Implementation and validation of a new actuator disk model in *SU2*

Ettore Saetta, Lorenzo Russo, Benedetto Mele, Renato Tognaccini

TAARG (Theoretical and Applied Aerodynamic Research Group),
Dipartimento di Ingegneria Industriale,
Università di Napoli Federico II

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Objective

To introduce a new general actuator disk model in *SU2 vsn 6.2.0*.[a]

Contents:

- Introduction.
- Current *SU2* Actuator Disk Model.
- New actuator disk model.
- Validation and applications.
- Automatic generation of propeller input.
- Conclusions.

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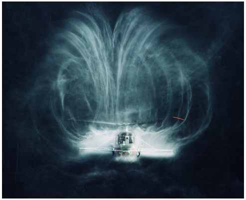
[a] This study is part of a cooperation with *CIRA* within the *EU* funded *IRON* (*Innovative turbopROp configuratioN*) research program, part of *Clean Sky 2-REG* program (GAM-2020-REG implemented on H2020 under GA 945548).

Flows induced by rotary wings

The flows induced by **rotary wings** is of fundamental importance in many fields.



- In Aeronautics it is a crucial topic for the airframe integration.
- The most simple and effective method to simulate rotary wing effects is the adoption of an **actuator disk model**.
- **Pros**: low computational cost, well captured effects on airframe.
  Cons: blade geometry not resolved, unsteady effects neglected.

Distributed Electric Propulsion (DEP)

- The future of the propulsion systems is moving to the DEP.
- Many research programs all over the world are investigating DEP.
- The industrial engineering department of the University Federico II is collaborating with CIRA[b] at the DEP research.
- The actuator disk model is fundamental for performance prediction by fast CFD analyses.

X-57 Maxwell (NASA)

Helios (NASA)

[b] Italian Aerospace Research Center

The actuator disk model in CFD

- Model developed by *Rankine* and *Froude* in the second half of the 19^{th} century.
- First *CFD* applications in the late 80's[c].
- In *CFD* codes the actuator disk can be modeled as a *boundary condition* or introducing *source terms* in the *Navier-Stokes* equations.
- Nowadays, almost every *CFD* software has an actuator disk model; for example:
  - *Fluent*: constant/linear piecewise *Fan* boundary condition.
  - *Star-CCM+*: *Virtual Disk Model* with three different methods.
  - *ElsA* (ONERA): source terms distribution.
  - *ZEN* (CIRA): actuator disk modelled using propeller performance.
  - *SU2*: simplified model, no swirl, constant pressure jump along the disk.
- Need to introduce a more powerful model in SU2.

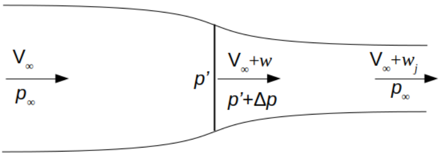
[c] For instance: A. Kassies, R. Tognaccini, Boundary conditions for Euler equations at internal block faces of multi-block domains using local grid refinement (1990), AIAA Paper 90-1590. *Kassies* and *Tognaccini* (1990).

The Actuator Disk Model

- The propeller is considered as a discontinuity surface.
- Pressure (p) and tangential velocity ωr (swirl) jumps through the actuator disk.
- It induces an axial velocity w.

Simple Momentum Theory (constant pressure jump Δp across the disk):

- No swirl $(\omega = 0)$
- Induced velocity: $w = \frac{1}{2} w_j$
- Total thrust: $T = 2\rho A \left(V_\infty + w\right) w$
- Total power: $P = T \left(V_\infty + w\right)$
- Efficiency: $\eta = \frac{T V_\infty}{P} = \frac{1}{1+a}$



General Momentum Theory (variable $\Delta p\left(r\right)$ and swirl $\omega\left(r\right)$ along the disk):

- $\mathrm{d}T = 4\pi\rho V_\infty^2 \left(1 + a\right) a r \mathrm{d}r$
- $\mathrm{d}Q = 4\pi\rho V_\infty \Omega \left(1 + a\right) a' r^3 \mathrm{d}r$
- $\mathrm{d}P = 4\pi\rho \left[V_\infty^3 \left(1 + a\right)^2 a r \mathrm{d}r + \Omega^2 V_\infty \left(1 + a\right) a'^2 r^3 \mathrm{d}r\right]$
- $\mathrm{d}P = \Omega \mathrm{d}Q$

