiency

Open rotor design ideas, investigating in USA (GE) and Europe – DREAM and CLEAN SKY projects

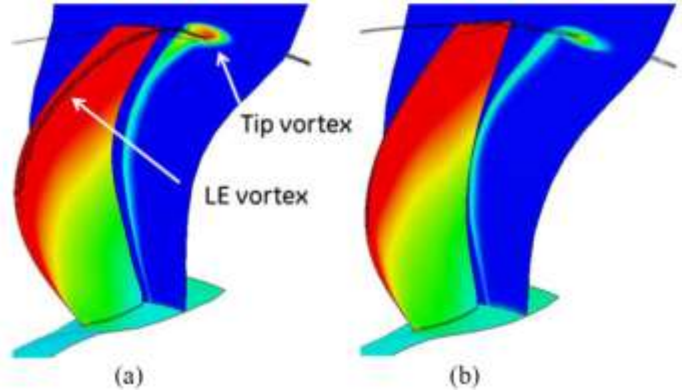
1. R1 tip streamline is higher than R2 tip.
2. LE vortex and tip vortex control:

- at Take off mode possible high incidence angles initiate flow separation from leading edge of rotor blade resulting in LE and tip vortices integration with the increased intensity;
- during aero- acoustic design the flow along the LE must stay attached which provides less intensity of the resulting tip vortex;
- In order to avoid the LE vortex generation at operating modes with high incidence angles (for example, Take off) additional curvature of the profile near the leading edge was introduced [ASME Turbo EXPO, Montreal, CIAM paper GT2007-27817], so that the flow above the suction side stayed attached;
- In order to increase the tolerance to negative incidence angles at high speed modes two changes are made in profile thickness distribution for improvement of aerodynamic design only:
  1. distribution of maximal thickness shifts in LE direction;
  2. blade thickness increasing at pressure side near LE



Open rotor tip streamline illustrating aft clipping

CIAM – participant of DREAM project



R1 takeoff condition CFD results for (a) aero-only design and (b) aero-acoustic design

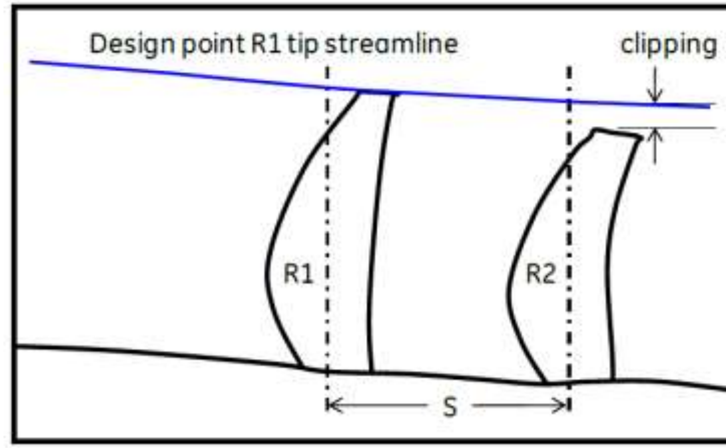
CIAM

Open rotor. Open rotor designs for low noise and high efficiency

Open rotor design ideas

3. *Axial spacing increasing reduces noise by means of mixing the wakes and vortices until they hit the aft rotor; however due to constriction of streamline downstream the R1, the place where the R1 tip vortex hit the aft rotor shifts inside. Therefore the magnitude of the R2 clipping should be optimized taking into account values of axial spacing, load and efficiency. For UDF relative axial spacing was equal to $S/\bar{D}$=0.28, for COMBY (CIAM) $S/\bar{D}$=0.281*

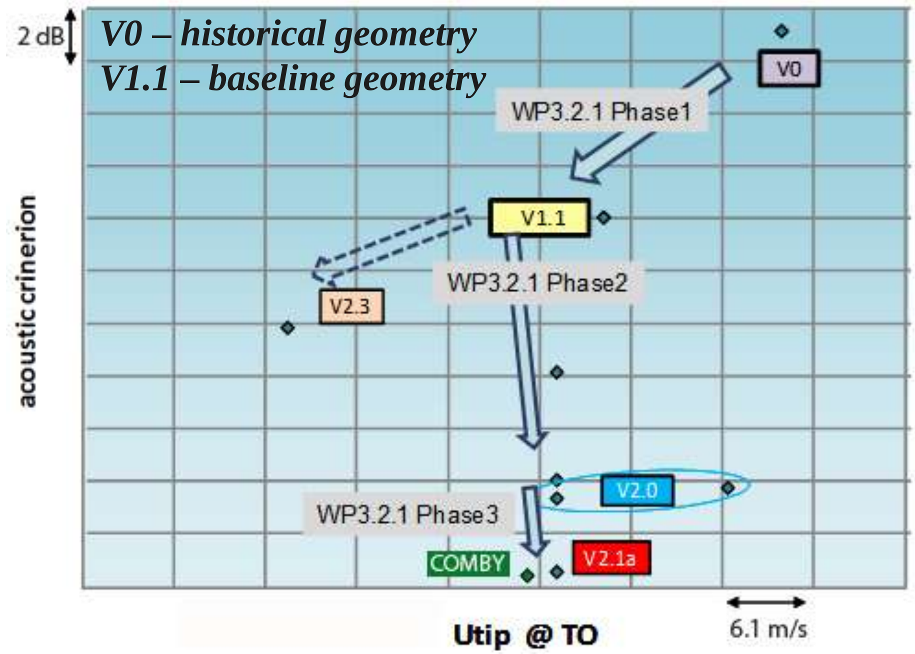
4. *Increasing of axial spacing between propeller blades of AN-70 aircraft prop fan on 46% resulted in noise reduction on 6 EPNdB (sum of three certification points)*



Axial spacing between R1 and R2

Open rotor. Optimized prop fans, developed in frame of European project DREAM. CIAM participated in the DREAM project

Assessment of acoustic performances



*- **V2.0** – geometry, developed on base of numerical optimization of baseline geometry V1.1 taking into consideration aerodynamic and acoustic criterions.*
Main approach to noise reduction – to ensure the front rotor tip vortices passing above the second rotor blade.

