Contra-Rotating Propeller Modelling For Open Rotor Performance Simulations

by

Alexiou, Frantzis, Aretakis,

Riziotis, Roumeliotis, Mathioudakis

National Technical University of Athens

Motivation

- The **Open Rotor** configuration enables ultra-high bypass ratio and high propulsive efficiency thus reducing fuel burn and emissions compared to an equivalent thrust turbofan

- For open rotor preliminary design performance evaluations, 0-D cycle models are needed employing CRP performance **maps** for robustness and fast execution

- Currently in the public literature, CRP performance models do not accurately represent the **physics** of a CRP system and or do not account for all the independent parameters that govern the operation of the CRP system

Objectives

Develop a **methodology** for modelling contra-rotating propellers (CRP) for engine performance calculations:

1. **Generate** CRP performance characteristics taking into account the effects of induced velocities, flight Mach number, speed ratio and blade pitch angles
2. **Develop** a mathematical model for CRP that uses these characteristics
3. **Integrate** the CRP component in an open rotor engine performance model and perform design and off-design simulations

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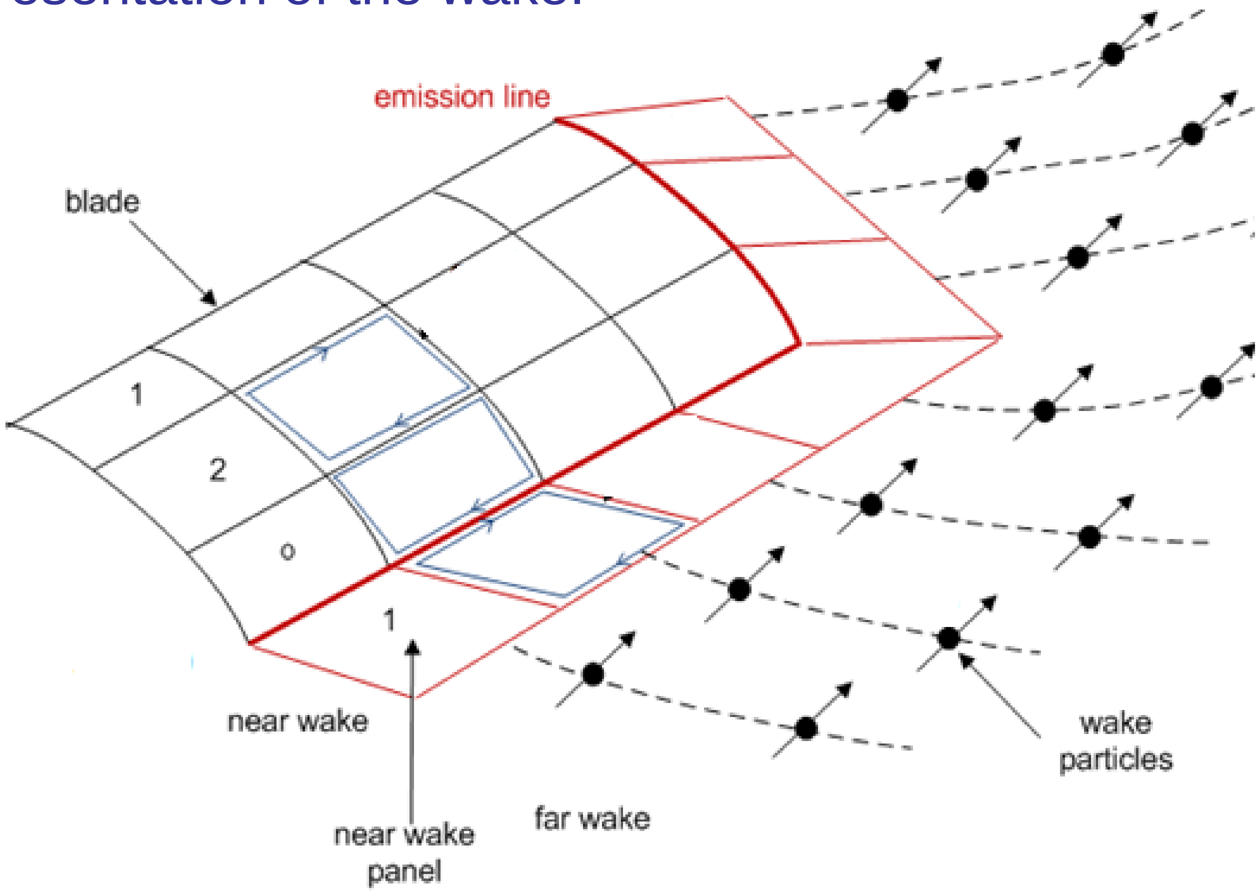
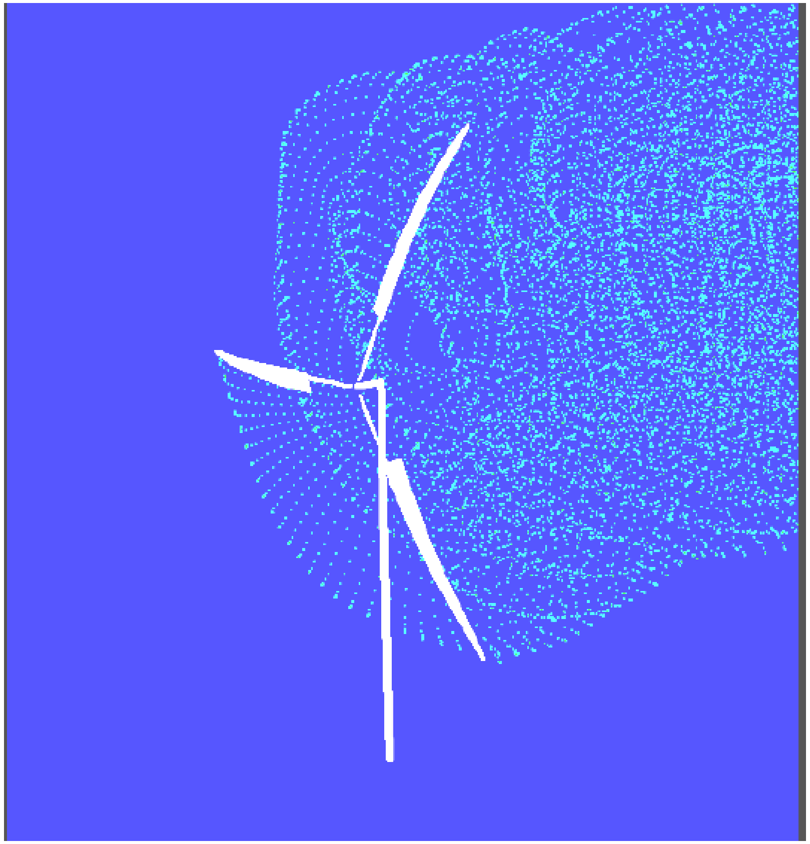
Free-Wake Lifting Surface Model - GENUVP

