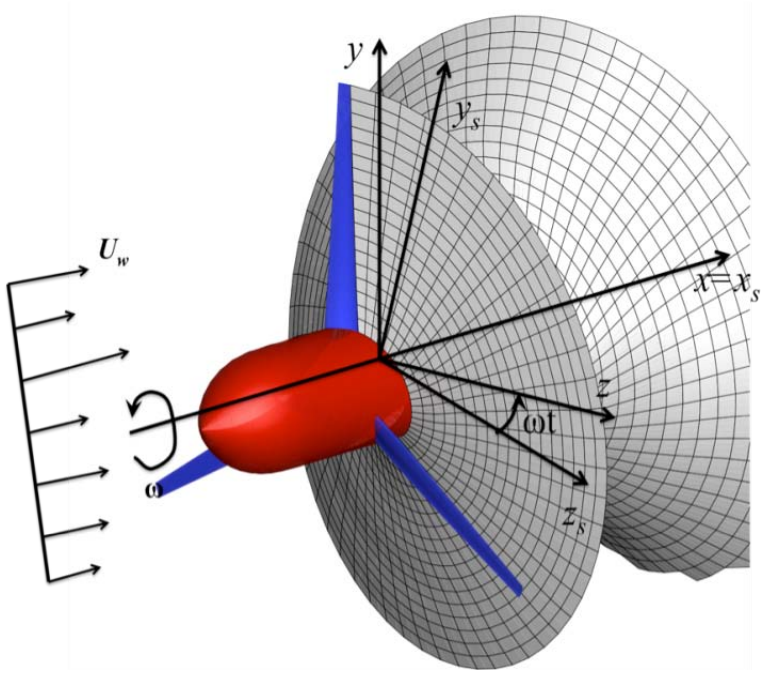
Marine and Hydrokinetic Device Modeling/Design Workshop
NREL, Golden, Colorado
March 1-2, 2011



Prediction of performance and design of tidal/ocean current turbines

by Spyros A. Kinnas (kinnas@mail.utexas.edu)
Ocean Engineering Group
Civil , Architectural and Environmental Engineering, UT Austin

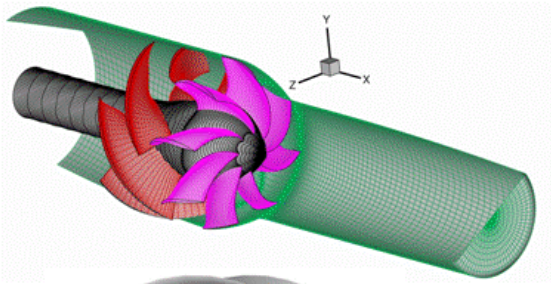
March 1, 2011

Details of our work on turbines may be found in

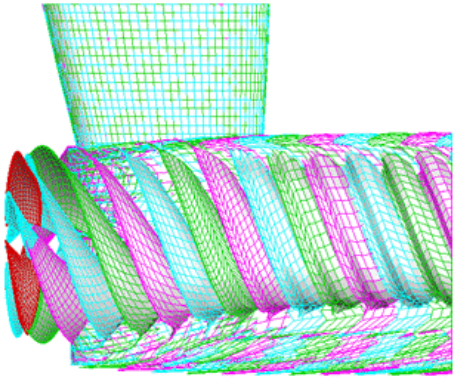
- Xu W. and Kinnas, S. A.,"Performance Prediction and Design of Marine Current Turbines", in *16th Offshore Symposium*, Texas Section of The Society of Naval Architects & Marine Engineers (SNAME), Houston, Texas, February 9, 2010.
- Wei Xu (MS, Ocean, UT, August 2010 - pdf can be downloaded from Kinnas homepage: http://www.caee.utexas.edu/prof/kinnas/home.html
- Kinnas, S.A., Xu, W., Yu, Y.-H., and He, L. "Computational Methods for the Design and Prediction of Performance of Tidal Turbines", *Journal of Offshore Mechanics and Arctic Engineering* (May 2011, to appear-revised version of OMAE'10 conference paper).
- He, L., Xu, W., and Kinnas, S.A. "Numerical Methods for the Prediction of Unsteady Performance of Marine Propellers and Turbines", ISOPE 2011 (June 2011, Maui)

Quick review of OEG's most recent research on marine propulsors

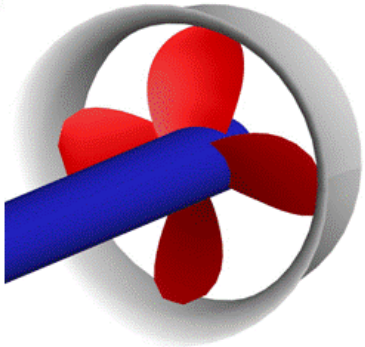
Pump of water-jet



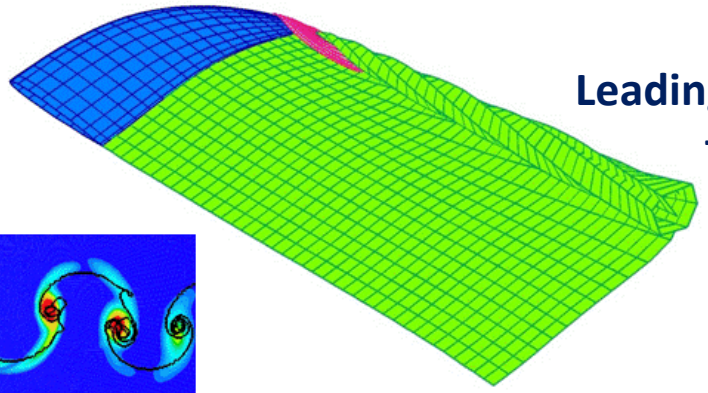
Propeller/rudder interaction



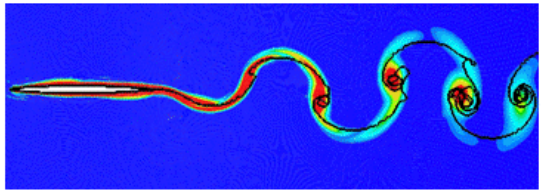
Ducted propellers



Leading edge vortex tracking



Heaving hydrofoil



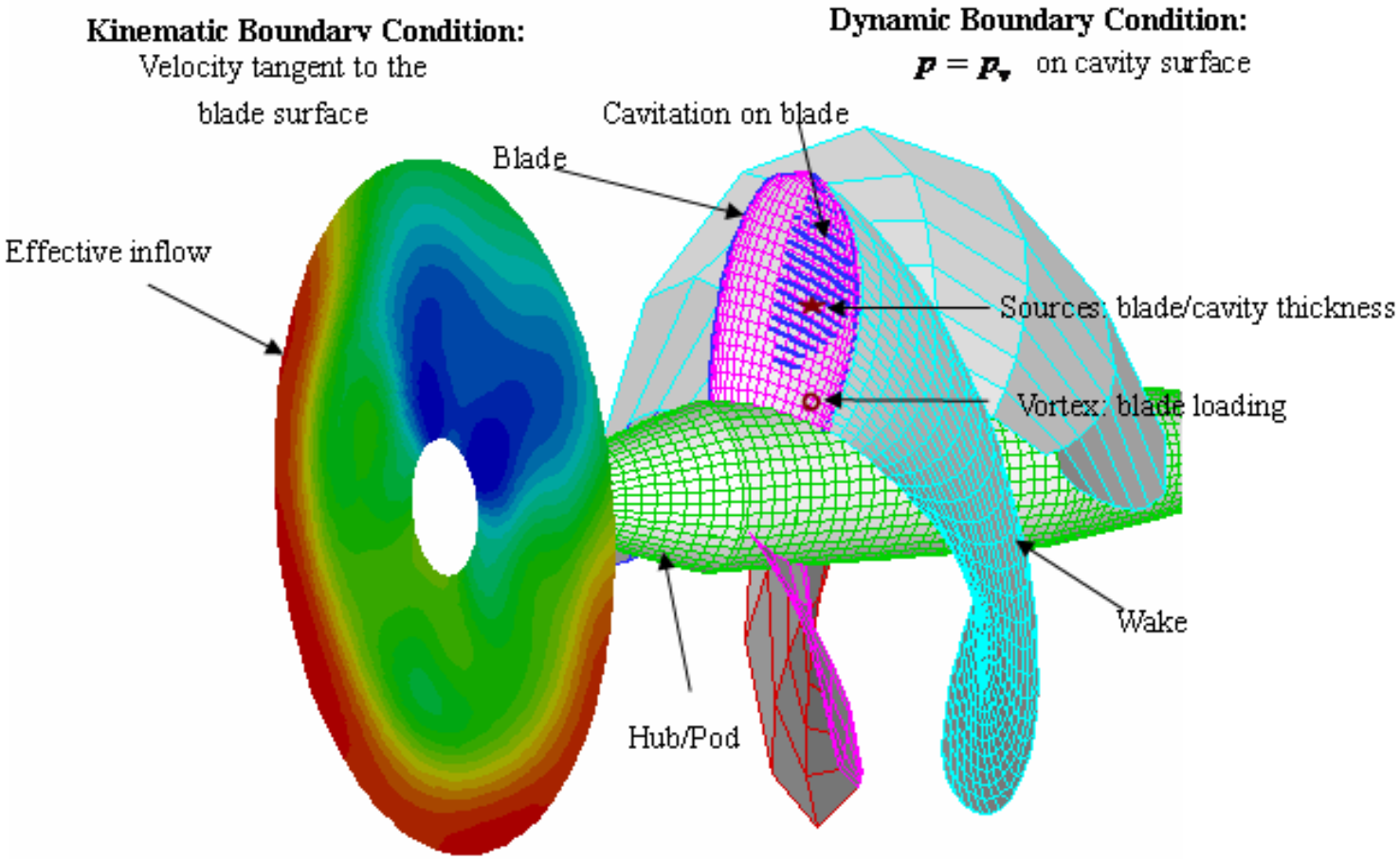
Computational Hydrodynamics Laboratory – UT Austin

Some recent marine propulsors we have analyzed…

Contra-rotating props

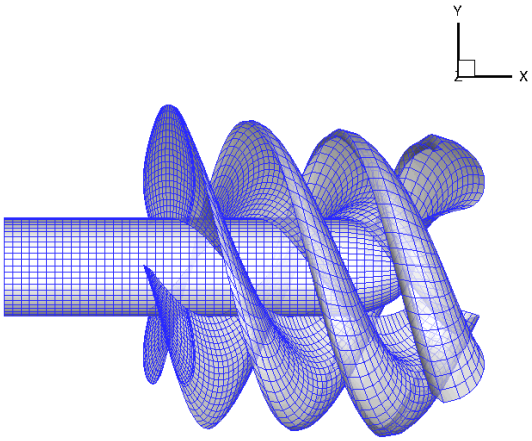
Podded prop

Definition of parameters in our propeller analysis models

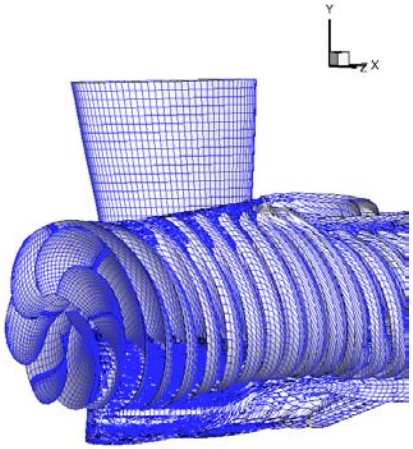


MPUF-3A: most recent version of PUF-3A vortex/source-lattice (placed on mean camber surface) method