$a = \frac{w}{V_\infty}$

$a' = \frac{\omega}{2\Omega}$

Q: torque

SU2 Actuator Disk Model

Based on the Simple Momentum Theory

- Constant pressure jump.
- No *swirl*.
- Requires temperature jump difficult to determine a-priori.

```
% Actuator disk boundary type (VARIABLES_JUMP, NET_THRUST, BC_THRUST,
%                               DRAG_MINUS_THRUST, POWER)
ACTDISK_TYPE= VARIABLES_JUMP
%
% Actuator disk jump definition using ratio or difference (DIFFERENCE, RATIO)
ACTDISK_JUMP= DIFFERENCE
%
% Actuator disk boundary marker(s) with the following formats (NONE = no marker)
% Variables Jump: ( inlet face marker, outlet face marker,
%                   Takeoff pressure jump (psf), Takeoff temperature jump (R), Takeoff rev/min,
%                   Cruise  pressure jump (psf), Cruise temperature jump (R), Cruise rev/min )
% Net Thrust: ( inlet face marker, outlet face marker,
%               Takeoff net thrust (lbs), 0.0, Takeoff rev/min,
%               Cruise net thrust (lbs), 0.0, Cruise rev/min )
% BC Thrust: ( inlet face marker, outlet face marker,
%              Takeoff BC thrust (lbs), 0.0, Takeoff rev/min,
%              Cruise BC thrust (lbs), 0.0, Cruise rev/min )
% Drag-Thrust: ( inlet face marker, outlet face marker,
%                Takeoff Drag-Thrust (lbs), 0.0, Takeoff rev/min,
%                Cruise Drag-Thrust (lbs), 0.0, Cruise rev/min )
% Power: ( inlet face marker, outlet face marker,
%          Takeoff power (HP), 0.0, Takeoff rev/min
%          Cruise power (HP), 0.0, Cruise rev/min )
MARKER_ACTDISK = ( ACTDISK, ACTDISK_BACK, 70.5, 10, 0, 70.5, 10, 0 )
```

New Actuator Disk Model

Based on the General Momentum Theory

Axial and rotational (*swirl*) interference factors vary along the actuator disk radius.

- Typical available data of a propeller are the *thrust* and *power* distributions.

User input:

- Propeller performance: ***Thrust***, ***Power*** and ***Radial Force*** Coefficients: $\frac{dC_T}{d\overline{r}}(\overline{r})$, $\frac{dC_p}{d\overline{r}}(\overline{r})$, $\frac{dC_R}{d\overline{r}}(\overline{r})$.
- Static temperature jump not required.

```
% --------------- SECTION DEDICATED TO ACTUATOR DISK -----------------------%
ACTDISK_TYPE= VARIABLES_JUMP
ACTDISK_JUMP= DIFFERENCE
ACTDISK_FILE = YES
ACTDISK_FILE_NAME= InputActDisk
MARKER_ACTDISK = ( TIP-DISK, TIP-DISK_BACK )
```

Config. File

```
NAME= TIP-DISK
NAME_BACK= TIP-DISK_BACK
CENTER= 10.740117 12.286 4.789556
AXIS= 1.0 0.0 0.0
RADIUS= 1.25
ADV_RATIO= 2.39605
NROW= 37
r/R            dCT/d(r/R)            dCP/d(r/R)            dCR/d(r/R)
0.2031280840   0.0200663015515702    0.0890674839425840    0.0
0.2235606970   0.0199636559219987    0.0932674380647361    0.0
0.2439933100   0.0217076220184585    0.0982980106429351    0.0
...            ...                   ...                   ...
...            ...                   ...                   ...
0.9591347740   0.4349376731962520    1.1470356258811900    0.0
0.9795673870   0.3772882005154550    0.9746048293570620    0.0
```

External File (*InputActDisk*)

Relations between propeller performance and local variables

Local force per unit area: $F(\overline{r}) = (F_A(\overline{r}), F_\theta(\overline{r}), F_R(\overline{r}))$

Thrust coefficient: $C_T = \frac{T}{\rho_\infty n^2 D^4}$
Power coefficient: $C_P = \frac{P}{\rho_\infty n^3 D^5}$
Radial Force coefficient: $C_R = \frac{F_R}{\rho_\infty n^2 D^4}$