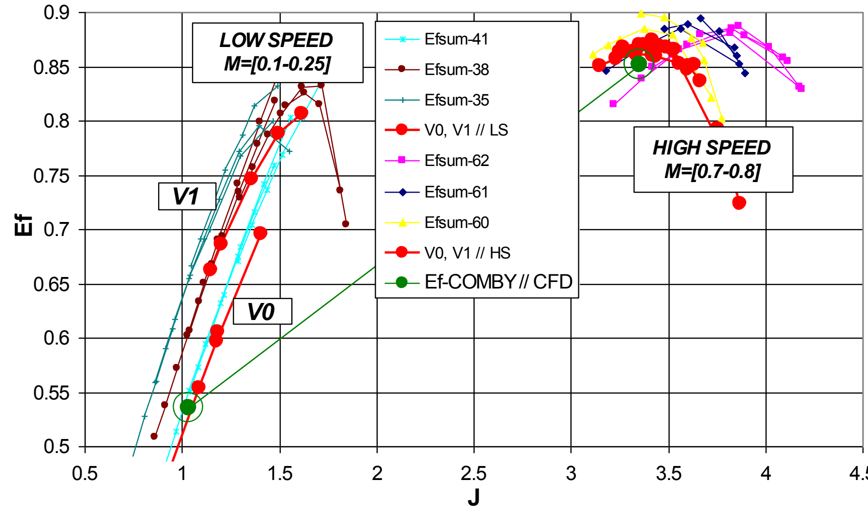
*- **V2.1a** – geometry, developed on base of geometry V2.0 numerical optimization by means of aerodynamic, acoustic and mechanical criterions application.*
Main approach to noise reduction is the same as for V2.0 geometry plus additional tip vortices attenuation.

*- **V2.3** – geometry, developed on base of methodology applied for single rotor fan design.*

For assessment of prop fan acoustic features Snecma used specific acoustic criterion, defined taking into account mean flow field parameters. Assessment was made for M=0.2. According to this acoustic criterion the prop fan V2.3 is the noisiest; the prop fans COMBY and V2.1a are the least noisy. The criterion takes into account interaction noise only.

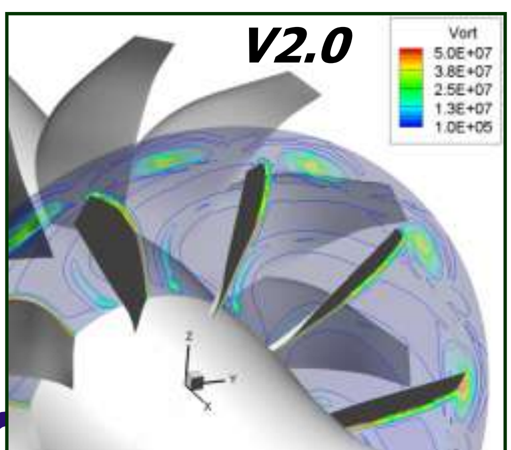
Open rotor. COMBY. CIAM project

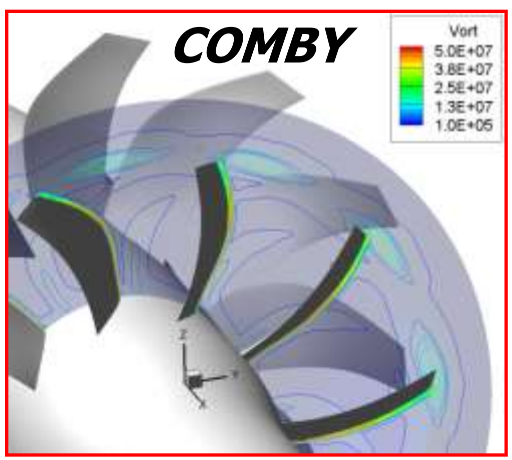
Challenge: OR noise reduction keeping high aerodynamic parameters

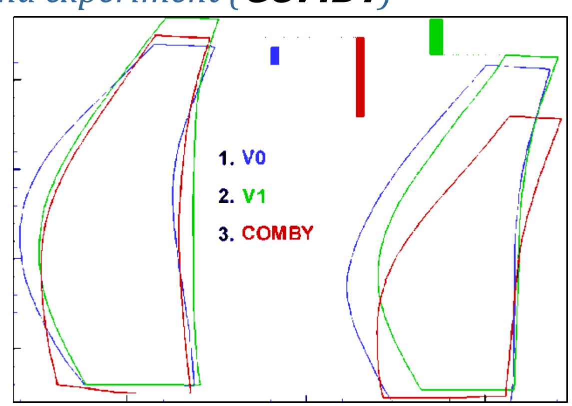


*Comparison of CFD (**COMBY** - CIAM, V0 – historical – UDF(GE), V1 - baseline) and experiment (**COMBY**)*

*Unsteady flow fields computations for two versions: **V2.0** and **COMBY** (CIAM): tip vortices intensity reduction for **COMBY***





