# METHOD FOR CALCULATION OF PROPELLER AERODYNAMIC CHARACTERISTICS AND ITS OPTIMIZATION WITH NOISE TAKING INTO ACCOUNT IN FRAMEWORK OF EWT-TSAGI APPLICATION PACKAGE

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# Content

- Relevance
- Computational method
- Testing
- Propeller optimization

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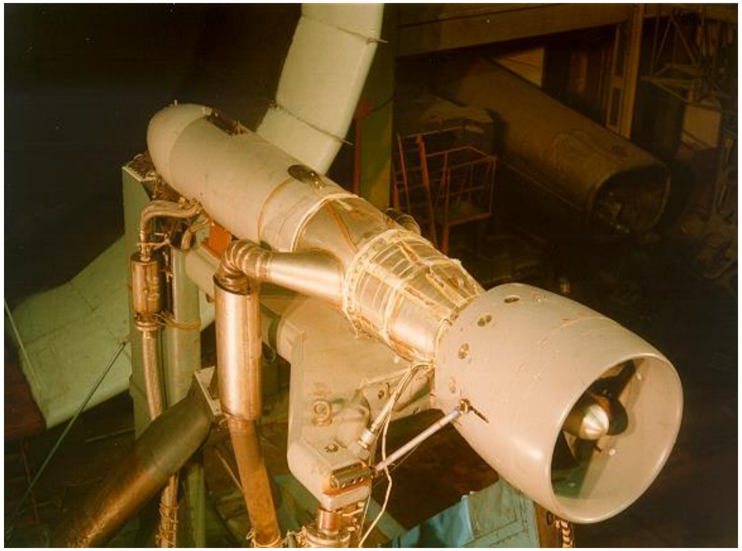
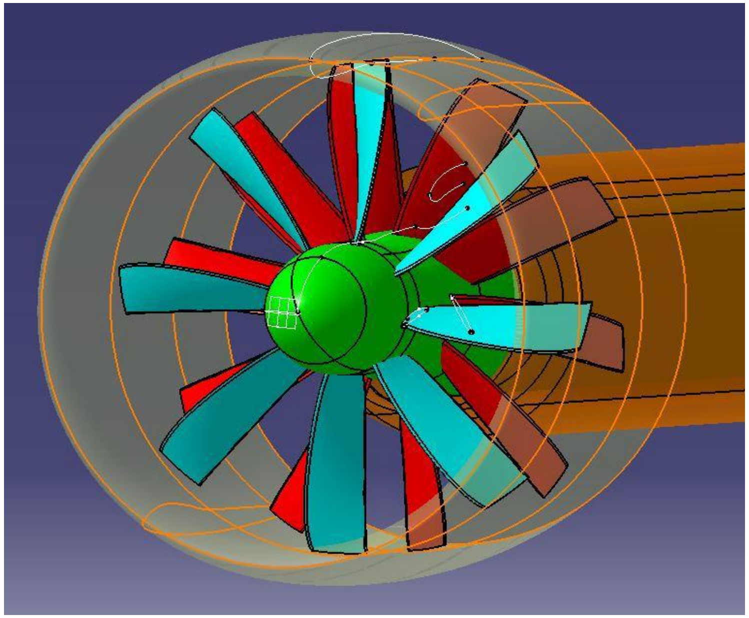
- Propeller optimization

# Large-scale test rig simulation

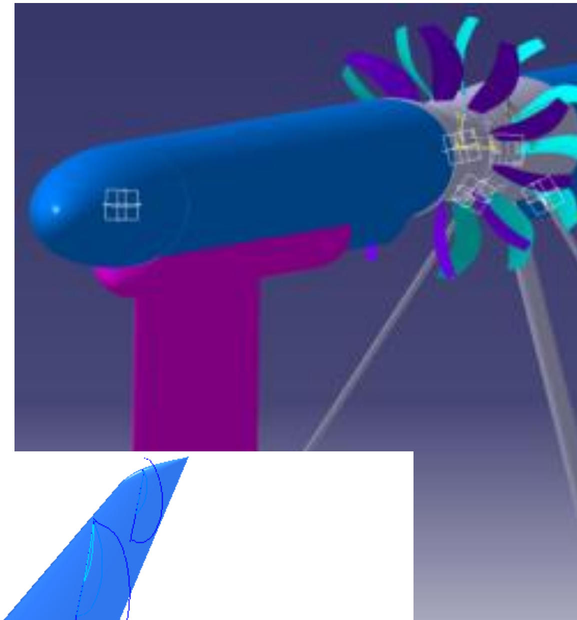
- Additional data
- Off-nominal behavior simulation
- Blade optimization
- Visualization
- Investigation of interference with WT