Propeller in heaving motion



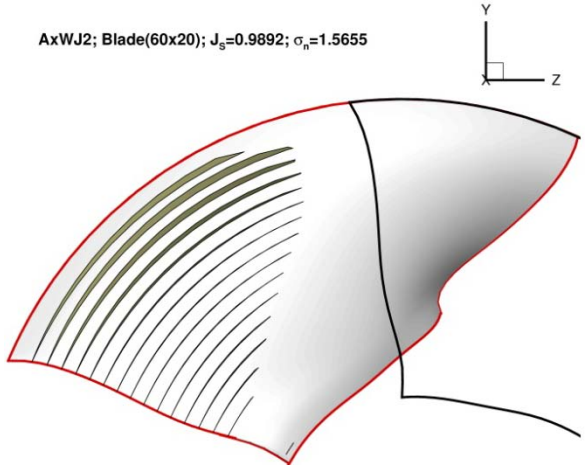
Propeller wake/rudder interaction



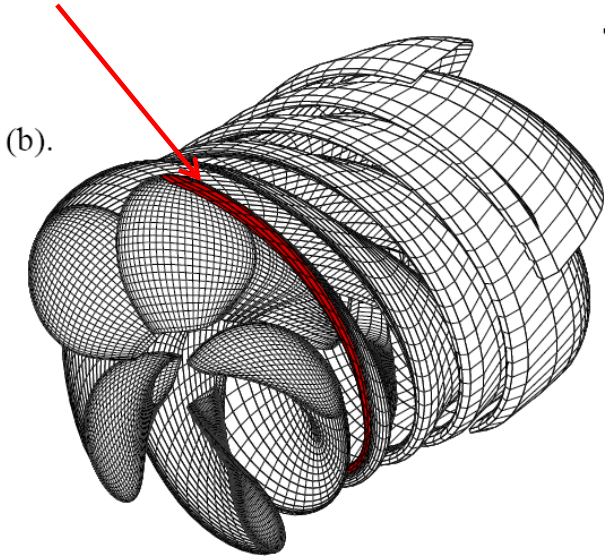
- Fully-unsteady (NOT quasi-steady)
- Handles back and/or face sheet cavitation with determined cavity detachment
- Effects of viscosity via friction coefficient (specified or function of local Reynolds #) applied on wetted part
- Includes effects of thickness/loading coupling and non-linear effects of camber /inflow on pressure/cavity shape
- Includes hub (pod or duct) effects via simplified image or panel model
- Coupled with our Euler code (GBFLOW) or RANS (Fluent, OpenFOAM, …) for the evaluation of effective wake or interaction with duct, hub, pod, or hull
- Includes simplified or fully-unsteady trailing wake alignment, and most recently, rigid motions of prop

PROPCAV: Boundary Element Method (BEM: panels placed on blade surface), based on wetted code PSF-10/PUF-10

Cavity patterns on rotor Of water-jet



Leading edge vortex model



- Fully-unsteady (NOT quasi-steady)
- Handles back and/or face sheet cavitation with determined cavity detachment
- Has been extended and applied on surface-piercing propellers
- Effects of viscosity via friction coefficient, or via coupling with XFOIL (integral boundary layer code)
- Includes hub (pod, duct, or water-jet casing) effects via panel model
- Can be applied on rotor or stator and include their interaction (time-averaged)
- Includes treatment of developed tip vortex cavity
- Has been coupled with RANS (Fluent) in the case of water-jets
- Includes simplified or fully-unsteady trailing wake alignment, and most recently, rigid motions of prop
- Currently being extended to include effects of leading edge vortex.

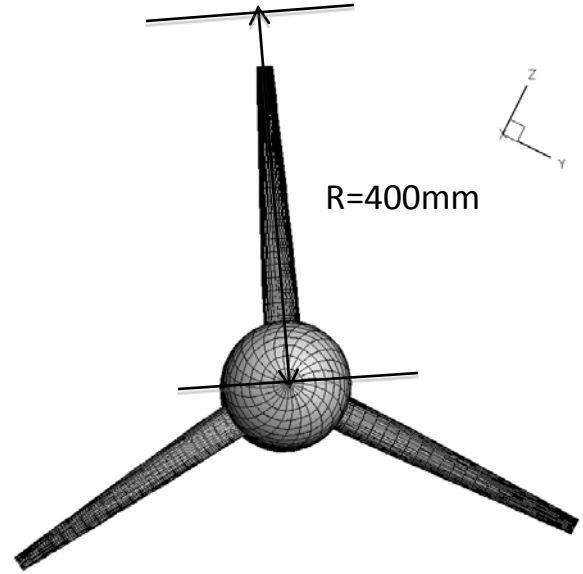
Application of MPUF-3A/PROPCAV in the case of turbines

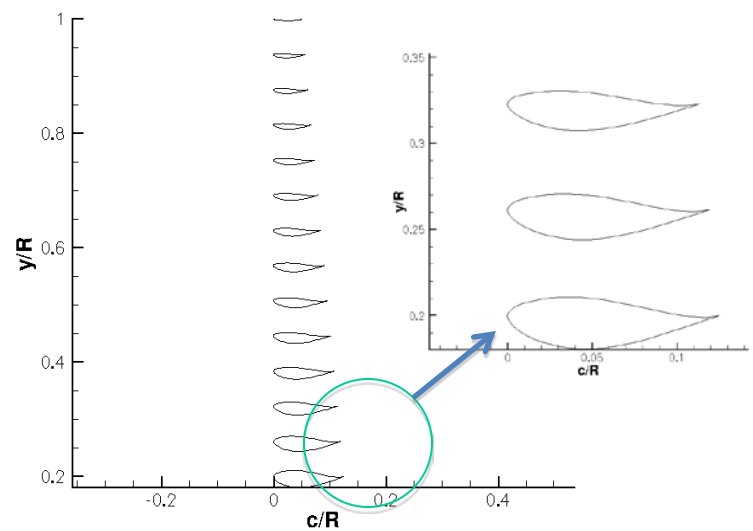
Turbine Model (Bahaj et al, 2007)

$$Tip\ speed\ ratio: TSR = \frac{\omega R}{V}; \omega\ is\ rotational\ velocity\ in\ rad/\sec$$

$$and\ V\ is\ the\ current\ speed\ in\ m/s$$

Advance Ratio: $J = V / nD = \pi / TSR$

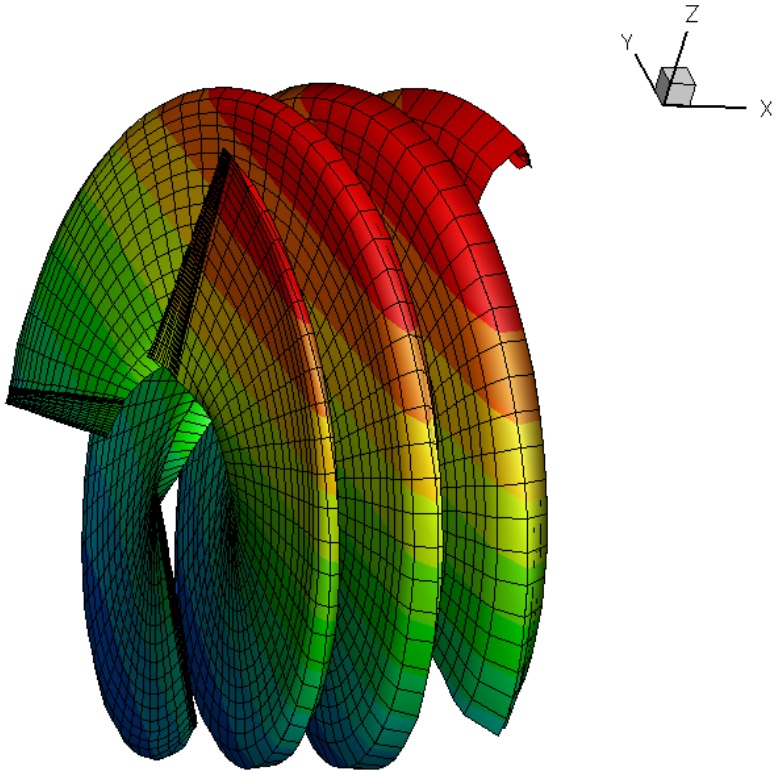




Unsteady wake alignment in MPUF-3A (He and Kinnas, PROPS 2009)

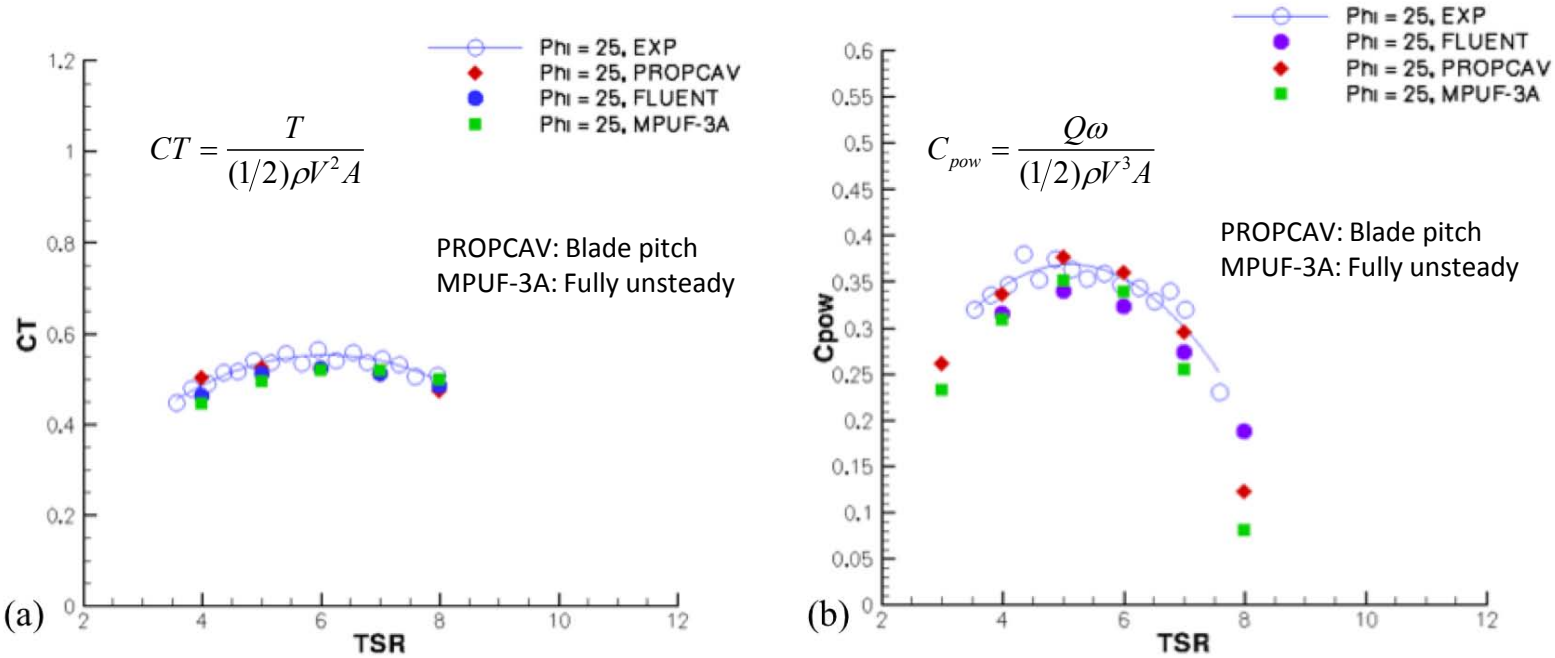
- **Alignment is crucial in predicting turbine performance**

- **Not having the correct wake might lead to higher predicted efficiencies (more than the Betz ideal of 59%!)**



Thrust and Power Coefficients

- Comparison of results from different methods with the experimental measurements－25 degrees hub pitch, zero yaw and no hub: (a) thrust coefficient , CT, for different TSR (Tip speed ratio) (b) power coefficient, Cpow, for different TSR.