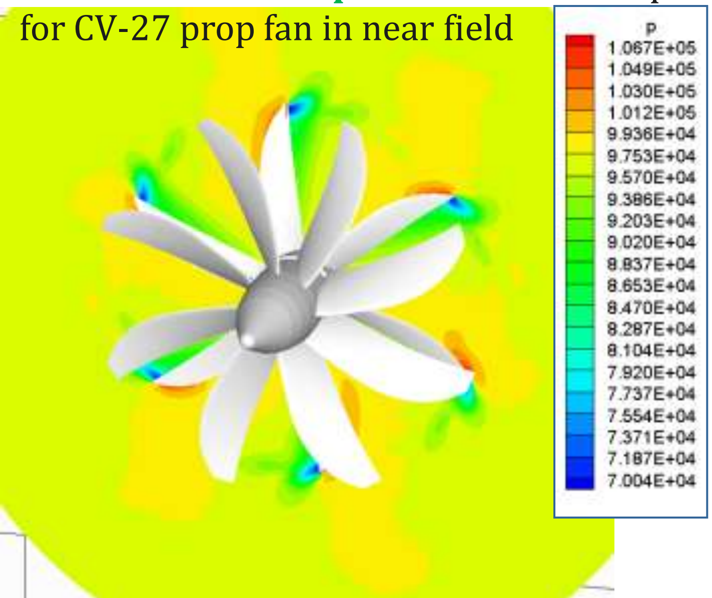


Geometry comparison
***COMBY** - 23% clipping*

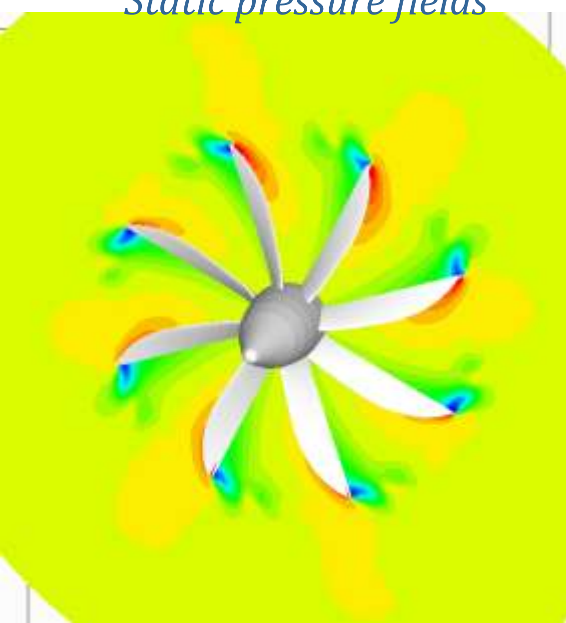
Open rotor. Optimization of CV-27 prop fan (AN-70 aircraft)

Goal: comply with the ICAO Chapter IV requirements with certain margin

Results of **acoustic performances** computation for CV-27 prop fan in near field