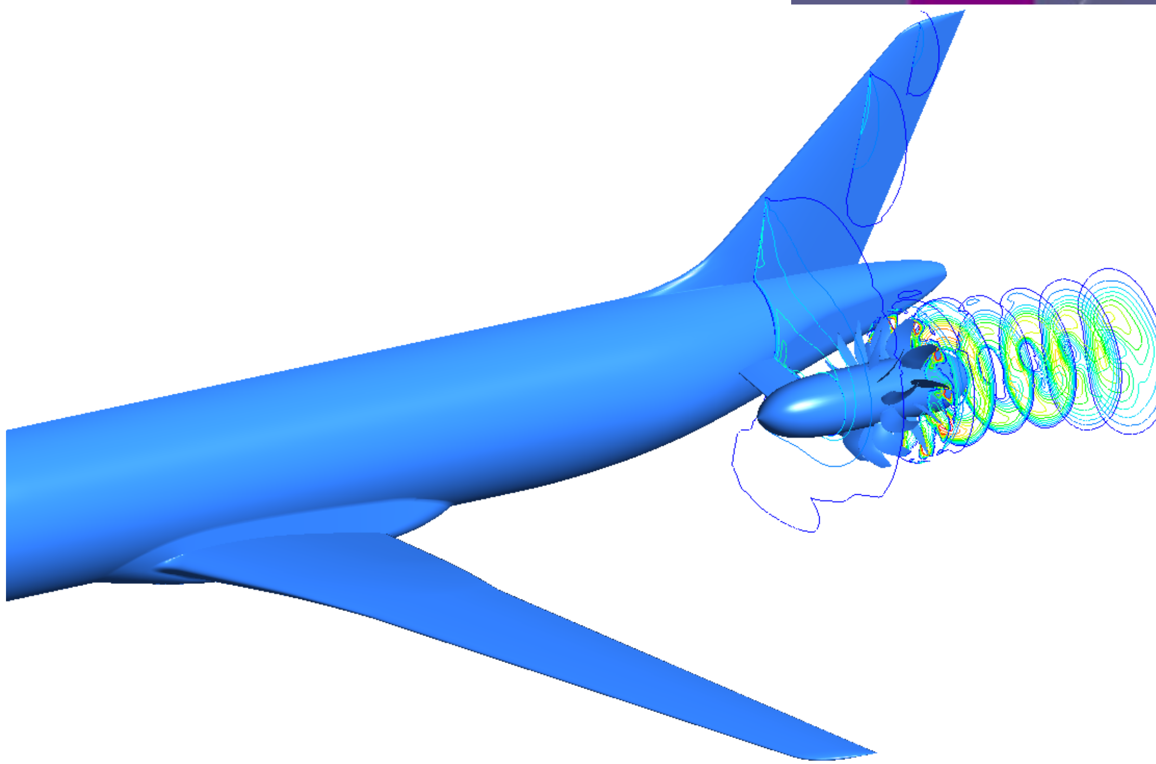




# Interference of CROR with airframe

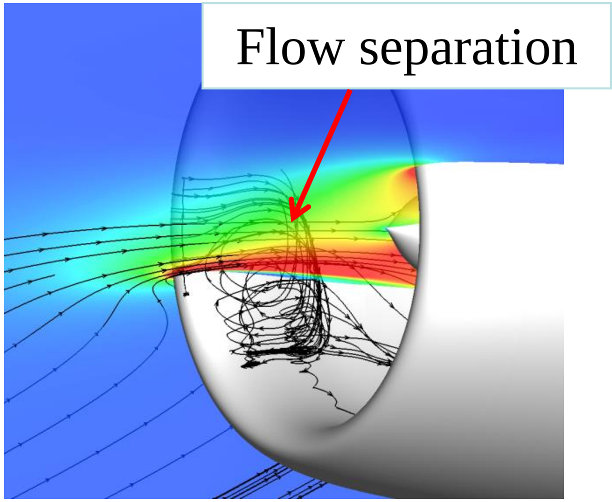
- Airframe influence on prop characteristics
- Flow control for flow irregularity diminishing
- Support of experimental investigations

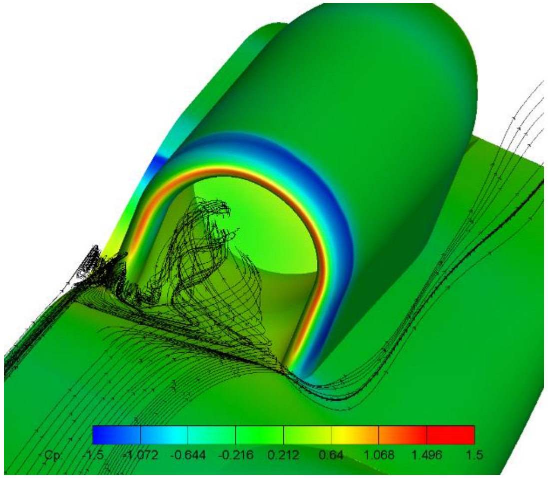


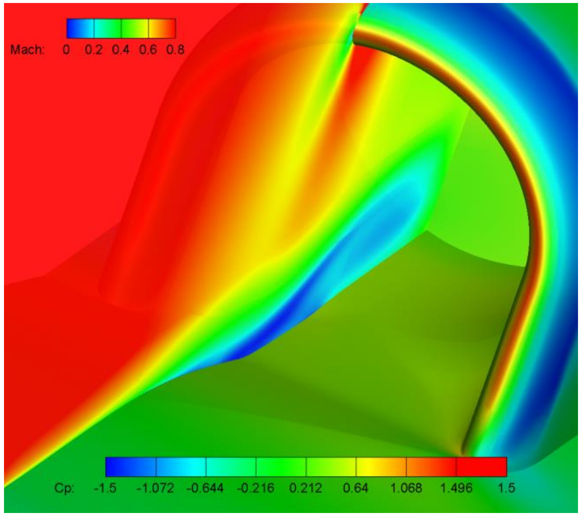


# Flow separation in an inlet

- Fan influence on a inlet flow
- Particular importance is a cross wind on takeoff regime
- It is necessary to simulate fan both numerically and experimentally