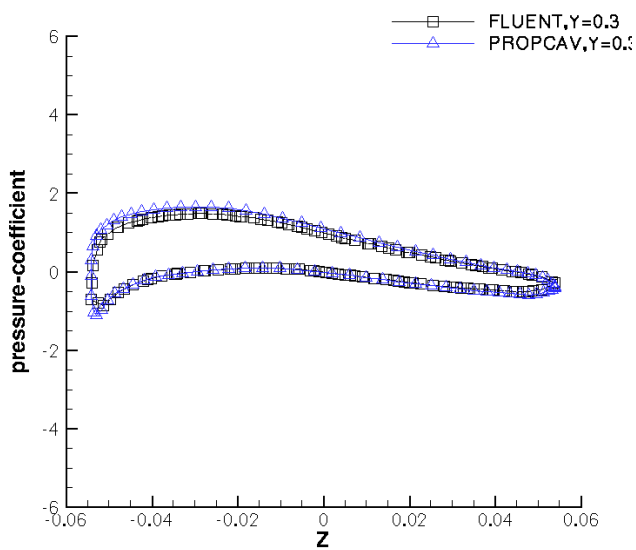


Pressure Coefficients predicted by PROPCAV & RANS

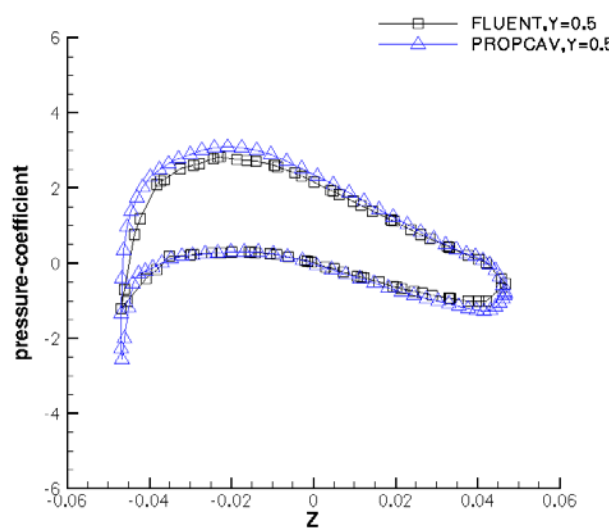
- Comparison of Pressure coefficients (C_p) at various Y from FLUENT and PROPCAV
- 25 degrees hub pitch, zero yaw and no hub
- TSR=6.0

$$C_p = \frac{P - P_0}{0.5\rho n^2 D^2}$$

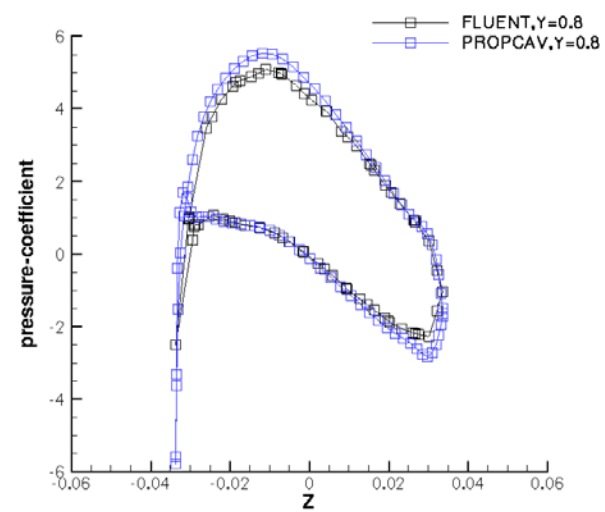
-Cp at Y=0.3



-Cp at Y=0.5



-Cp at Y=0.8



Prediction of cavity pattern from PROPCAV

(uniform current speed profile)

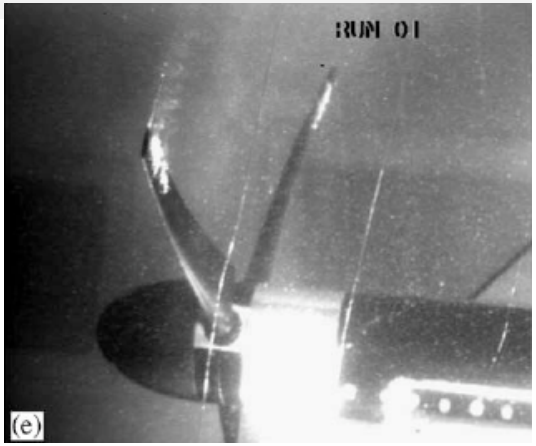
CASE:

- 0 yaw angle
- 25 degrees hub pitch
- Tip speed ratio (TSR) : 7.5
- Cavitation number : 3.9

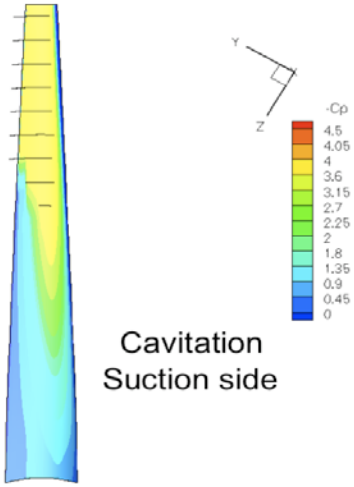
$$\sigma_n = (P_{shaft} - P_{vapor}) \Big/ (\frac{\rho}{2} n^2 D^2)$$

- Uniform inflow

►**Photo of cavitation from the experiment**

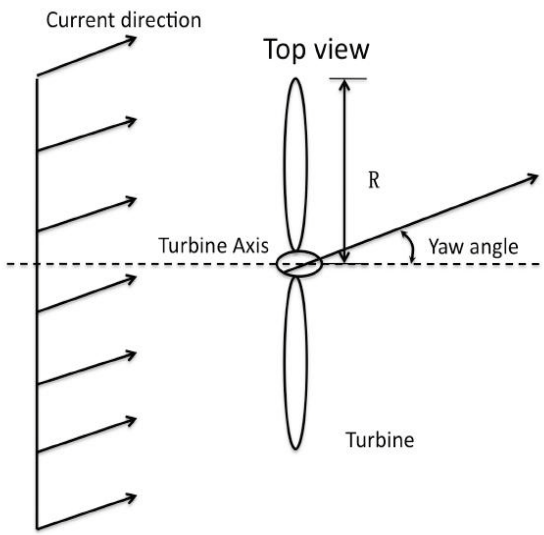


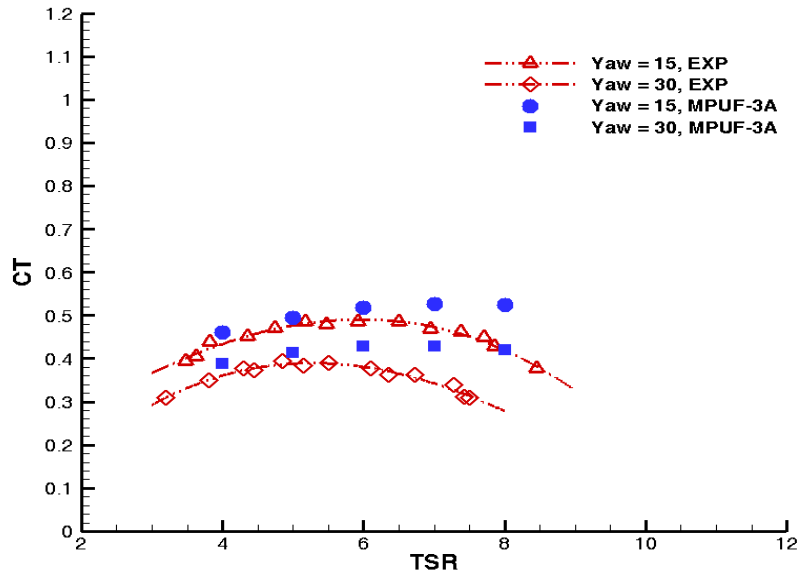
►**The cavitation patterns and pressure contour of the suction side from PROPCAV**

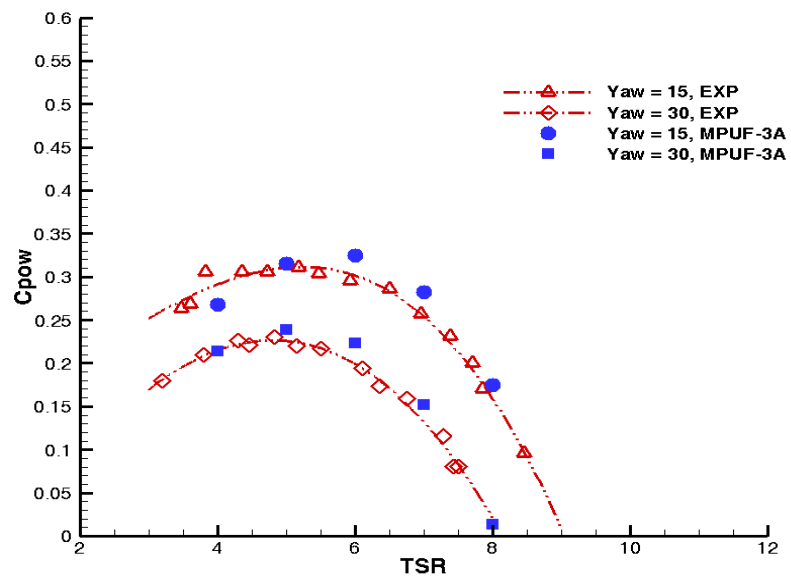


Note: The turbine in the photograph is left-handed while the turbine model in PROPCAV is right-handed. That means the results from PROPCAV must be mirrored relative to the vertical plane in order to make comparisons with the experiment

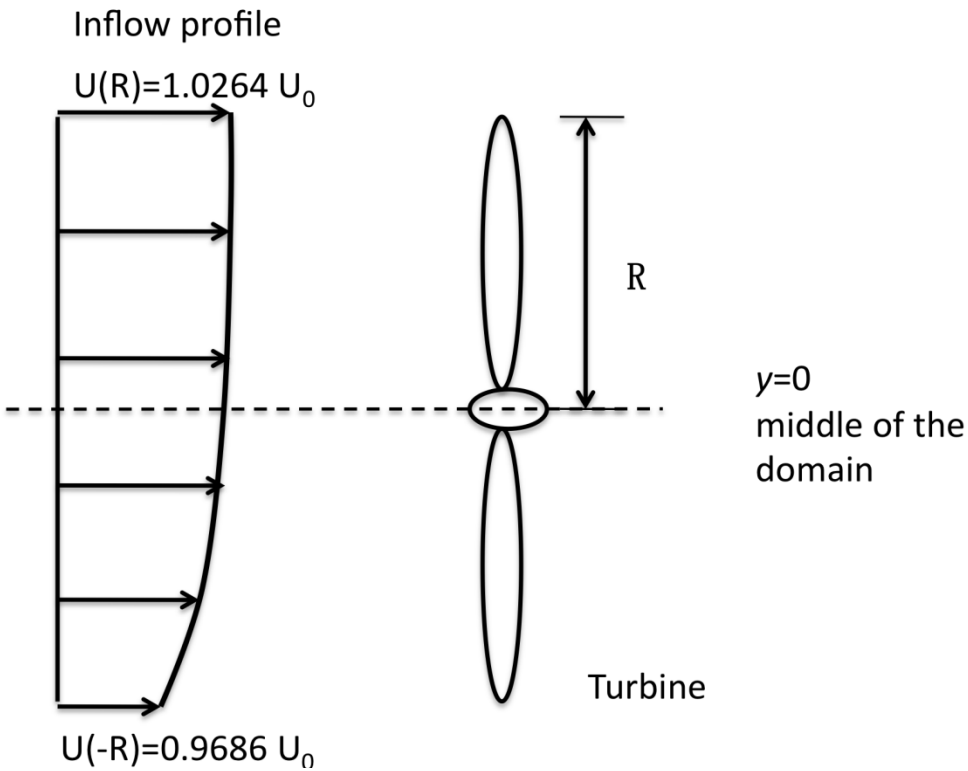
Application of MPUF-3A in the case of inflow with yaw