Axial force per unit area:

$$F_A(\overline{r}) = \Delta p(\overline{r}) = \frac{2\gamma p_\infty V_\infty^2}{J^2 \pi \overline{r}} \left(\frac{\mathrm{d}C_T}{\mathrm{d}\overline{r}} \right)$$

Tangential force per unit area:

$$F_\theta(\overline{r}) = \frac{2\gamma p_\infty M_\infty^2}{(J\pi\overline{r})^2} \left(\frac{\mathrm{d}C_P}{\mathrm{d}\overline{r}} \right)$$

Radial force per unit area:

$$F_R(\overline{r}) = \frac{2\gamma p_\infty V_\infty^2}{J^2 \pi \overline{r}} \left(\frac{\mathrm{d}C_R}{\mathrm{d}\overline{r}} \right)$$

$J = \frac{V_\infty}{nD}$: advance ratio. n: rounds per second. D: disk diameter. γ: specific heat ratio.

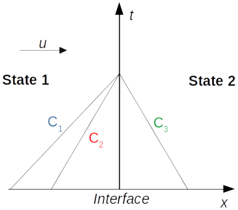
Numerical boundary conditions at disk interface

- The Actuator Disk is an interface in *SU2*, necessary consistency and stability of the boundary conditions.
- General guideline: to be consistent with 1D characteristic theory.

Subsonic inviscid flow

- C_1: $R^+ =$ constant along $\frac{\mathrm{d}x}{\mathrm{d}t} = u + c$
- C_2: $s =$ constant along $\frac{\mathrm{d}x}{\mathrm{d}t} = u$
- C_3: $R^- =$ constant along $\frac{\mathrm{d}x}{\mathrm{d}t} = u - c$

c: speed of sound;
s: entropy;
$R^{\pm} = u \pm \frac{2c}{\gamma - 1}$: acoustic Riemann invariants.



- 1D interface: 2 data extrapolated from State 1; 1 data extrapolated from State 2.
- 3D interface: 4 data extrapolated from State 1; 1 data extrapolated from State 2.

Local Mathematical Model

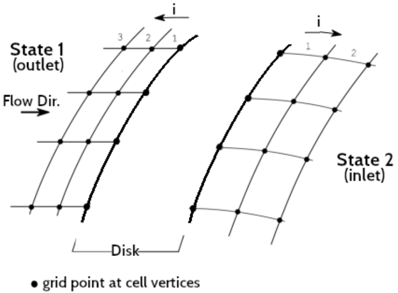
According to characteristic theory

State 1 (outlet)

- *1 data imposed*:
  - pressure $p_1 = p_2 - \Delta p$
- *4 data extrapolated from upstream*:
  - entropy s_1
  - Riemann invariant R_1^+
  - tangential velocity $\underline{V}_{t1}$

State 2 (inlet)

- *4 data imposed*:
  - pressure jump Δp
  - continuity $(\rho V_n)_2 = (\rho V_n)_1$
  - swirl $\Delta (\rho \underline{V}_t)$
- *1 data extrapolated from downstream*:
  - Riemann invariant R_2^-

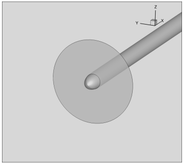


Test Case: Actuator Disk with semi-infinite spinner

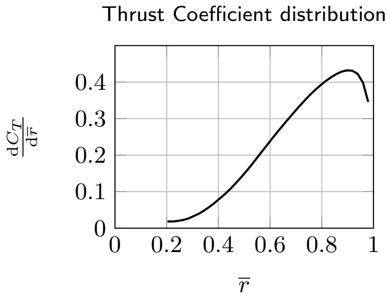
Input data

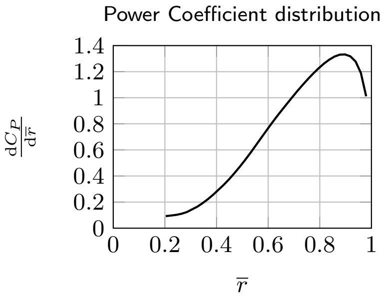
Physical Problem: *RANS* - **Turbulence Model**: *SA*
Spatial discretization: *JST*