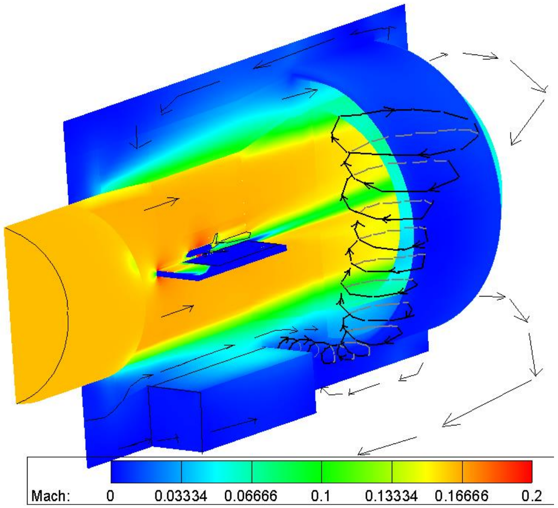



- Currency
- Computational method (solver RoS)
- Testing
- Propeller optimization

# EWT–TsAGI characteristics

- Structured mesh
- TsAGI explicit and implicit GKR (TVD) based scheme
- Euler, Navier–Stokes, Reynolds
- Rotating systems
- q- ω, SST, SA based TsAGI turbulence models
- LES
- Steady and non-steady solvers
- Fractional time stepping
- Acoustic program
- MPI, multithreads




EWT – Electronic Wind Tunnel

# Implicit scheme. Smoother

$$\frac{\vec{u}^{\,n+1}_{i,j,k}-\vec{u}^{\,n}_{i,j,k}}{\tau^n}+\frac{1}{V_{i,j,k}}\cdot\left[\sum_{i,j,k}\left(\vec{F}_{i+1/2}-\vec{F}_{i-1/2}\right)\right]^{n+1}-\vec{W}_{i,j,k}=0$$

«explicit» part

Roe linearization

$$u^{n+1}=u^n-\frac{\tau^n}{V_i}\left(\vec{F}^{\,n}_{i+\frac{1}{2}}-\vec{F}^{\,n}_{i-\frac{1}{2}}\right)+\left(-RM^n_{i-1}\Delta\vec{u}_{i-1}+RM^n_i\Delta\vec{u}_i+RM^n_{i+1}\Delta\vec{u}_{i+1}\right)-\vec{W}_{i,j,k}$$

Linear system:

$$-RM^n_{i-1}\Delta\vec{u}_{i-1}+\left[1+\frac{\tau^n}{V_i}RM^n_i\right]\Delta\vec{u}_i+RM^n_{i+1}\Delta\vec{u}_{i+1}=-\frac{\tau^n}{V_i}\left(\vec{F}^{\,n}_{i+\frac{1}{2}}-\vec{F}^{\,n}_{i-\frac{1}{2}}\right)-\vec{W}$$

Next step value:

$$\vec{u}_i^{\,n+1}=\vec{u}_i^{\,n}+\Delta\vec{u}_i$$

# Localization

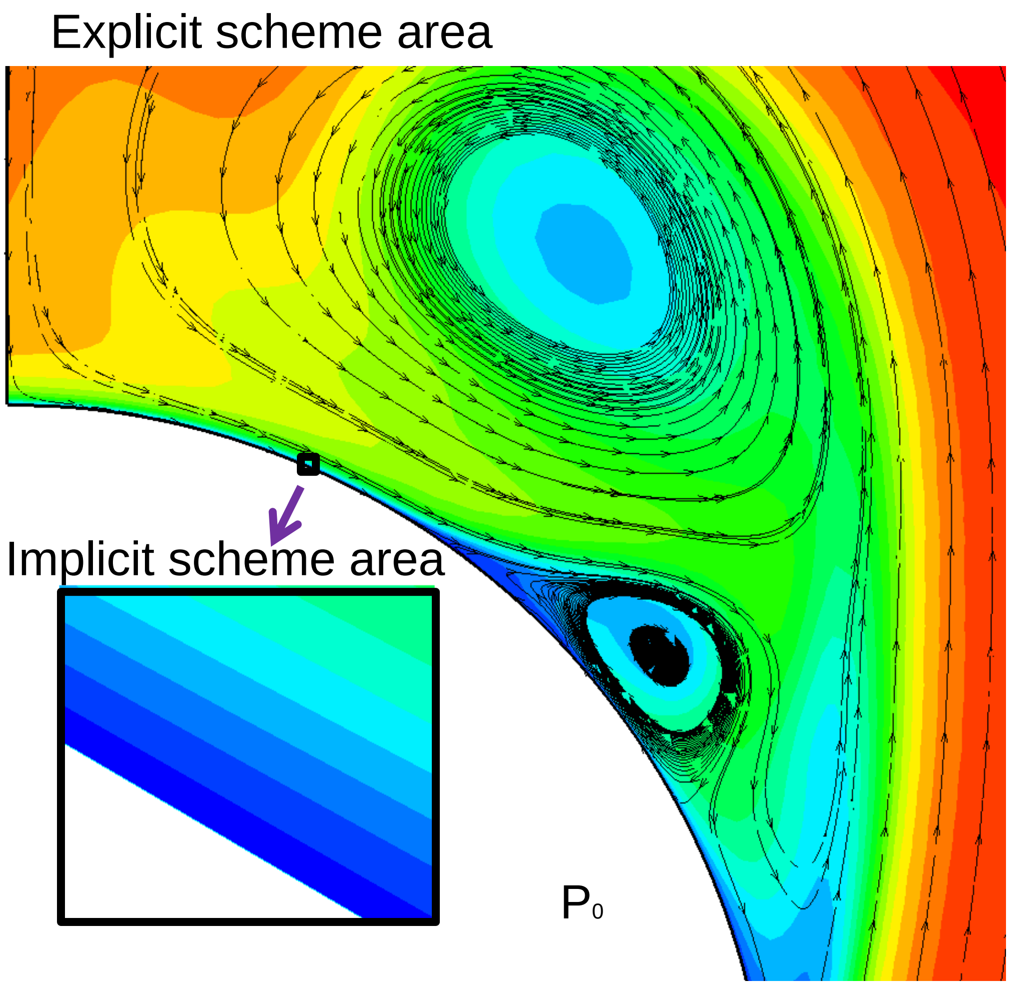
$$\begin{pmatrix} [\,] & [\,] & 0 & . & 0 & 0 & 0 \\ [\,] & [\,] & [\,] & . & 0 & 0 & 0 \\ 0 & [\,] & [\,] & [\,] & . & 0 & 0 \\ . & . & . & . & . & . & . \\ 0 & 0 & . & [\,] & [\,] & [\,] & 0 \\ 0 & 0 & 0 & . & [\,] & [\,] & [\,] \\ 0 & 0 & 0 & . & 0 & [\,] & [\,] \end{pmatrix} \cdot \begin{pmatrix} . \\ . \\ \Delta u_{i-1} \\ \Delta u_i \\ \Delta u_{i+1} \\ . \\ . \end{pmatrix} = \begin{pmatrix} . \\ . \\ . \\ . \\ . \\ . \\ . \end{pmatrix}, \quad where\ \Delta\vec{u} \stackrel{def}{=} \begin{bmatrix} \Delta\rho \\ \Delta\rho u \\ \Delta\rho E \end{bmatrix}$$