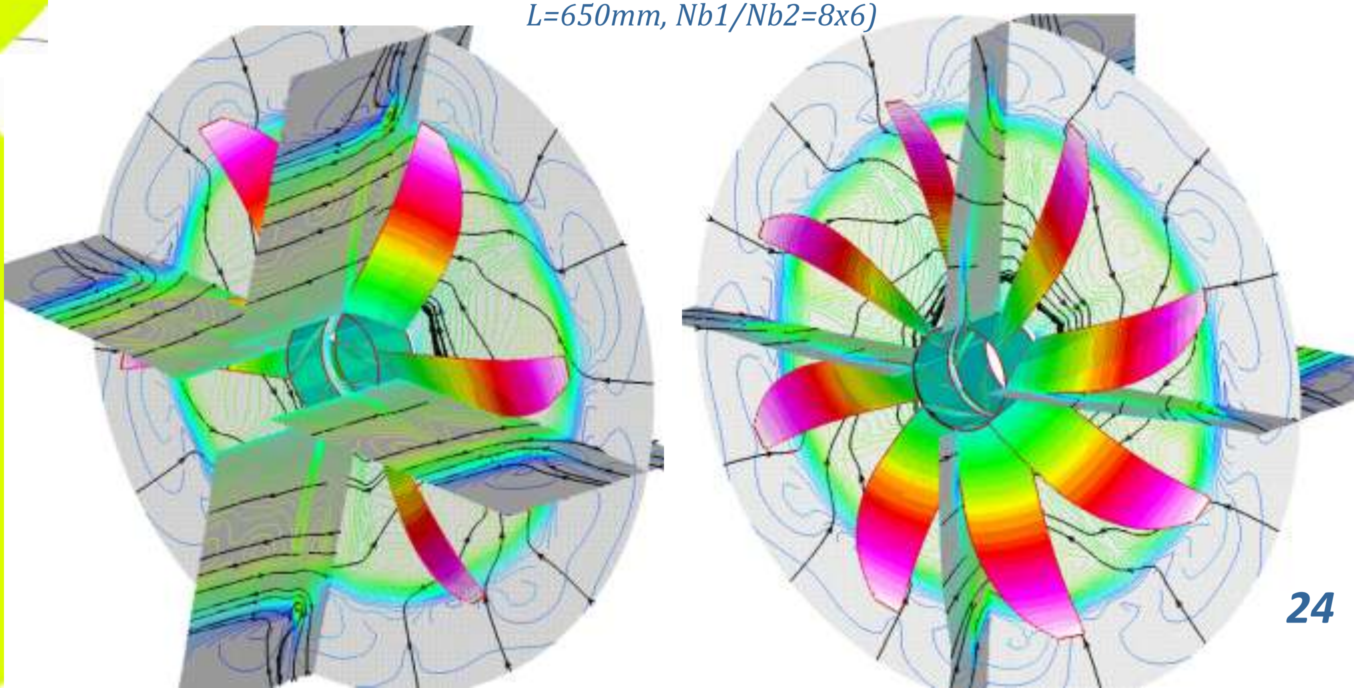


Static pressure fields



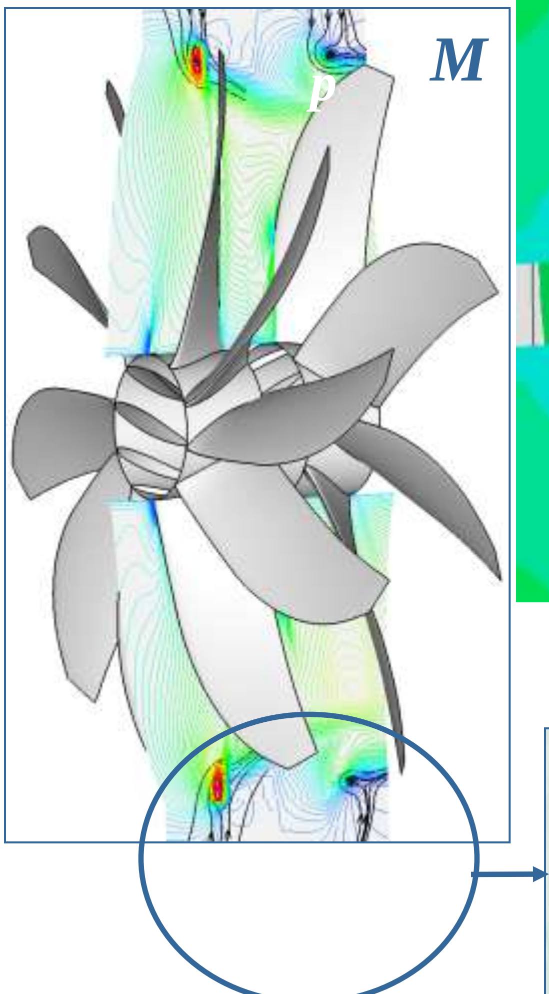
Results of **aerodynamic performances** computation for CV-27 prop fan

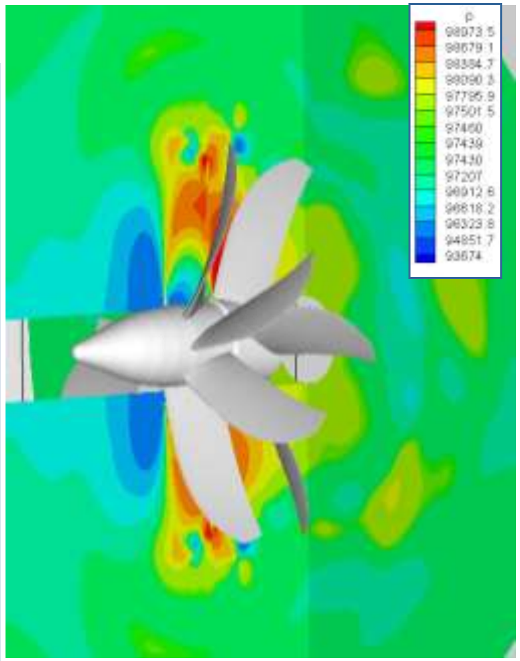
Mach number flow field in absolute coordinate system and instant streamlines on surfaces of basic sections in section downstream the front rotor (H=0, M=0.03, L=650mm, Nb1/Nb2=8x6)

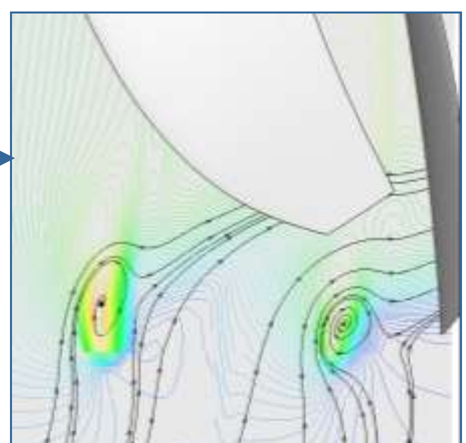


Open rotor. Results of acoustic performances computation for CV-27 prop fan in near field

Results of tone noise computation for counter rotating prop fan







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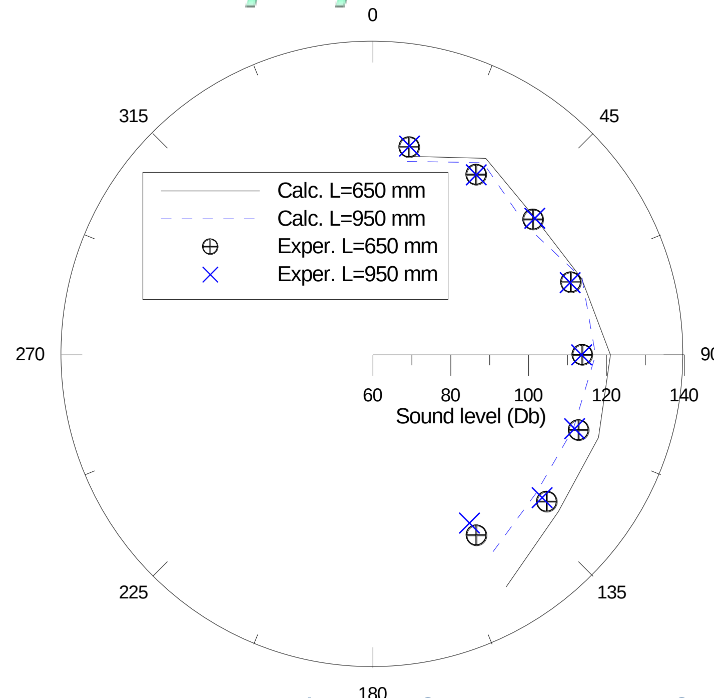
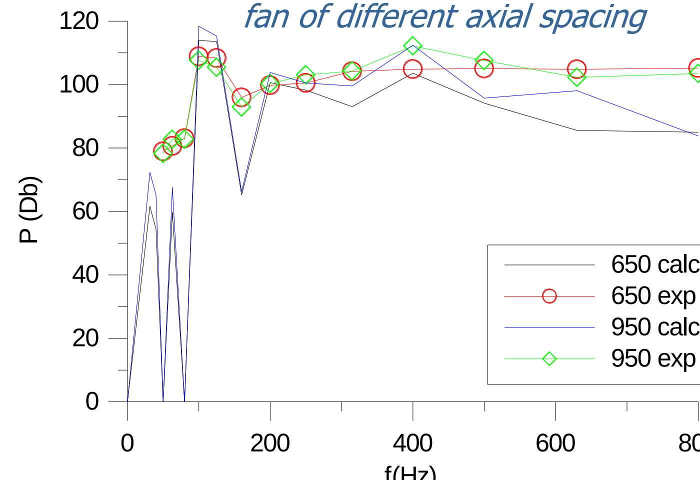