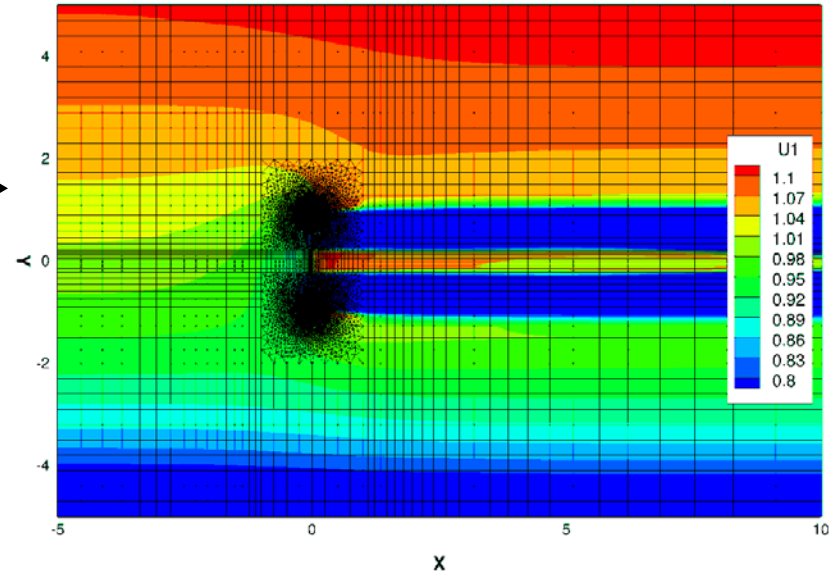


APPLICATION OF MPUF-3A COUPLED WITH NS-3D (UT'S NAVIER-STOKES CODE) TO TURBINE SUBJECT TO NON-UNIFORM CURRENT

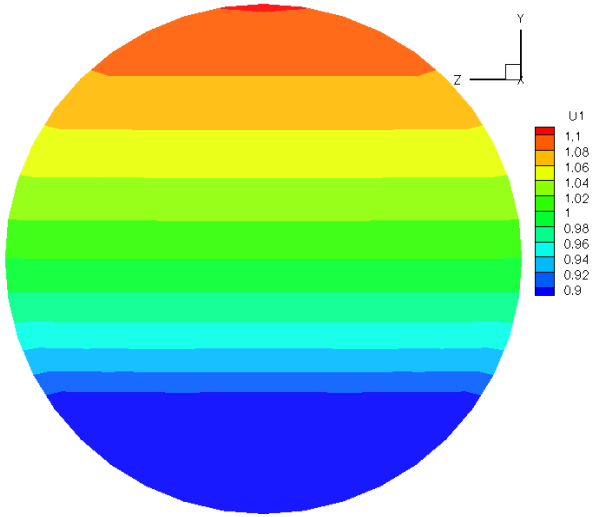


Q: What should be the proper inflow to the turbine?
A: NOT the current velocity in the absence of turbine (what we call nominal wake), rather it should be the effective inflow (see next slide)

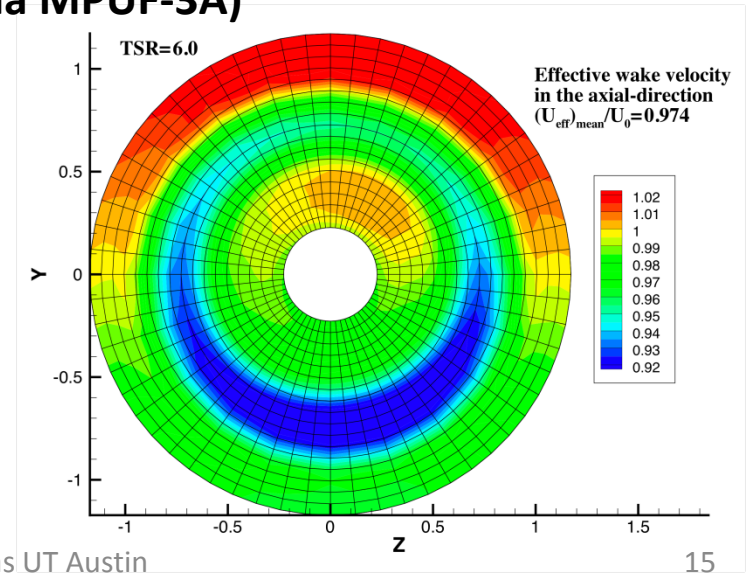
Grid and flow-field predicted by NS-3D : The turbine is modeled with body forces at the location of its blades – The strength of the body forces are determined using the pressure distribution over the blades predicted by MPUF-3A.



Nominal wake = inflow in the ABSCENSE of turbine

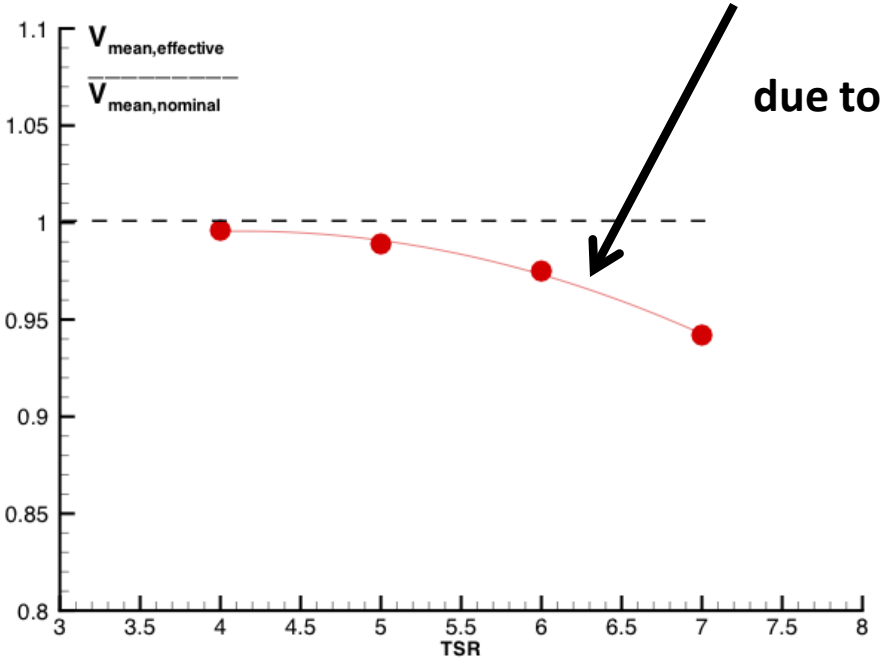


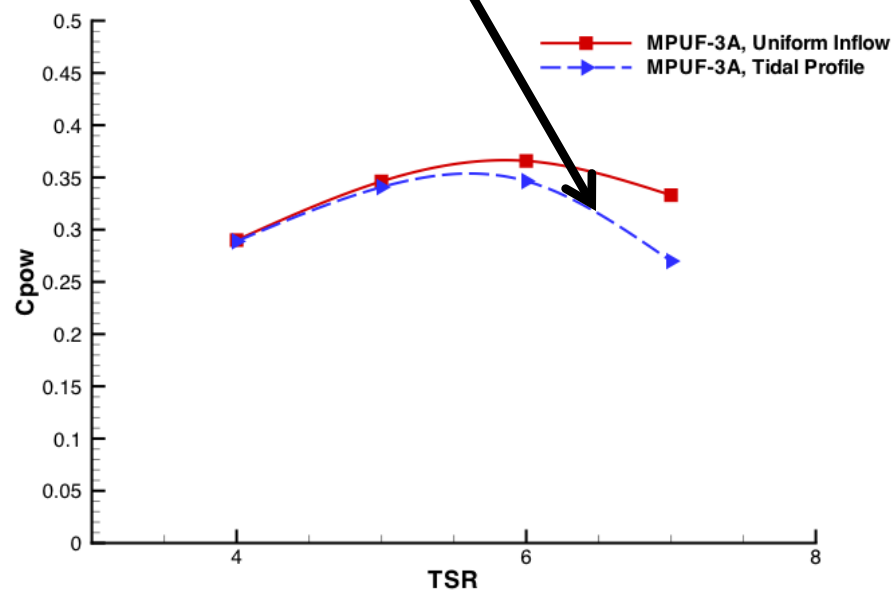
Effective wake= (Total flow in the presence of turbine: evaluated via NS-3D)-(Induced by turbine: evaluated via MPUF-3A)



Mean of effective wake inflow<Mean of nominal wake and…

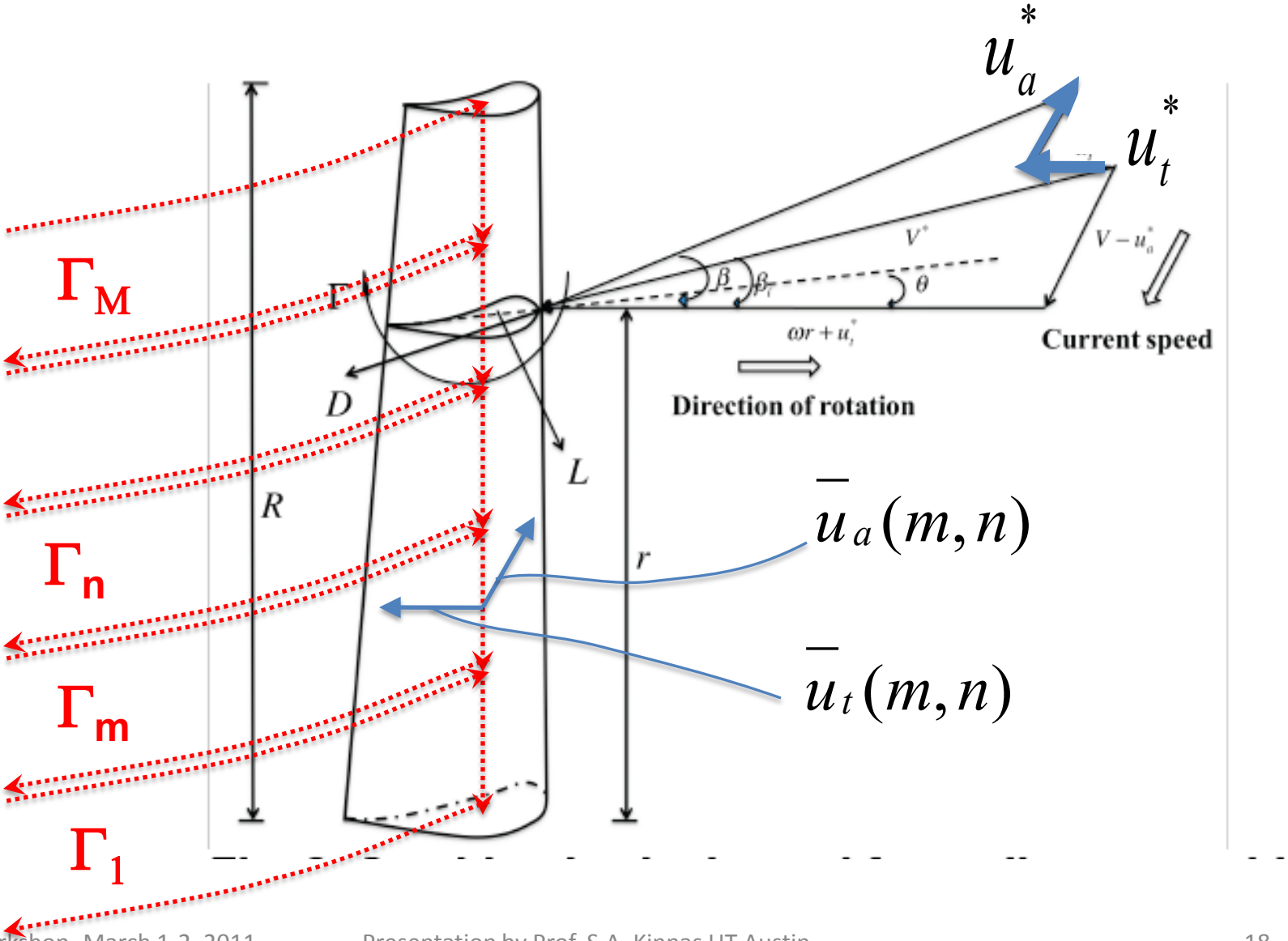
due to that the delivered power by the turbine reduces