Example: 1-D Euler (for simplification)

Gauss-Zeidel

$$\left[1+\frac{\tau^n}{V_i} RM_i^n\right]\Delta\vec{u}_i^{\,k+1} = -\frac{\tau^n}{V_i}\left(\vec{F}^{\,n}_{i+\frac{1}{2}} - \vec{F}^{\,n}_{i-\frac{1}{2}}\right) + RM_{i-1}^n \Delta\vec{u}_{i-1}^{\,k+1} - RM_{i+1}^n \Delta\vec{u}_{i+1}^{\,k}$$

# Zonal approach




Implicit scheme:
- Large computation time per step
- CFL can be larger than 1
- Effective only with huge CFL
- Results: incorrect description of global-scale processes

Zonal approach:
- Ignoring small-scale processes in boundary layer, assuming them as quasi-steady
- Correct global-scale processes description
- Global-scale processes predominate the behavior of boundary layer

Zone separation:
- main (inviscid) area - explicit scheme
- thin layer near wall - implicit scheme

Thanks to E. Kazhan

# RANS on rotating system of coordinates for absolute velocity

The flow through the faces of the rotating mesh

$$\frac{\partial \vec{U}}{\partial t}+\sum_i \frac{\partial \vec{F}_r}{\partial x_i}=\vec{W}_r \quad \vec{U}=\begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \\ \rho k \\ \rho \varpi \end{bmatrix}, \quad \vec{\mathbf{F}}_r=\vec{\mathbf{F}}-(\vec{\Omega}\times\vec{R})\vec{U} \quad \vec{W}_r=\begin{bmatrix} 0 \\ -\rho(V_y w - V_z v) \\ -\rho(-V_x w + V_z u) \\ -\rho(V_x v - V_y u) \\ 0 \\ S(k) \\ S(\omega) \end{bmatrix}$$

An amendment to the Coriolis force

For rotation around the axis X:

$$V_x=0,\ V_y=-z\omega,\ V_z=y\omega$$

Special thanks to: Dr. V. Titarev

Additional terms are entered into the calculation of flows associated with the flow due to the rotation of the grid. In the source term is the correction to the Coriolis force.

# Solver modifications

- The solution of the Riemann problem of the discontinuity decay on moving mesh
- Modification of the boundary conditions:
  - ❑ slip condition - given the speed of rotation
  - ❑ impermeability condition –
    condition is stated for $V = V_{flow} - V_{side}$
  - ❑ the "Riemann" condition – mesh rotation speed is taken into account in determining the direction of flow
- For the explicit scheme is the correction in the time step
- Row matrix are modified for implicit schemes
- Zonal approach for time step is used
- Families is used for objects with deferent rotational speed