Directivity diagram for two versions of prop fan of different axial spacing



Comparison of numerical and experimental spectra in far field of open CRF

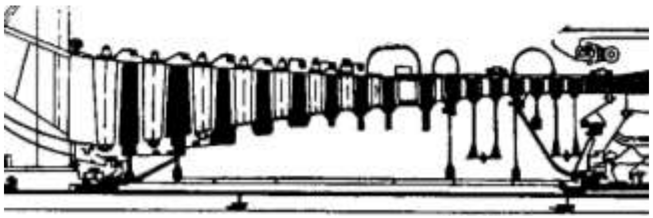
Trends in HPC for turbofan development

Main trends:

1. Increasing aerodynamic loading $(\pi^*_{st})_{av}$; use of wide chord blades (low aspect ratio)
2. Number of blades reduction at pressure ratio increasing

CF6-32 3 generation z_{bl}=2260

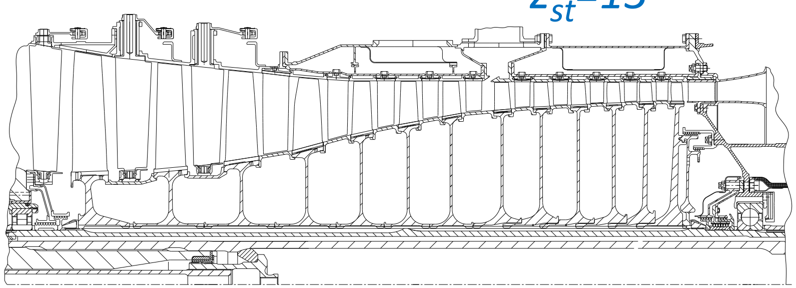
Number of blades z_{st}=16



π^*_c=14.7

PC-90A 4 generation z_{bl} = 2055

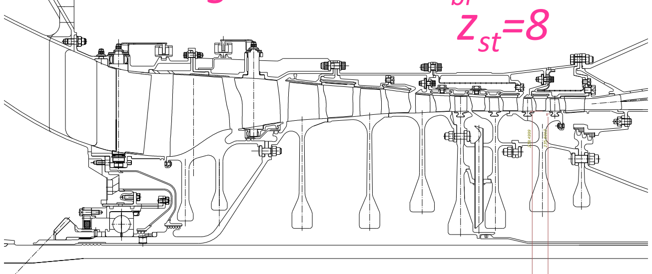
z_{st}=13



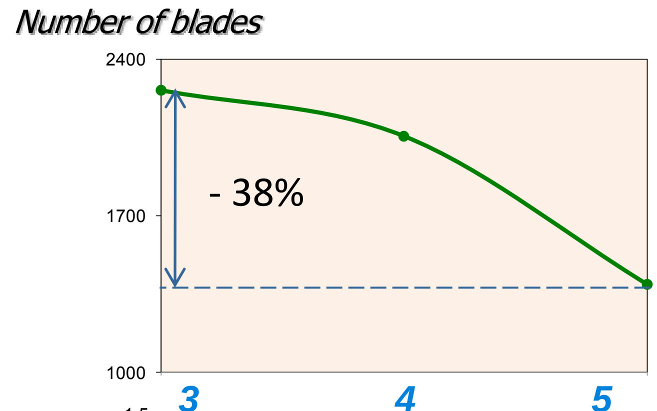
π^*_c=15.5

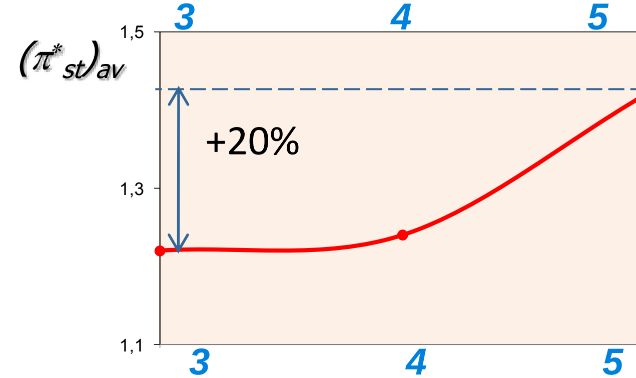
PD-14 5 generation z_{bl} =1394

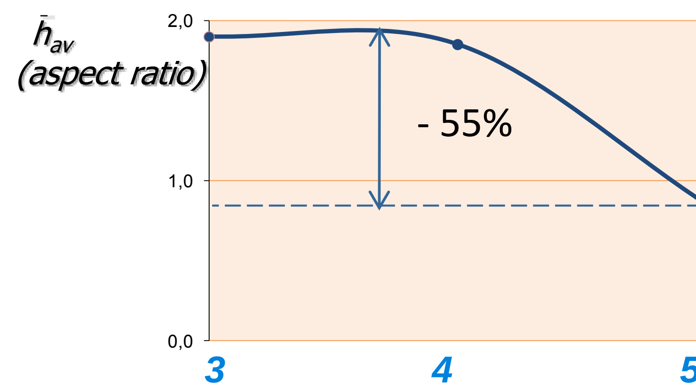
z_{st}=8



π^*_c=16 ÷19





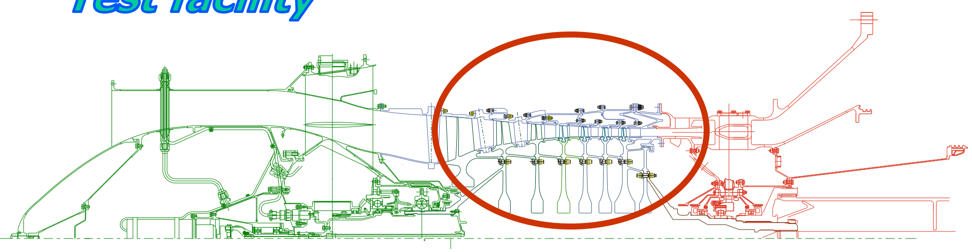


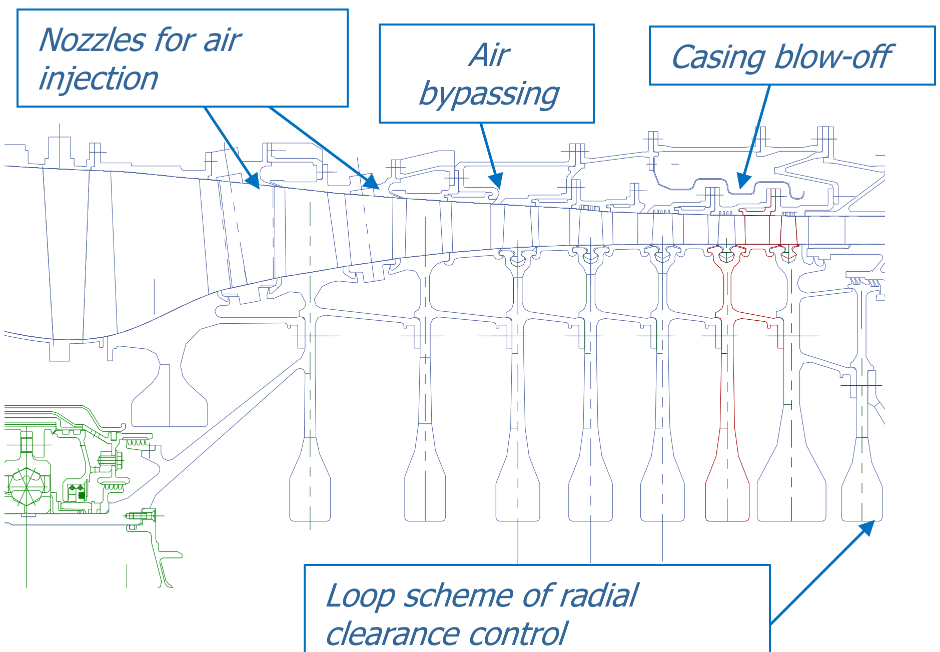
Experimental HPC of CIAM with stage number z=7 and $\pi^*_c \approx 14$ for advanced turbofan engine

High pressure compressor

Number of stage	7