M_∞	0.56
α	0°
Re_D	36.5×10^6
J	2.8
C_T	0.18



Propeller data:



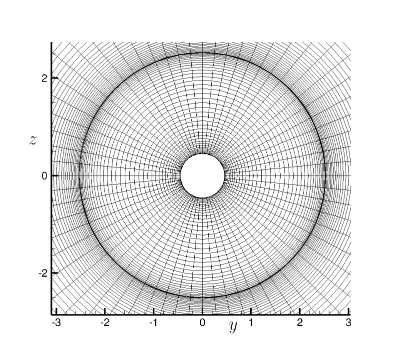


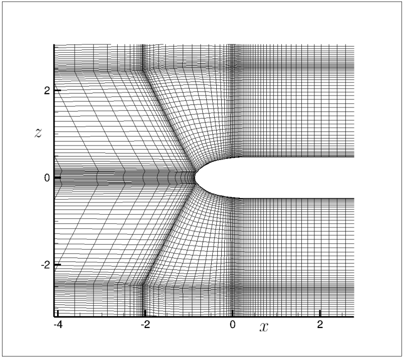
Test case provided by CIRA.

Test Case: Actuator Disk with semi-infinite spinner

Mesh details

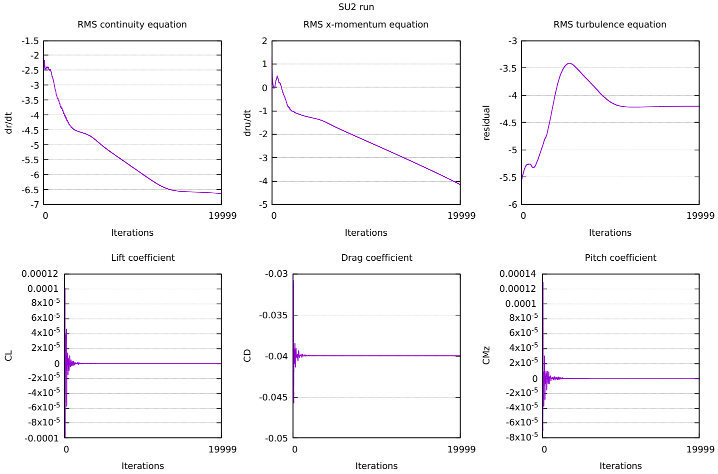
Total Number of Cells	792576
Boundary elements on disk	3712





Test Case: Actuator Disk with semi-infinite spinner

Convergence history

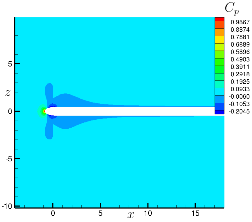


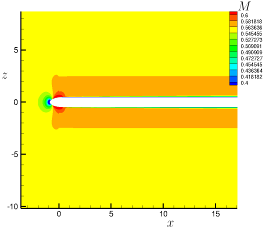
$$M_\infty = 0.56,\ \alpha = 0^\circ,\ Re_D = 36.5 \times 10^6,\ J = 2.8,\ C_T = 0.18,\ CFL = 4.$$

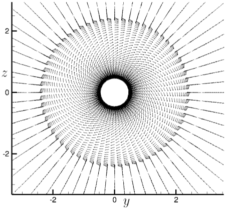
Test Case: Actuator Disk with semi-infinite spinner

Comparison with *ZEN(CIRA) RANS* solver

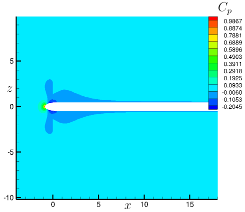
SU2 (UNINA)

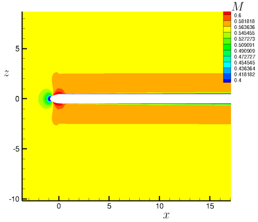


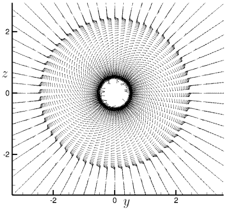




ZEN (CIRA)