- Currency
- Computational method
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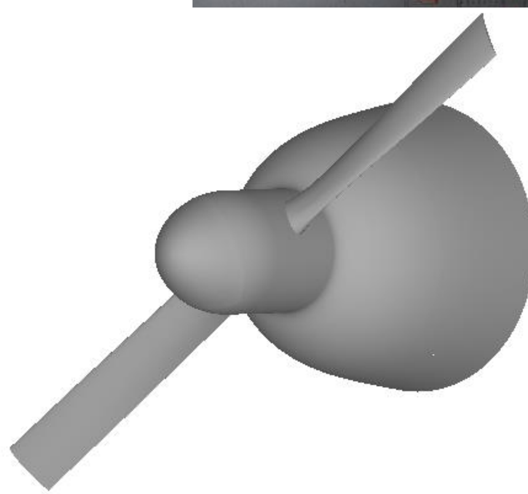
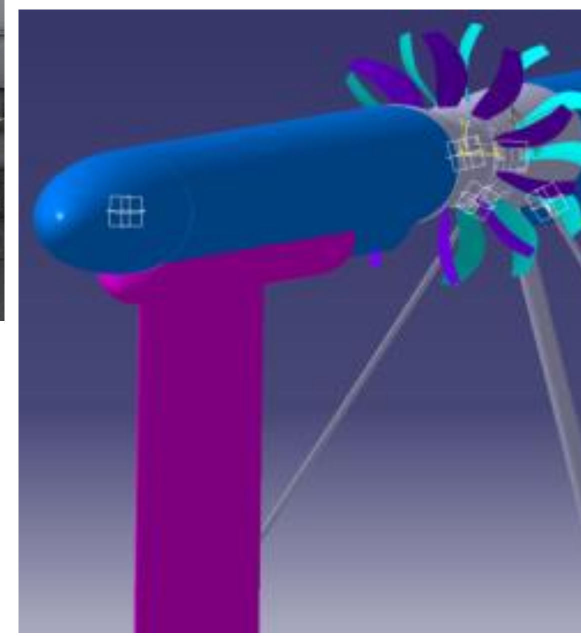
- Propeller optimization

# Test cases

Test cases are created using experimental data:

- Six-bladed prop (D=0.8 m)
- Two-bladed prop (D=2.9 m)
- Contra rotating prop (D=0.32 m)