Circumferential speed	409 m/s

Test facility





Objectives of the study:

- State-of-the-art in HPC design checkout
- Verification of analysis methodologies (gas dynamics, heat and strength)
- Radial clearance control and adjustment
- Simulation of flight cycle
- Confirmation of life time according to specification
- HPC design optimization
- Measurement and control system integration

High pressure compressor

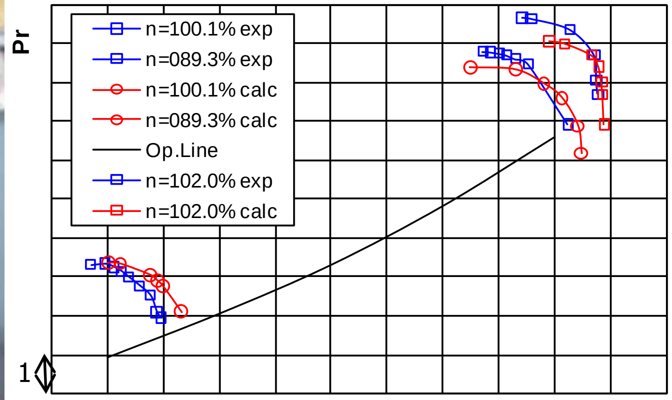
Unsteady interaction between rotor and IGV:

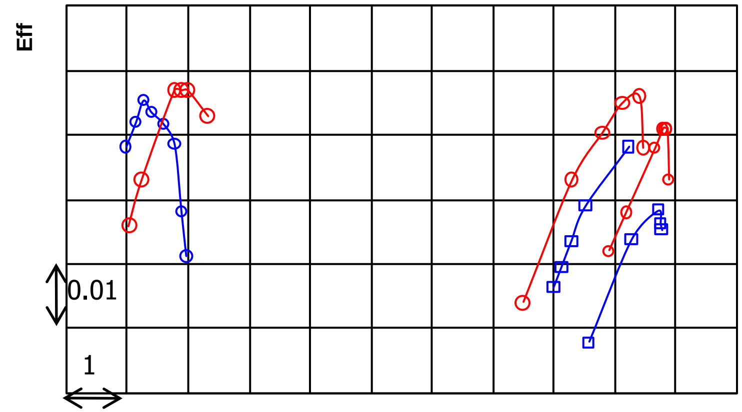
Another technique for reducing losses and improving the flow at the HPC inlet – shifting detached shock wave inside the R1 blade-to-blade channel at the same level of R1 aerodynamic load avoiding the mismatching of the HPC rows

3D inverse problem – effective tool for R1 profile modification, simultaneously shifting detached shock wave inside the R1 blade-to-blade channel keeping the same level of R1 aerodynamic load

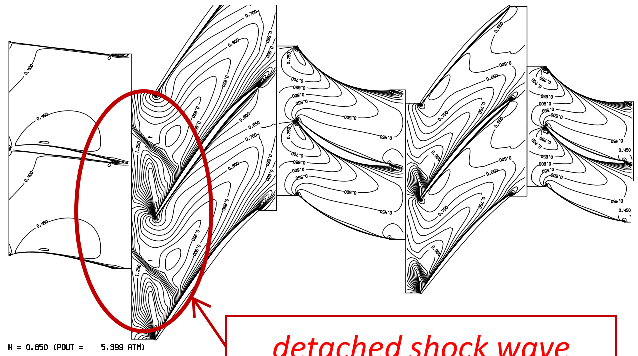
Modified 6-stage HPC of advanced turbofan