Optimum loading (circulation) distribution along span

UT's Lifting Line OPTimization models: LLOPT & LLOPT-BASE



Efficiency=Power Coefficient:

$$\eta = C_{pow} = \frac{Q\omega}{0.5\rho\pi R^2 V^3}$$

Must maximize Torque, Q

$$Q = \rho Z V^2 R^3 \sum_{m=1}^{M} \left[1 - \sum_{n=1}^{M} \bar{\Gamma}_n \bar{u}_a(m,n) \right] \Delta\bar{r}\ \bar{r}_m\ \bar{\Gamma}_m$$

Induced axial velocity:

$$\frac{u_a^*(m)}{V} = \sum_{n=1}^{M} \bar{\Gamma}_n \bar{u}_a(m,n)$$

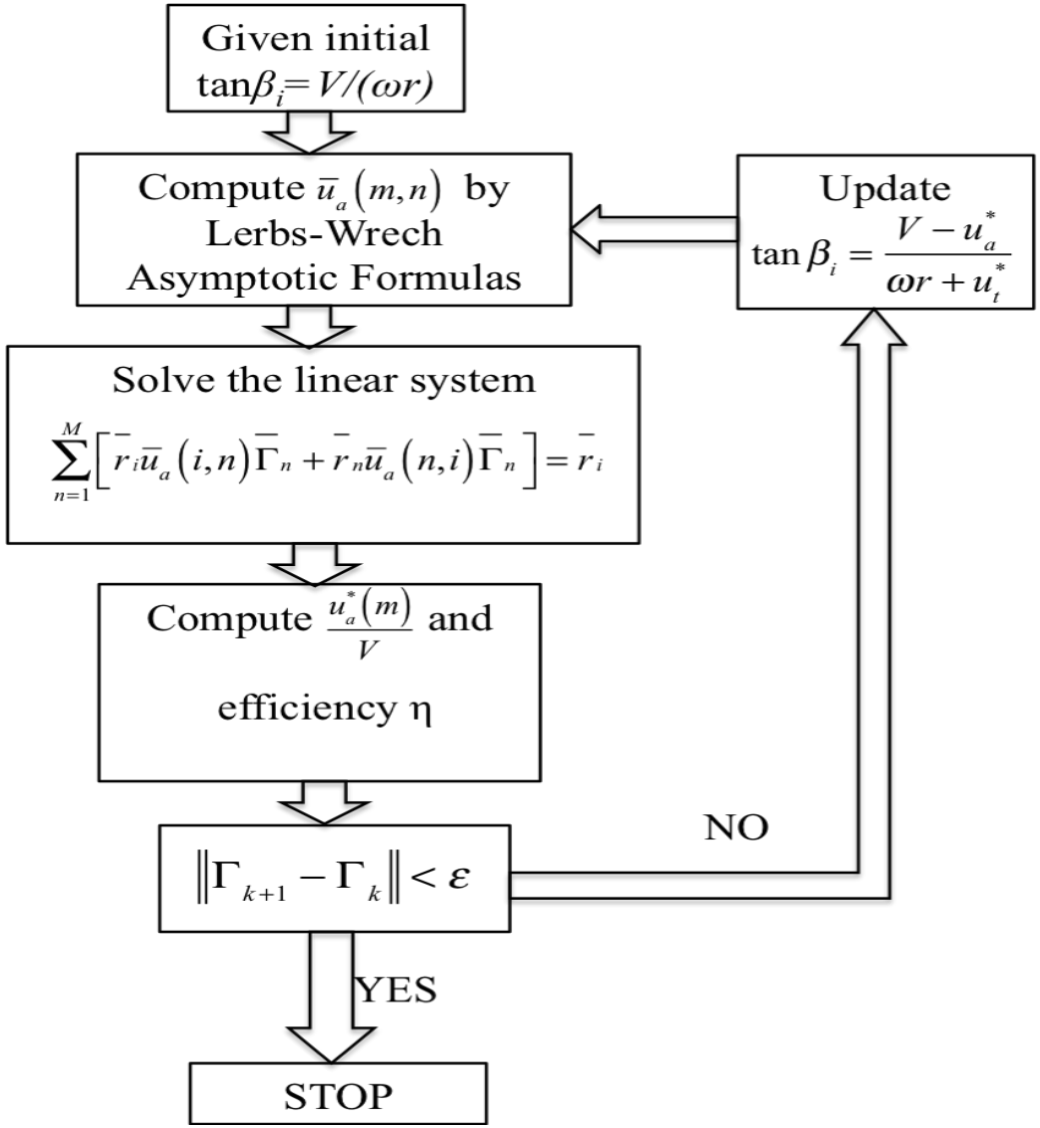
To maximize torque:

$$\frac{\partial Q}{\partial \bar{\Gamma}_i} = 0$$

Linearization (assumption):

$$\frac{\partial \bar{u}_a(m,n)}{\partial \Gamma_i} = 0,\ i=1,\ldots,M$$

LLOPT


Given initial
$\tan\beta_i = V/(\omega r)$
Compute $\bar{u}_a(m,n)$ by
Lerbs-Wrech
Asymptotic Formulas
Update
$\tan\beta_i = \frac{V - u_a^*}{\omega r + u_t^*}$
Solve the linear system
$\sum_{n=1}^{M}\left[\bar{r}_i\bar{u}_a(i,n)\bar{\Gamma}_n + \bar{r}_n\bar{u}_a(n,i)\bar{\Gamma}_n\right] = \bar{r}_i$
Compute $\frac{u_a^*(m)}{V}$ and
efficiency η
$\|\Gamma_{k+1} - \Gamma_k\| < \varepsilon$
NO
YES
STOP

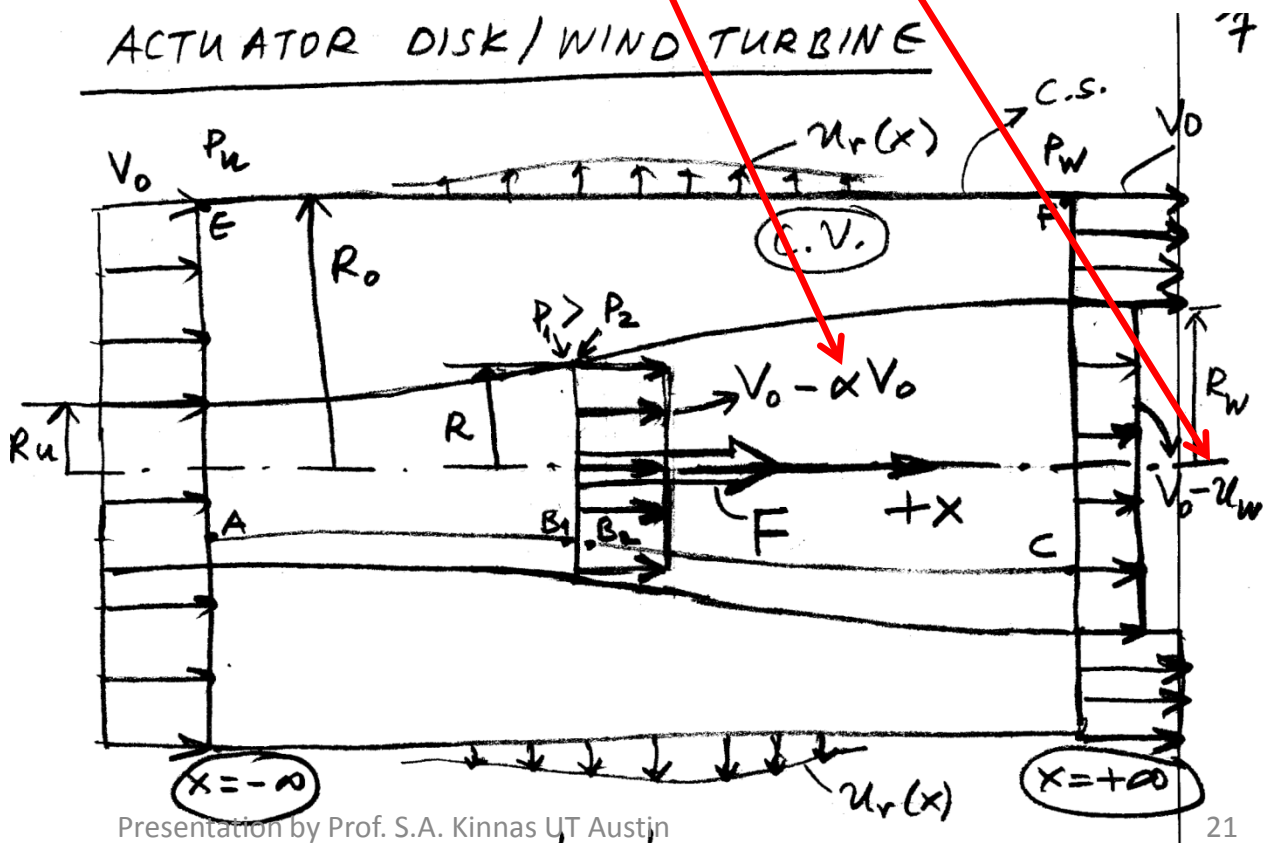
Betz's efficiency for ideal case:

$C_{pow}=4\alpha(1-\alpha)^2=0.593$ max value for $\alpha=1/3$; $u_w=2V_o/3$)