Solvers must be verified

# Test rig

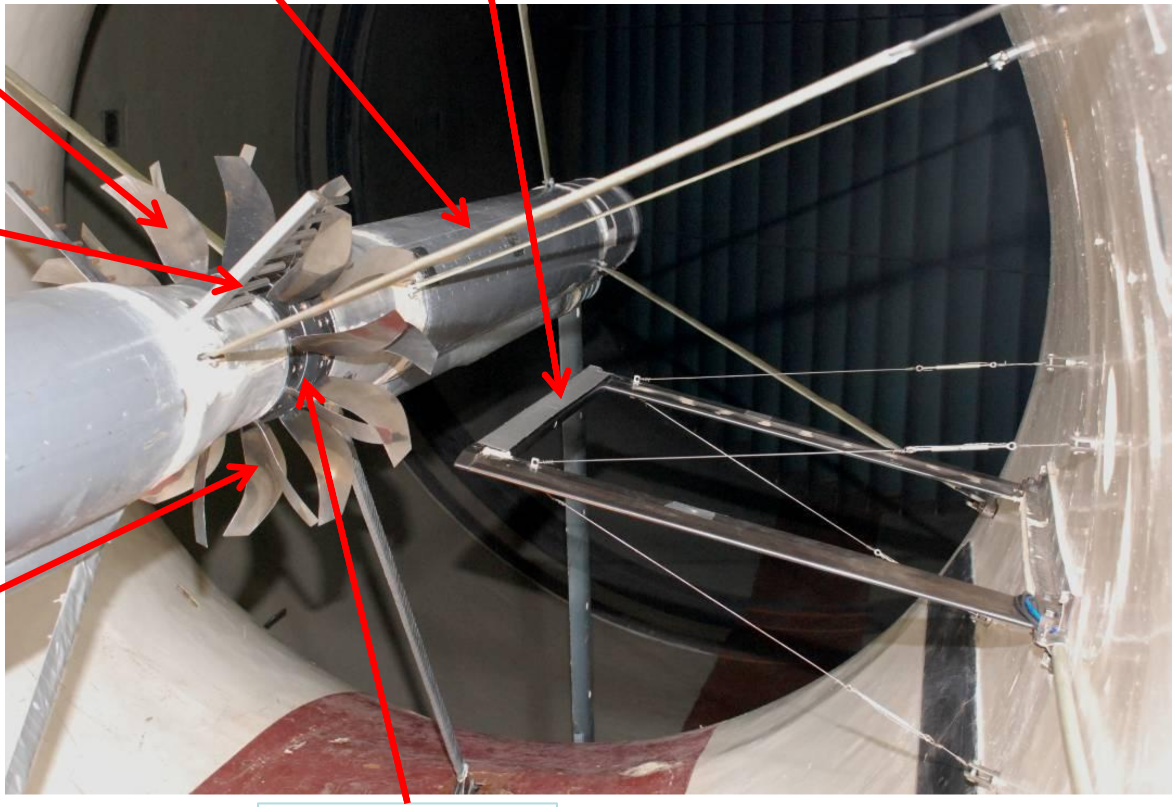
Production

Acoustic

Balance

PSP

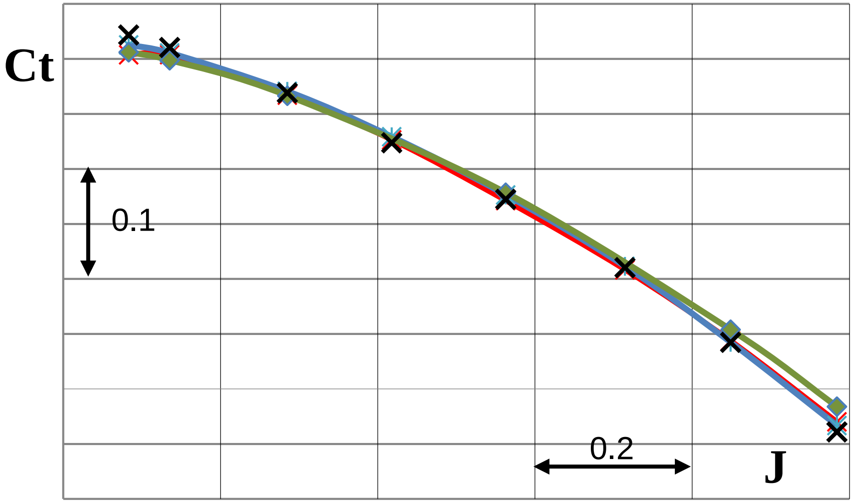
Aerodynamic

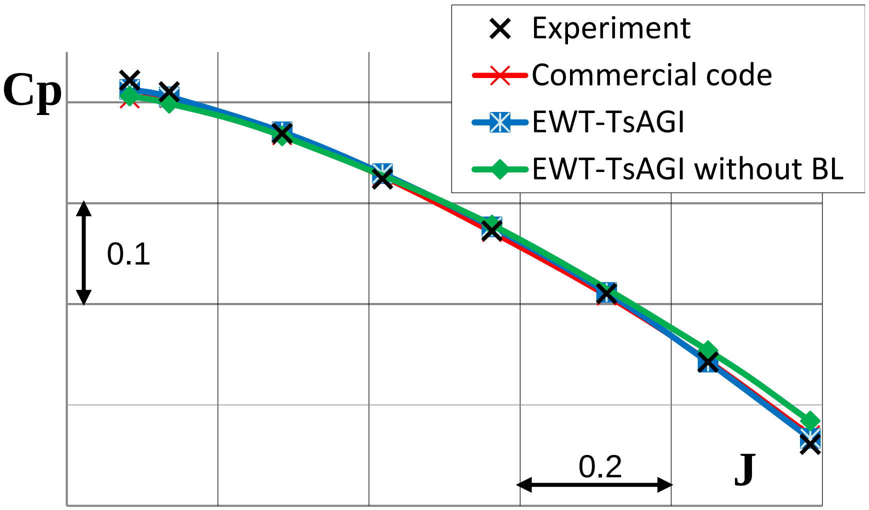


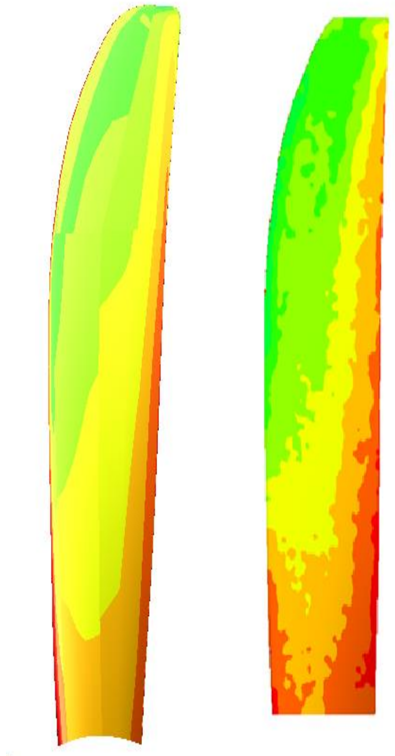
Deformations and vibration

Telemetry

# Verification. Six-bladed prop



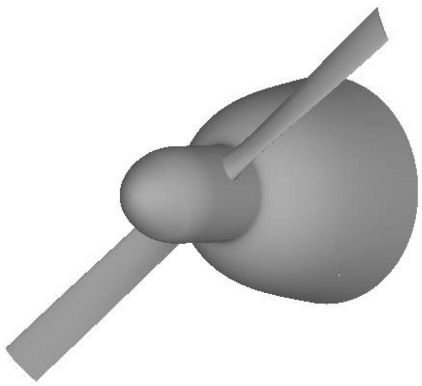
CFD PSP

Test data by Dr. Kishalov A.N.