HPC numerical and experimental performances





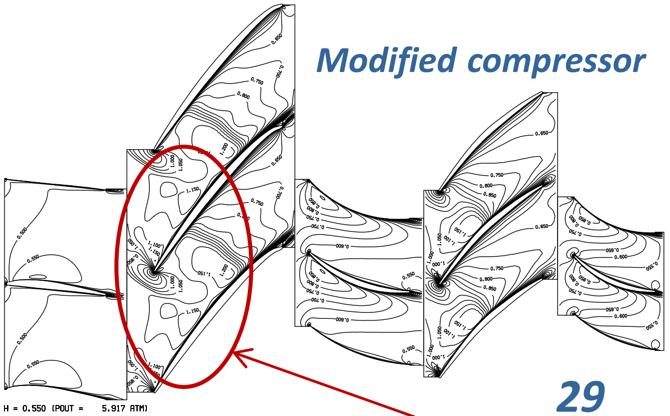
In comparison with the initial compressor in the modified one the surge margin was increased on 14%, mass flow rate - on 12% and appeared an opportunity to reach the operating mode of 100% RPM



detached shock wave

Mach number contours on rotation surface near tip. Initial and Modified compressor, corrected rotor speed 100%

Modified compressor

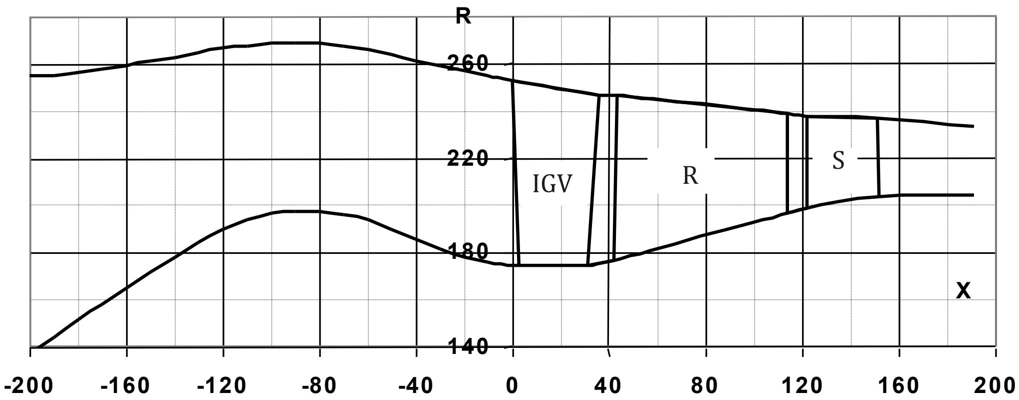


detached shock wave inside R1

Advantages

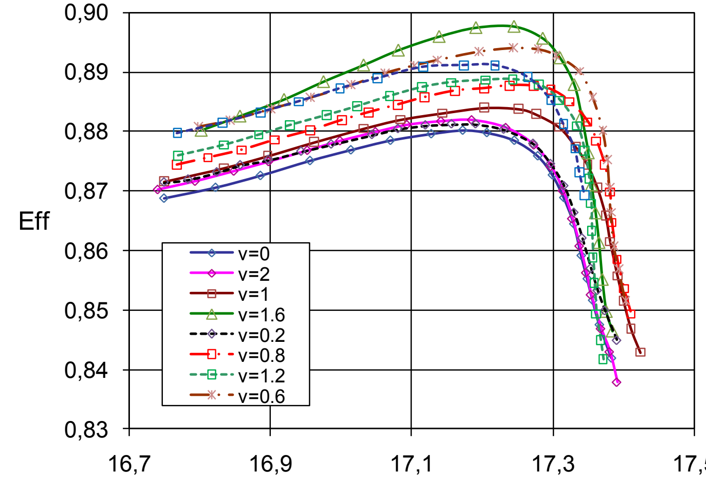
1. *Providing high surge margin $\Delta SM \geq 22\%$;*
2. *High level of efficiency. Within the range $\bar{n} = 80\% \div 100\%$ the efficiency is equal to $\eta^*ad = 84 \div 86\%$;*
3. *3D gas dynamic and strength methods of design for providing high gas dynamic stability margins without using casing treatment*

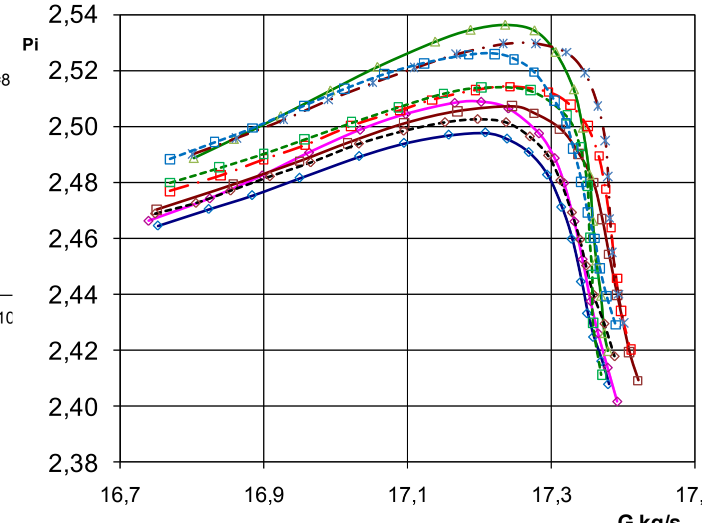
Clocking by example of typical first HPC stage models – high loaded K11 and A1 stages