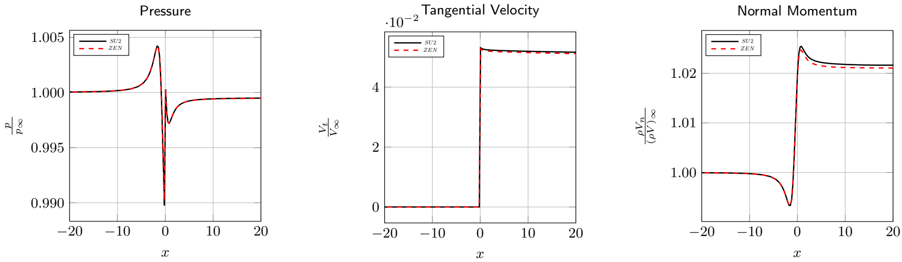


Pressure Coefficient | Mach Number | Tangential Velocity Vectors

Test Case: Actuator Disk with semi-infinite spinner

Comparison with *ZEN(CIRA) RANS* solver

- Distributions of flow properties in axial direction at $\overline{r} = 0.5$.

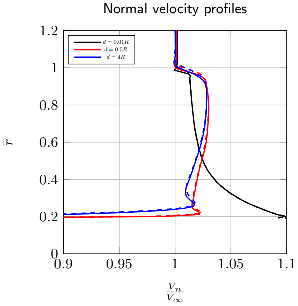


- Agreement with *ZEN(CIRA)* results.
- Agreement with Momentum Theory:
  - downstream axial induction is twice the value on the disk;
  - *swirl* is zero upstream and constant downstream.

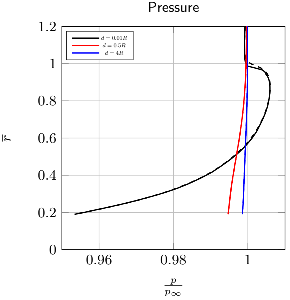
Test Case: Actuator Disk with semi-infinite spinner

Comparison with *ZEN(CIRA) RANS* solver

- Distributions of V_n and p in radial direction at different stations in the wake.



— : SU2; - - : ZEN.



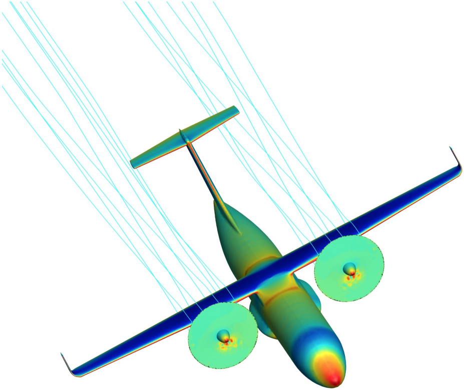
— : SU2; - - : ZEN.

- Agreement with *ZEN(CIRA)* results.
- Static pressure not equal to p_∞ in the streamtube due to the *swirl* term: possible conflict with far field boundary condition.

Application 1: Regional Turboprop A/C

$M_\infty = 0.5, Re_\infty = 19 \times 10^6, \alpha = 0°, C_T = 0.18$

- Activity within *SCAVIR* research program funded by Italian Ministry for the Research.
- A/C configuration developed by *Leonardo* Company.



SCAVIR research program in cooperation with Leonardo Company.

Application 1: Regional Turboprop A/C

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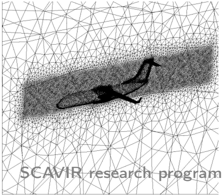
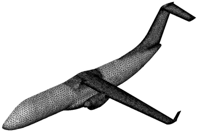
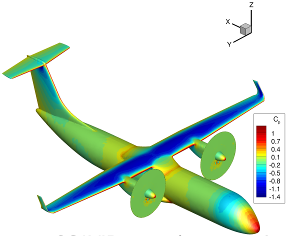
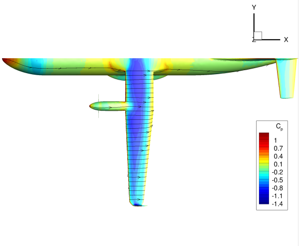




SCAVIR research program in cooperation with Leonardo Company.