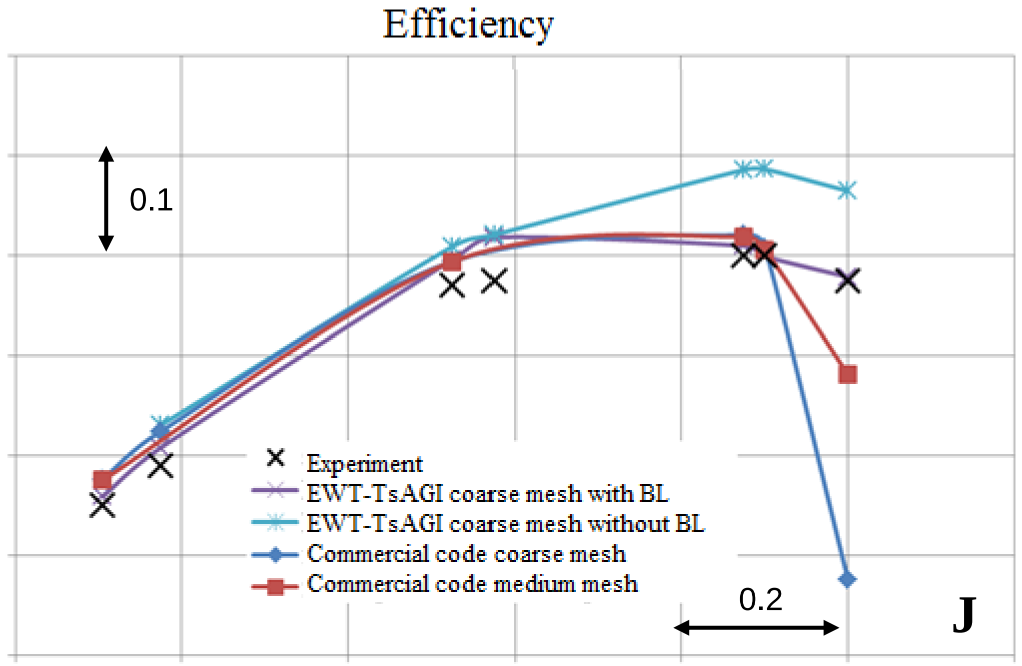
Precision – 3 - 4 %

# Verification. Two-bladed prop.

- Two-bladed prop
- Thing profiles
- Low speed
- Precision of efficiency computation ~ 4%



Test data by
Dr. Ostrouhov S.P.



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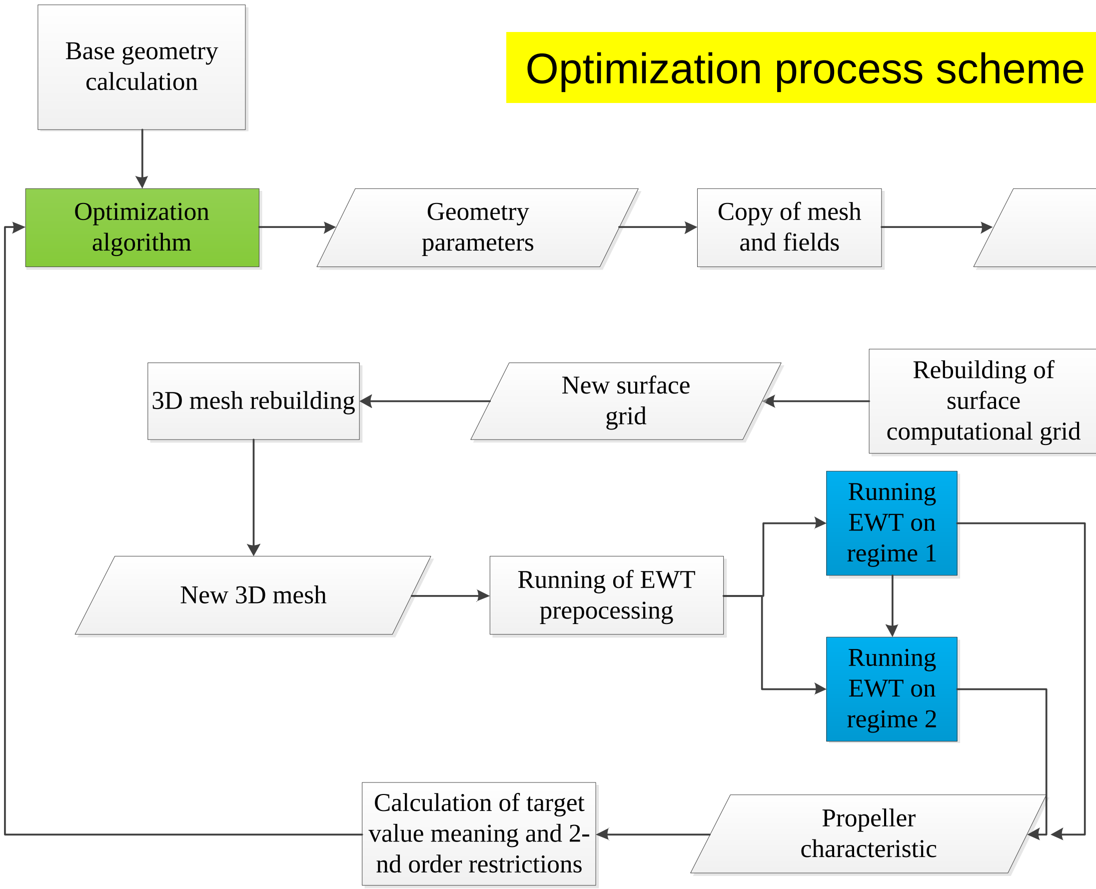
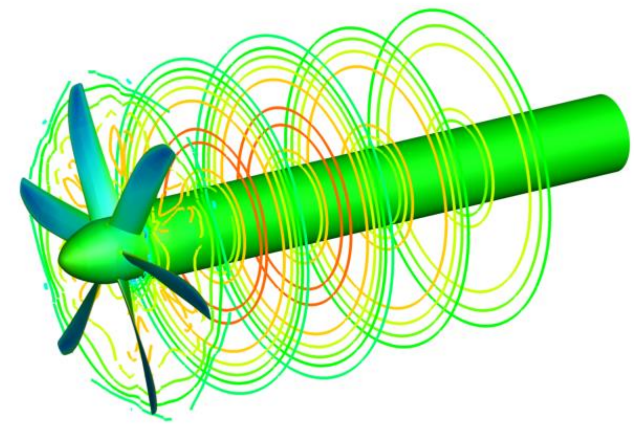
# Propeller optimization with noise taking into account