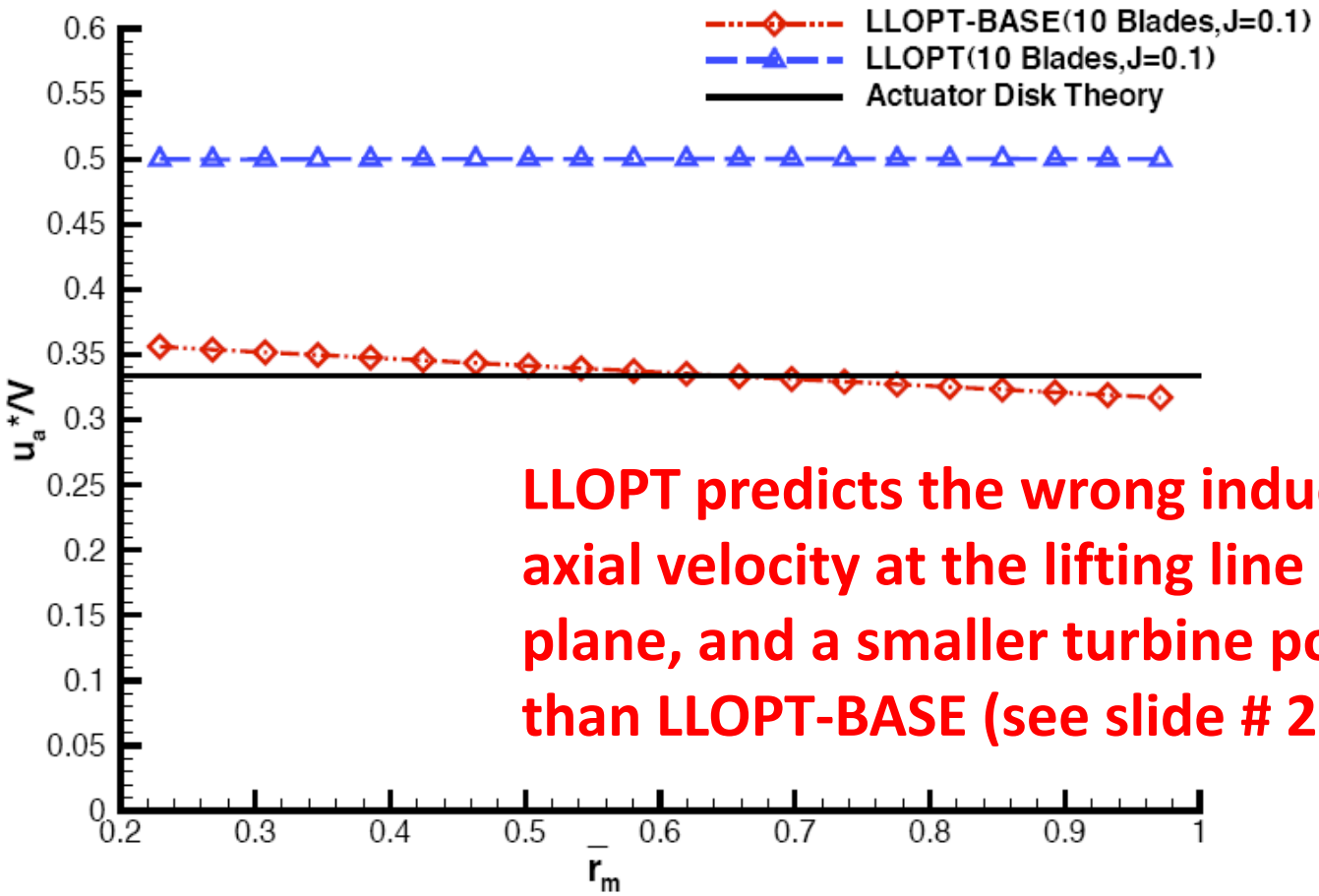
<u>Assumptions:</u>

- Negligible viscous forces
- Infinite number of blades
- No swirl downstream (**J→0 or TSR→∞**)

F=axial force on turbine



Optimum Circulation & Axial Induced Velocity at Turbine Plane; from LLOPT & LLOPT-BASE



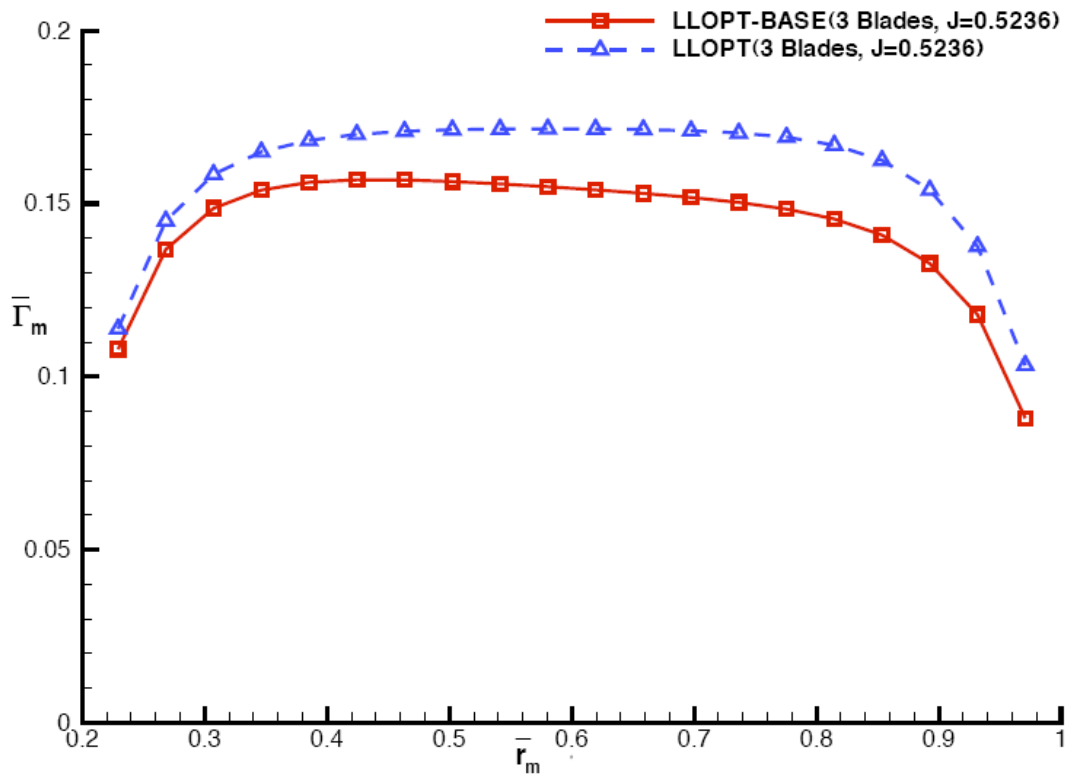
LLOPT predicts the wrong induced axial velocity at the lifting line plane, and a smaller turbine power than LLOPT-BASE (see slide # 25) !!

LLOPT-BASE

$$\Gamma(x) = \Gamma_{base}(x) g(x,k,h)$$

$$g(x,k,h) = kx + h - 0.5k(R - r_h),$$

$$r_h \le x \le R,\ k_1 \le k \le k_2,\ h_1 \le h \le h_2,$$

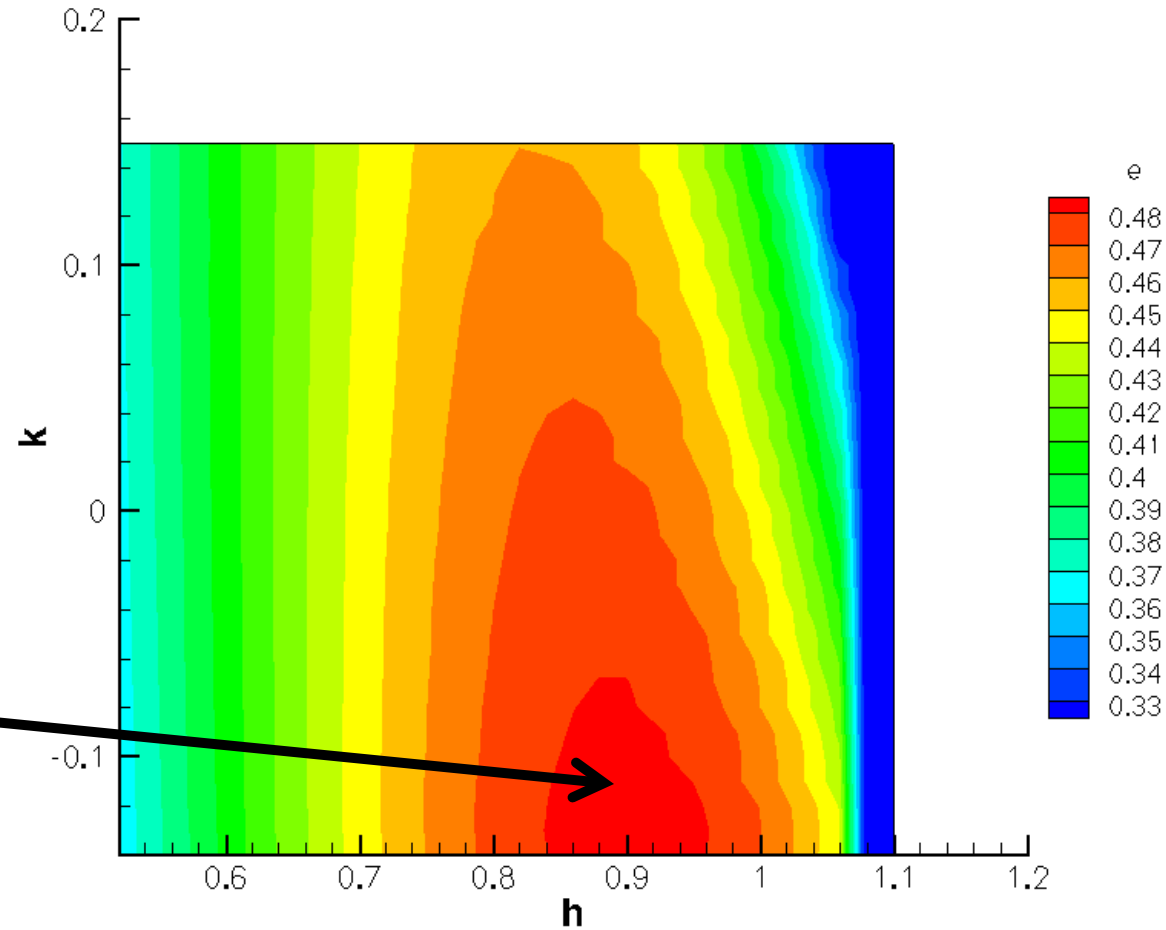


LLOPT-BASE

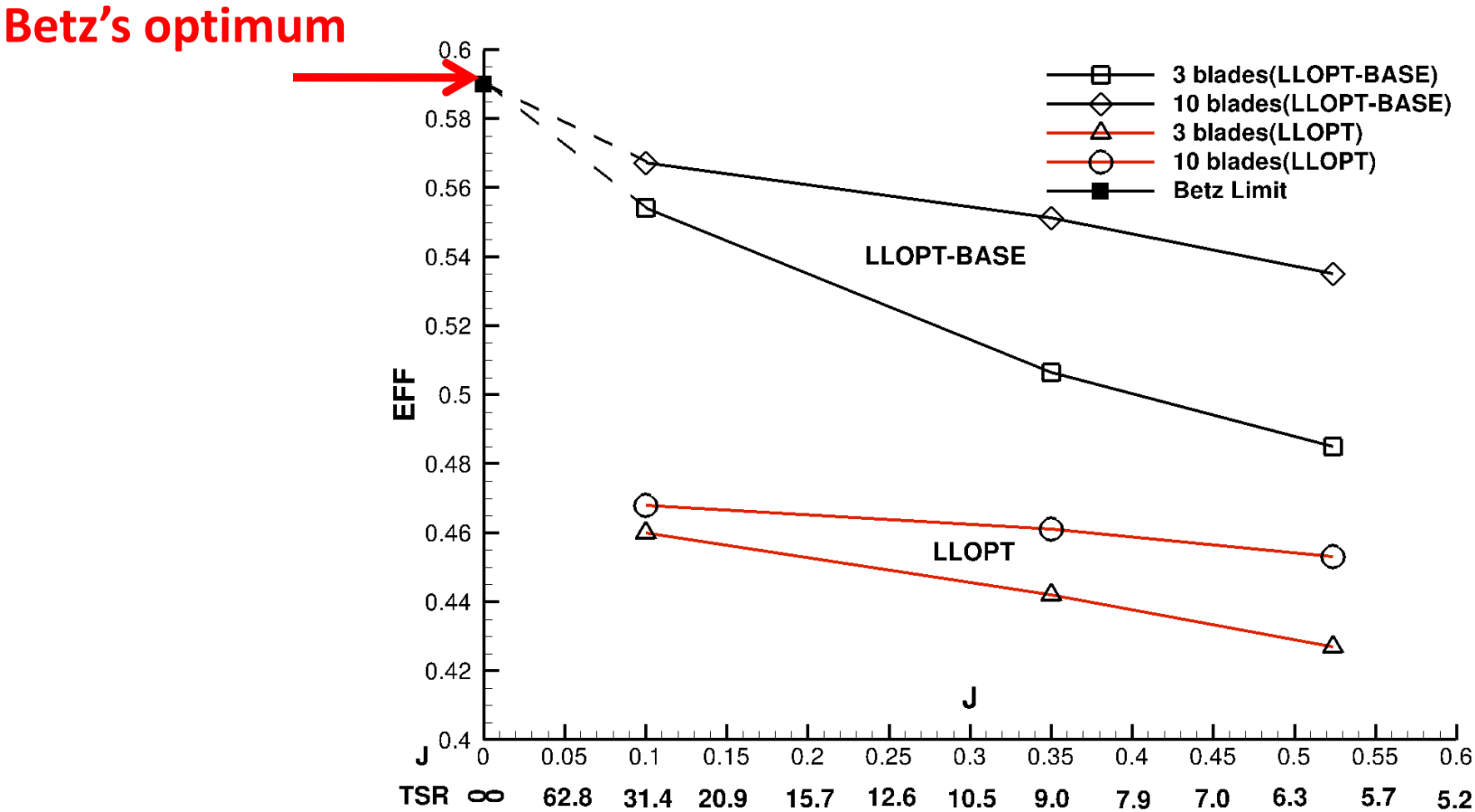
$$\Gamma(x) = \Gamma_{base}(x) g(x,k,h)$$