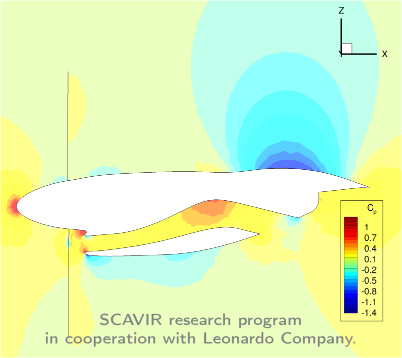


SCAVIR research program in cooperation with Leonardo Company.

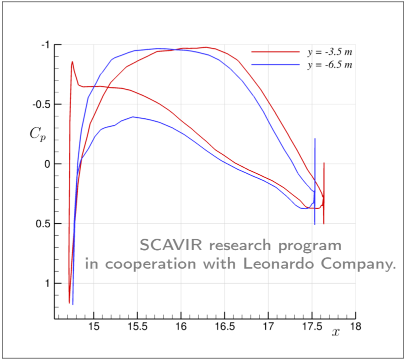
12 million grid elements (half configuration). Symmetrical flow for CPU saving implies counter-rotating propellers.

Application 1: Regional Turboprop A/C

$M_\infty = 0.5, Re_\infty = 19 \times 10^6, \alpha = 0°, C_T = 0.18$



Pressure Coefficient Contour at nacelle symmetry plane



Pressure Coefficient distributions along 2 wing sections in the propeller streamtube.

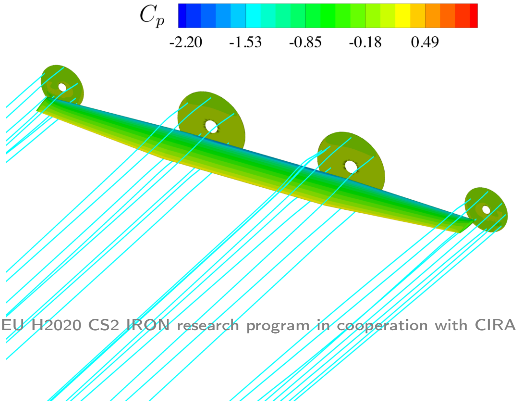
— downwash section

— upwash section

Application 2: Distributed Electric Propulsion (DEP)

$M_{\infty} = 0.48$, $Re_{\infty} = 16 \times 10^6$, $\alpha = 0°$

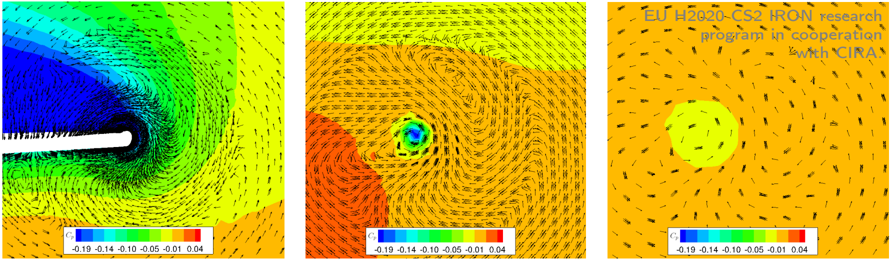
- Configuration and grid made by *CIRA*.



EU H2020 CS2 IRON research program in cooperation with CIRA.

Application 2: Distributed Electric Propulsion (DEP)

$M_\infty = 0.48$, $Re_\infty = 16 \times 10^6$, $\alpha = 0°$



$d = 1.5R$ $d = 3R$ $d = 5R$

Cross flow at different distances in the wake.

- *Swirl* introduction in the actuator disk model allows to capture the induced fluid rotation opposite to the tip vortex.

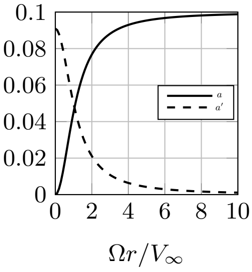
Automatic generation of propeller input

Based on the optimal propeller theory

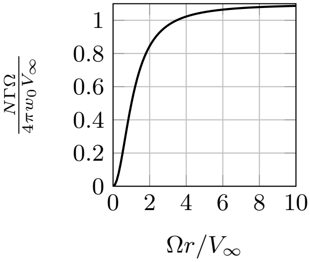
Problem: propeller details usually not available during aircraft preliminary design. Only overall propeller performance, such as C_T, J and Ω, are known.

How to simulate propeller effects in aircraft preliminary design?