## Optimization process scheme



Thanks to
A. Savelyev

- Solver RoS for propeller aerodynamical characteristics computation (RANS+SST)
- Noise changing estimation using empirical formula
- Second order restrictions is result characteristics restrictions
- Algorithm EGO (Efficient Global Optimization) — global optimization algorithm with simulation model, created by kriging method

# Noise estimation

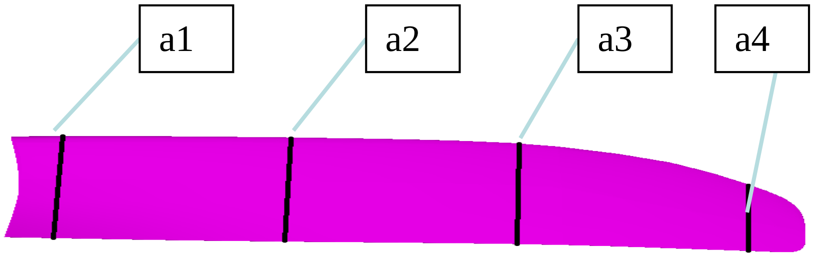
$$L_{\sum} = C_N \lg N_B + C_M M_u - C_D \lg kD_B - C_S \lg S + C_1$$

- $L_{\Sigma}$ – noise level,
- $N_B$ - power supplied prop,
- k – blades number,
- $D_B$- prop diameter,
- $C_1$ – constant depend on aircraft class and prop type,
- S – distance from noise source to microphone,
- $M_u = \frac{\varpi D_{в}}{2a}$ - peripheral Mach number,
- ω- rotational frequency,
- a – sound speed,
- $C_N$, $C_M$, $C_D$, $C_S$ – empirical constants.

# Optimization result

Target value – propeller efficiency

Profile angles a1-a4 – changed geometrical parameters (from -4$^{o}$ up to +4$^{o}$).



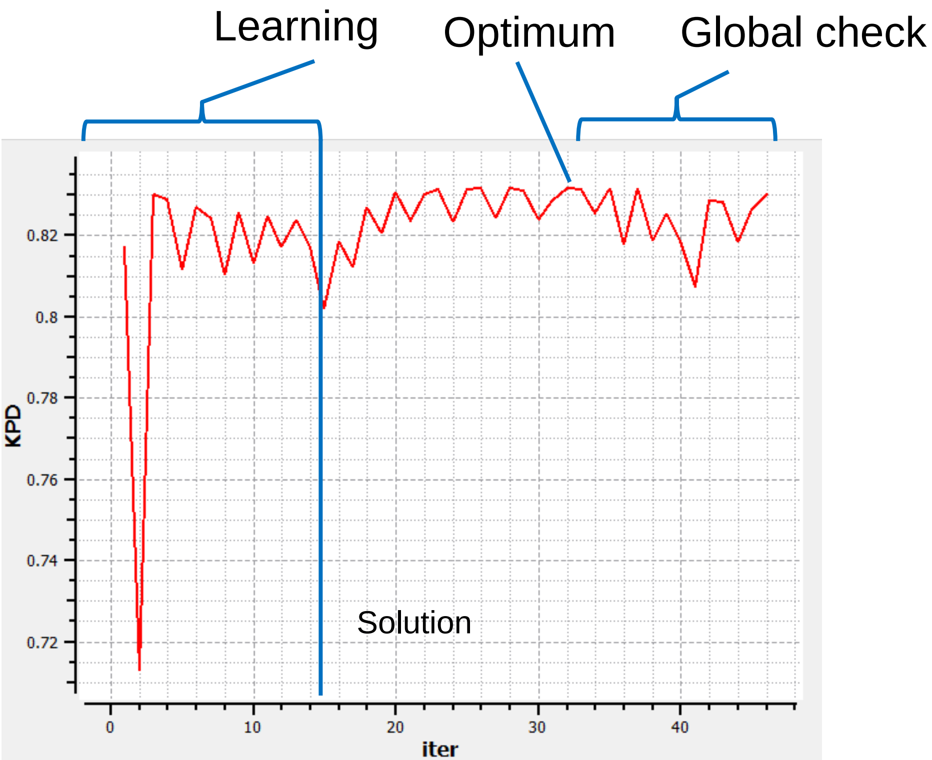

Propeller model optimization on takeoff regime:

- Efficiency increasing without restrictions – 5%;
- Efficiency increasing with restrictions – 1.2%.

Real propeller optimization on cruise regime:

- Restriction on thrust and noise on takeoff regime;
- Efficiency increasing - 0.3%.

| | | Base prop | Opt. prop |
|---|---|---|---|
| Cruise | Ct | 0.242 | 0.256 |
| | Cp | 0.778 | 0.824 |
| | η | 0.83 | 0.832 |
| Takeoff | Ct | 0.359 | 0.369 |
| | Cp | 0.322 | 0.333 |
| | η | 0.684 | 0.678 |
| | L, dB | 48.4 | 48.6 |



# Conclusions

Method of computation on rotating systems is added into software EWT-TsAGI. Solver validation and verification is carried out. Optimization circle is designed.

- Precision is 3-4% for six-bladed propeller test case on regimes without separations ($\lambda$=0.2÷0.8).
- Optimization of the real size propeller on cruise regime with restrictions is carried out. Propeller efficiency on cruise regime is increased on 0.3%.

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# THANK YOU FOR ATTENTION!