K-11 stage flow path

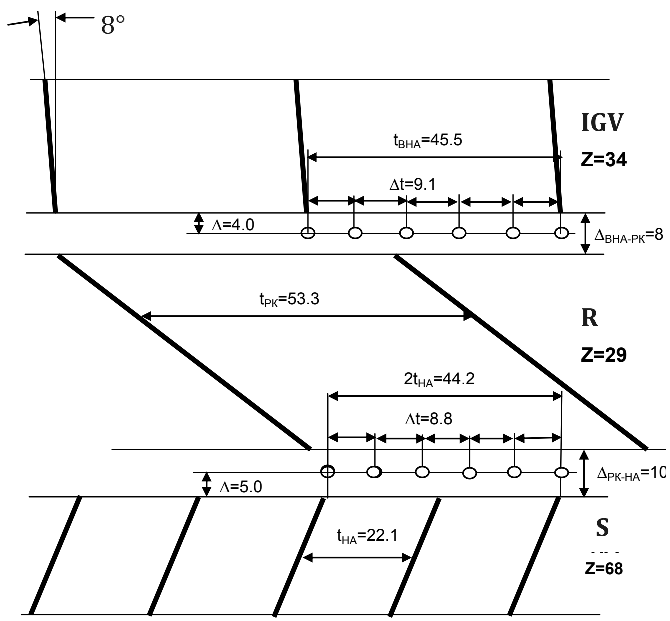
K-11 stage performances at designed speed $U_{c\ cor}$=428m/s at different circumferential position of stator relative to IGV





Designed parameters of К11 and A1 stages

Stage	K-11	A-1
$\bar{d}_1$	0.712	0.662
U_c m/s	428	421
$G_{air\ cor}$ kg/s	17.6	24.4
$\bar{H}_T$	0.535	0.507
π^*_c	2.47	2.32



Positions of pressure pulsation sensors on the K-11 stage casing

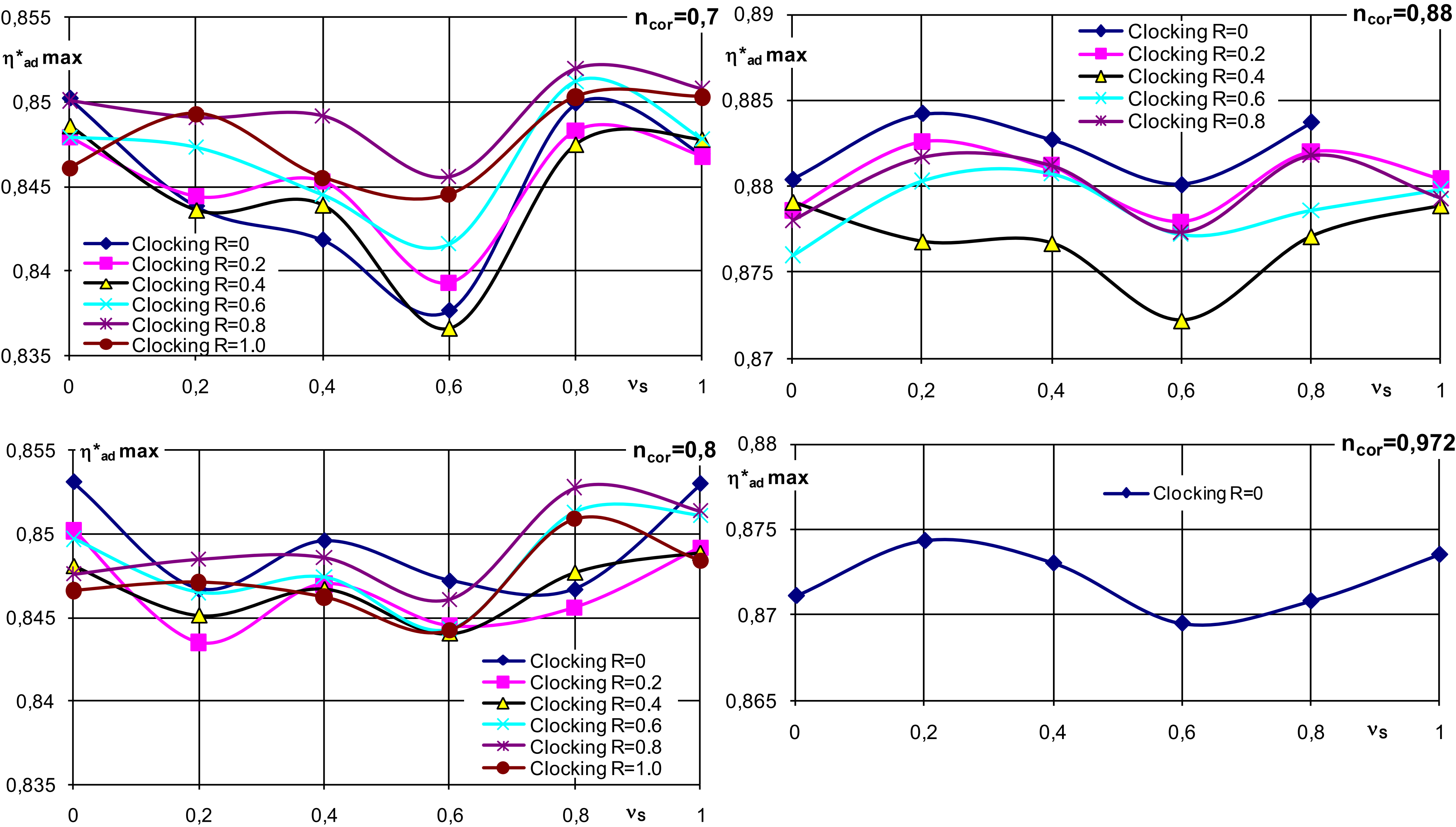
Gas dynamic effects of rotor-stator-rotor interaction – clocking effect:

In this case stator gas dynamic performances will vary due to potential vortex influence on its operation from bordering rotor rows flow disturbances

HPC-2 compressor has the unique possibility of separate and simultaneous study of stator-rotor-stator clocking effect on first stage stator and rotor-stator-rotor clocking effect on second stage rotor

Change in stator and rotor rows clocking positions is an effective tool of flow control in high loaded turbo machines, but up to now this tool has been practically out of use

Clocking by example of two stage compressor model



Variations in compressor maximal efficiency versus different stator and rotor clocking positions at different rotational speed