$$g(x,k,h) = kx + h - 0.5k(R - r_h),$$
$$r_h \le x \le R,\ k_1 \le k \le k_2,\ h_1 \le h \le h_2,$$

The analysis part of LLOPT is run for an array of discrete value of k and h, and the values that produce the largest efficiency (power) are selected (k=-0.13, h=0.9 in this case)



RESULTS FROM LLOPT & LLOPT-BASE



Turbine Blade Design (using CAVOPT-BASE originally developed under NNR-NE support)

- Blade design procedure (Kinnas et al, SNAME Transactions 2005) :

• **Select a base geometry** (the original experimental geometry is chosen as an example or can be designed based on the loading/circulation from LLOPT-BASE).

• Select parameters that are used to scale the base geometry (Pitch and chord and blade offsets of pressure and suction sides can be chosen here)

$$(P/D)_{design} = (P/D)_{base} \times x_1$$
$$(c/D)_{design} = (c/D)_{base} \times x_2$$
$$(Y_{p,s}/c)_{design} = (Y_{p,s}/c)_{base} \times x_3$$

x_1, x_2, x_3 are two multipliers corresponding to two design parameters (x_3=1/x_2 in order to keep the maximum thickness the same)

• Usually, 10×10×10 combinations of x_1,x_2,x_3 over a desired range are analyzed and the results are interpolated over that range

• set a lower bound and upper bound for each parameters and use PROPCAV to create a turbine performance database

• use nonlinear optimization method (CAVOPT-BASE) to search for the optimum geometry by specifying certain constraints

Case A: Using a known marine turbine as the base geometry

CAVOPT-BASE results-Fully Wetted Case

Original case (fully wetted):

- Blade geometry is that tested by Bahaj et al. at 25 degrees hub pitch, tidal velocity V=2.5m/s, TSR=5.0
- Cavitation number: N/A

Design constraint:

- no constraint

(All performance data in the database are fully wetted results)

- two parameters:

$$0.8 \le x_1 \le 1.2$$

$$0.8 \le x_2 \le 1.2$$

$$x_3 = 1 / x_2$$

design results:

$$x_1 = 0.803$$

$$x_2 = 1.006$$

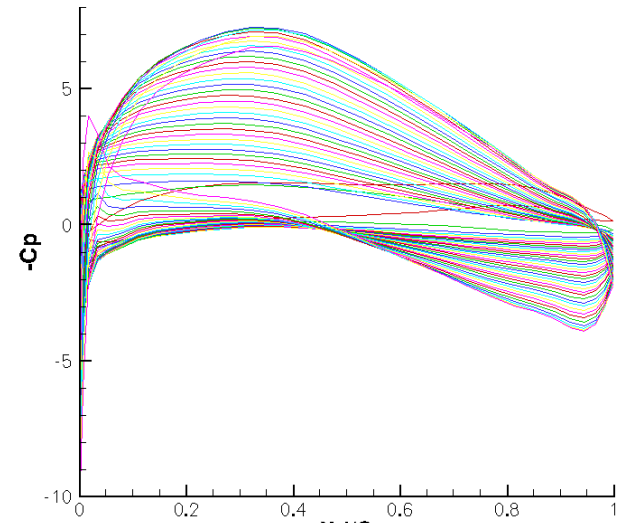
(chord stays the same and pitch decrease)

Only the pitch and chord length are varied in this case (x_3=1/x_2 in order to keep the maximum thickness to be the same)

CAVOPT-BASE results-Fully Wetted Case

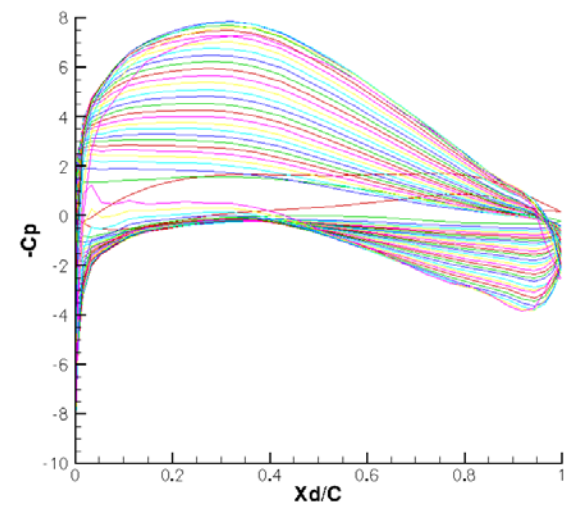
Original geometry
Cpow=0.39
CT=0.55

Pressure distribution for original case
C*pmin*=7.26



NEW Designed geometry
Cpow=0.412
CT=0.586

Pressure distribution for the design case
C*pmin*=7.78



Cpow increases by 5.6% but also CT increases by 6.5%

A balance must be found between the extra costs of the support structure (larger CT) and the extra power (larger Cpow) that can be generated.

Turbine Blade Design results-Cavitating Case

Original case (cavitation):

- 25 degrees hub pitch, TSR=5.0, steady cavitating case
- Cavitation number: 5.0

Design constraint:

- **-Cp < 5.0 (no cavitation)**

(All performance data in the database are fully wetted result)

- two parameters:

$$1.0 \le x_1 \le 1.2$$

$$0.3 \le x_2 \le 1.5$$

$$x_3 = 1 / x_2$$

design results:

$$x_1 = 1.00595$$

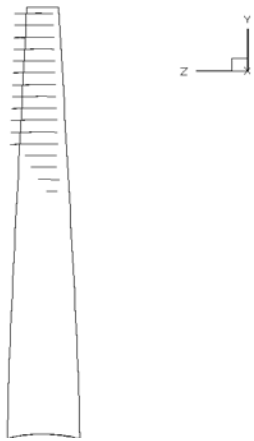
$$x_2 = 1.35108$$

(chord increases and pitch stays the same)

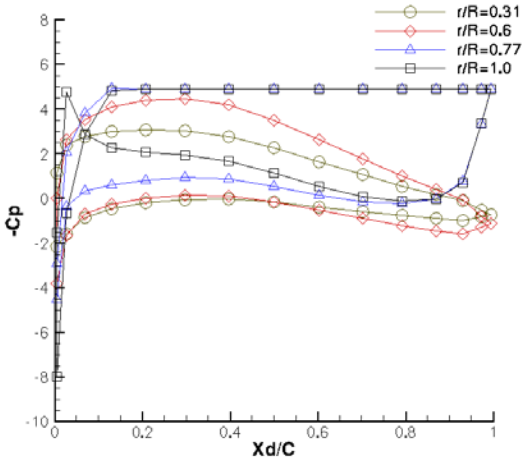
Only the pitch and chord length are varied in this case (the maximum thickness distribution along the radius is maintained the same)

Turbine Blade Design results-Cavitating Case

Original geometry
Cavitation occured
Cpow=0.3176
CT=0.486

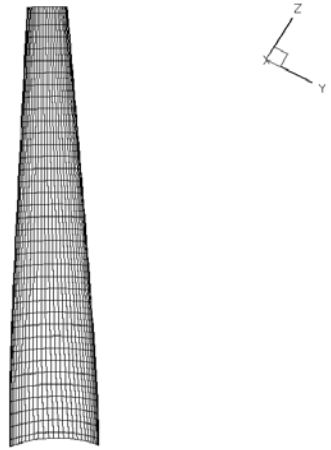


Pressure distribution for cavitating case

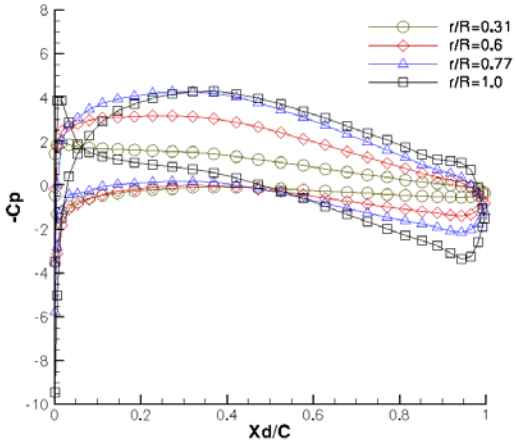


NEW Designed geometry
No cavitation
Cpow=0.371
CT=0.5163

Cpow increases by 16.8%
CT increases by 6.2%

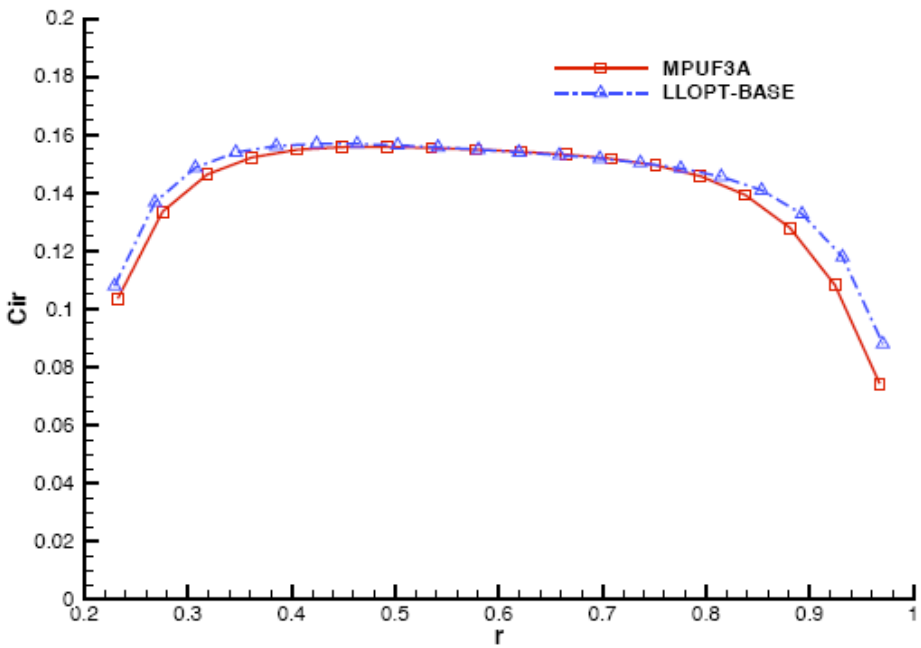


Pressure distribution for the designed wetted case



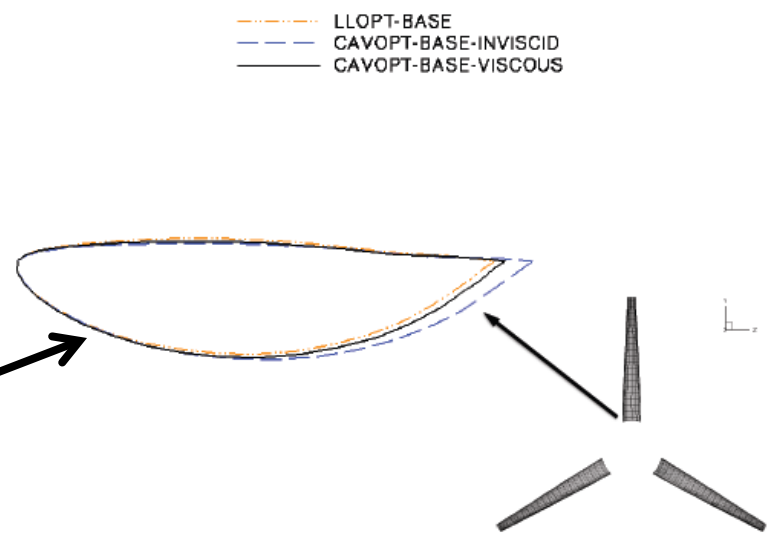
Case B: Determining the blade geometry based on the circulation determined by LLOPT-BASE, and by using Prandtl's lifting–line equation