Solution: written a *C++* code providing *thrust* and *power* distributions from global data using the inviscid theory of *optimal propeller*.[d]



Axial and rotational interference factors for the optimal propeller



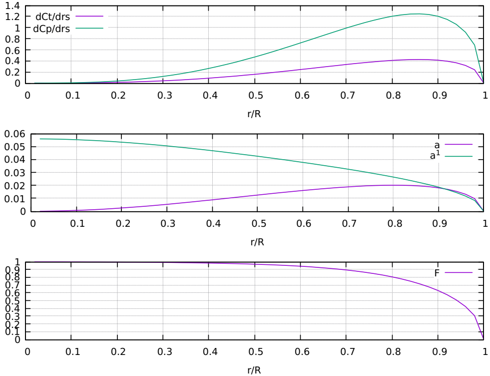
Non-dimensional circulation for the optimal propeller

[d] H. Glauert (1935), Airplane Propellers, in *Aerodynamic Theory*, Ed. W.F. Durand, Vol. IV, Springer.

Automatic generation of propeller input

Based on the optimal propeller theory

- *Input*: C_T, J, V_∞.
- *Outputs*: $\frac{dC_T}{d\overline{r}}(\overline{r})$, $\frac{dC_P}{d\overline{r}}(\overline{r})$, propeller data input file.



NAME=
NAME_BACK=
CENTER=
AXIS=
RADIUS= 2.5146
ADV_RATIO= 2.81487
NROW= 50

r/R	dCT/d(r/R)	dCP/d(r/R)	dCR/d(r/R)
0.02	1.30986e-05	3.90566e-05	0
0.04	0.000104637	0.000311994	0
0.06	0.000352334	0.00105053	0
0.08	0.00083252	0.00248224	0
0.1	0.00161949	0.00482859	0
0.12	0.0027849	0.00830311	0
0.14	0.00439713	0.0131097	0
0.16	0.00652084	0.0194408	0
0.18	0.00921638	0.0274763	0
0.2	0.0125394	0.0373818	0
0.22	0.0165404	0.0493076	0
0.24	0.0212646	0.0633879	0
0.26	0.0267514	0.0797396	0
0.28	0.0330342	0.0984618	0
0.3	0.0401402	0.119635	0
0.32	0.0480907	0.143321	0
0.34	0.0569	0.169561	0
0.36	0.0665763	0.198379	0
0.38	0.0771208	0.229777	0
0.4	0.0885281	0.263735	0
0.42	0.100786	0.300215	0
0.44	0.113874	0.339154	0
0.46	0.127767	0.380469	0
0.48	0.142428	0.424052	0
0.5	0.157815	0.469771	0
0.52	0.173877	0.517464	0
0.54	0.190552	0.566944	0
0.56	0.207769	0.617989	0
0.58	0.225444	0.670344	0
0.6	0.243482	0.723712	0
0.62	0.261773	0.777753	0
0.64	0.280189	0.832076	0
0.66	0.298583	0.886231	0
0.68	0.316788	0.9397	0
0.7	0.334607	0.991884	0
0.72	0.351815	1.04209	0
0.74	0.368148	1.08952	0
0.76	0.383296	1.13323	0
0.78	0.396893	1.17211	0
0.8	0.408503	1.20485	0
0.82	0.417597	1.22987	0
0.84	0.423526	1.24524	0
0.86	0.425475	1.24855	0
0.88	0.422386	1.2367	0
0.9	0.412835	1.20555	0
0.92	0.394781	1.1492	0
0.94	0.365035	1.05854	0
0.96	0.317836	0.917165	0
0.98	0.239435	0.686207	0
1	0	0	0

Conclusions

- Developed and implemented a new actuator disk model in *SU2* (vsn 6.2.0) with variable load and swirl along radius: ***thrust***, ***power*** and ***radial force*** coefficients as input parameters.
- Model validated by comparison with *CIRA* solver results.
- Model successfully applied to the analysis of a regional turboprop A/C and a DEP configuration.
- Written a *C++* code to generate *SU2* propeller input based on global variables (C_T, J, V_∞).

What is next?

We named our version *SU2 "Saetta"* (Arrow), nickname of the Italian WWII fighter Macchi MC 200... and incidentally my name!

If welcome, we are ready to implement the new actuator disk model in current official release *SU2 "Blackbird"*.