APPLICATION TO A DESIGN CASE (TSR=6, 3-BLADED, NACA 66 –MOD & A=0.8)



Predicted Cpow from various methods:

LLOPT-BASE (inviscid)	0.485
MPUF-3A (inviscid)	0.476
CAVOPT-BASE/MPUF-3A (with friction on)	0.434



Designed blade shape at the root

Case C: Using CAVOPT-3D. No need for base geometry. Pitch and camber distribution are determined by the non-linear optimization method.

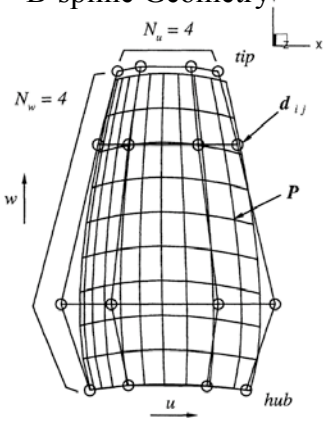
Blade Design-CAVOPT-3D (Mishima & Kinnas, JSR'97)

Geometry: B- Spline Geometry

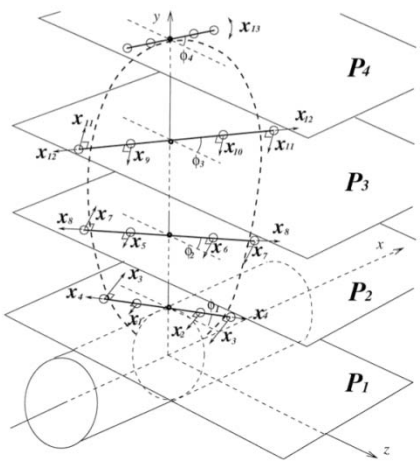
$$P(u,w) = [x(u,w), y(u,v), z(u,v)] = \sum_{i=0}^{Nu-1} \sum_{j=0}^{Nw-1} d_{ij} N_{i,4}(u) N_{j,4}(w)$$

$d_{i,j}$=B-spline control points
$N_{i,4}(u)$=B-spline basis of order 4
$N_{j,4}(w)$=B-spline basis of order 4
u,v=parameters for B-spline
N_u=number of B-spline control points in u-direction
N_w=number of B-spline control points in w-direction

B-spline Geometry



Design variables and vertex movement



Initial geometry with design variables x_0 ⇒ Initialization of linear optimization ⇒ linear optimization (initialization of quadratic optimization) ⇓ quadratic optimization ⇒ Analysis of the turbine at any step ⇒ Output design geometry and results

Application

CAVOPT-3D - Given Chord

Initial geometry:

- Manually created by specify 4x4 B-spline control points
- Fully wetted

Design objective and constraint:

- Maximize Cpow
- CT≤0.55

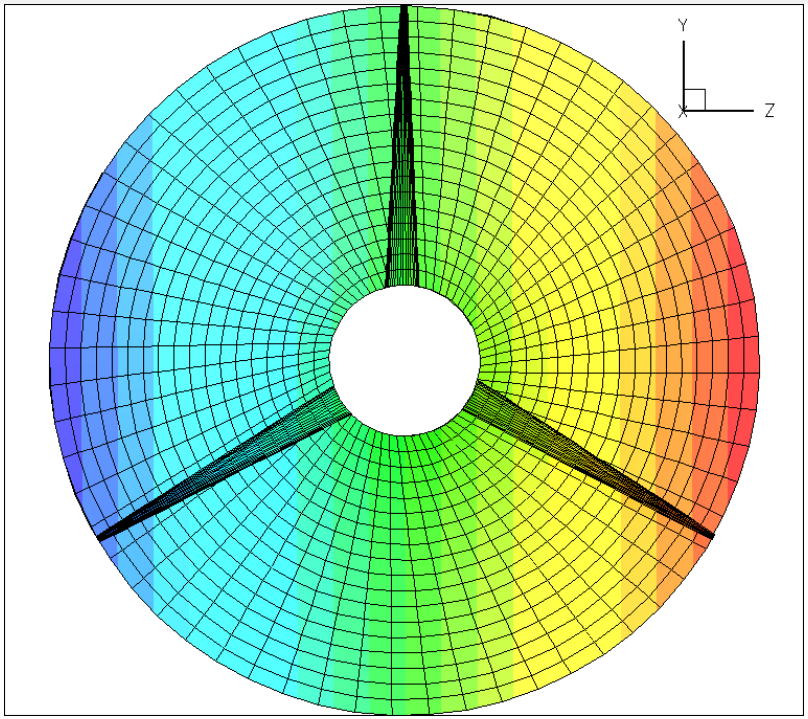
Chord Distribution:

r/R=0.2 c/D=0.125

r/R=0.4 c/D=0.106

r/R=0.8 c/D=0.069

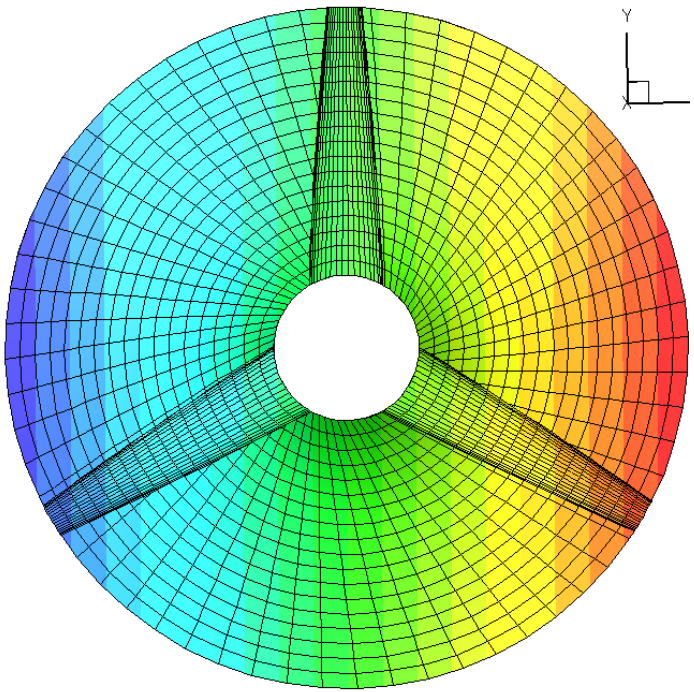
r/R=1.0 c/D=0.050

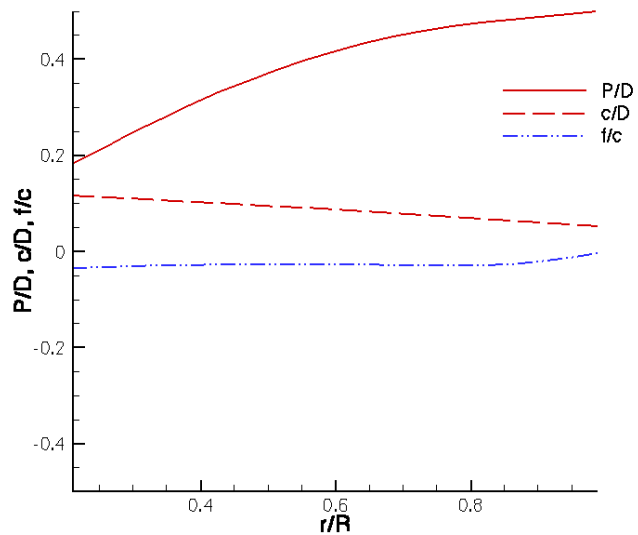


Initial Geometry

Application

CAVOPT-3D results – Given Chord

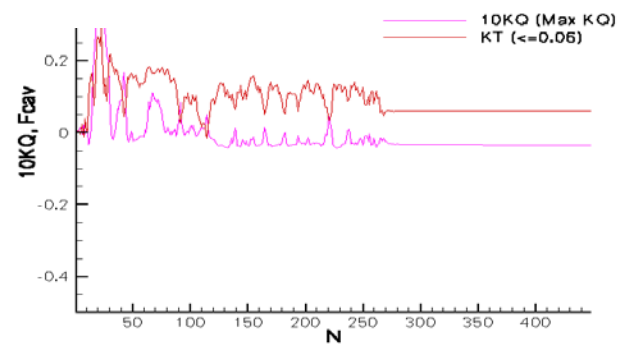




Design results for P/D, f/D and c/D

Design geometry
Fully Wetted
Cpow=0.386
CT=0.55

Convergence History of KQ and KT



What have we done?

- Modified our predictive methods so that they can apply to tidal turbines (also done in the case of non-uniform current)
- Applied our methods and RANS to a tested model and made comparisons with measurements
- Applied our non-linear optimization methods in several cases of wetted/cavitating turbines, and showed that the delivered power can be increased (with some increase in the axial turbine force) while the presence of cavitation can be eliminated (or reduced)

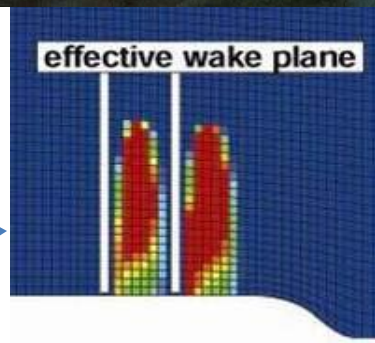
What we would like to do next?

•Extend our design methods in the case of contra-rotating turbines in order to improve efficiency. A preliminary design approach will be presented at OMAE'11 (Rotterdam, The Netherlands, June 19-24, 2011)

•Apply our methods in the case of the current being at a yaw angle relative to the flow direction. Some results from applying our methods and comparisons with experiments will be presented at ISOPE'11 (Maui, Hawaii, June 19-24, 2011)

•Validate/improve our methods further, especially in the case of non-uniform current

•Include turbine to turbine interference effects in the case of 2 turbines, or a farm, by coupling MPUF-3A, applied to each one of the turbines, with a RANS solver for the global flow-field, as already done in the case of contra-rotating propellers



•Apply our design methods to design a new (actual) turbine blade