The in house code **GENUVP** is a potential flow solver combining a panel representation of the solid boundaries (blades) with a vortex particle representation of the wake.

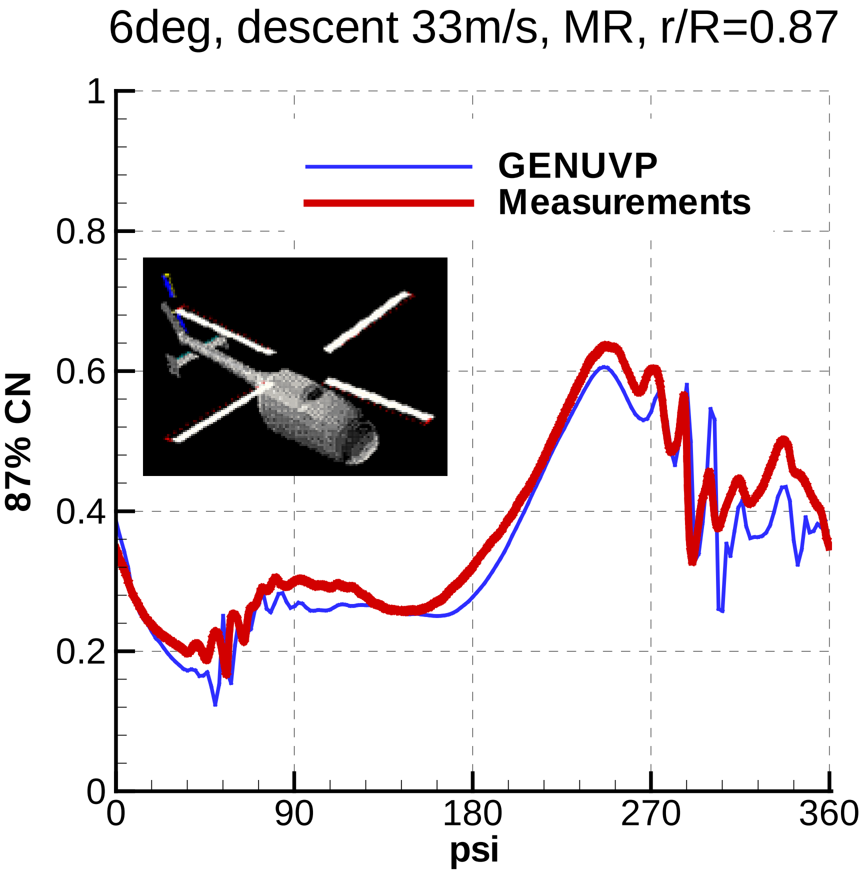


GENUVP Application Examples

GENUVP is used in the aerodynamic analysis of rotor/wing problems

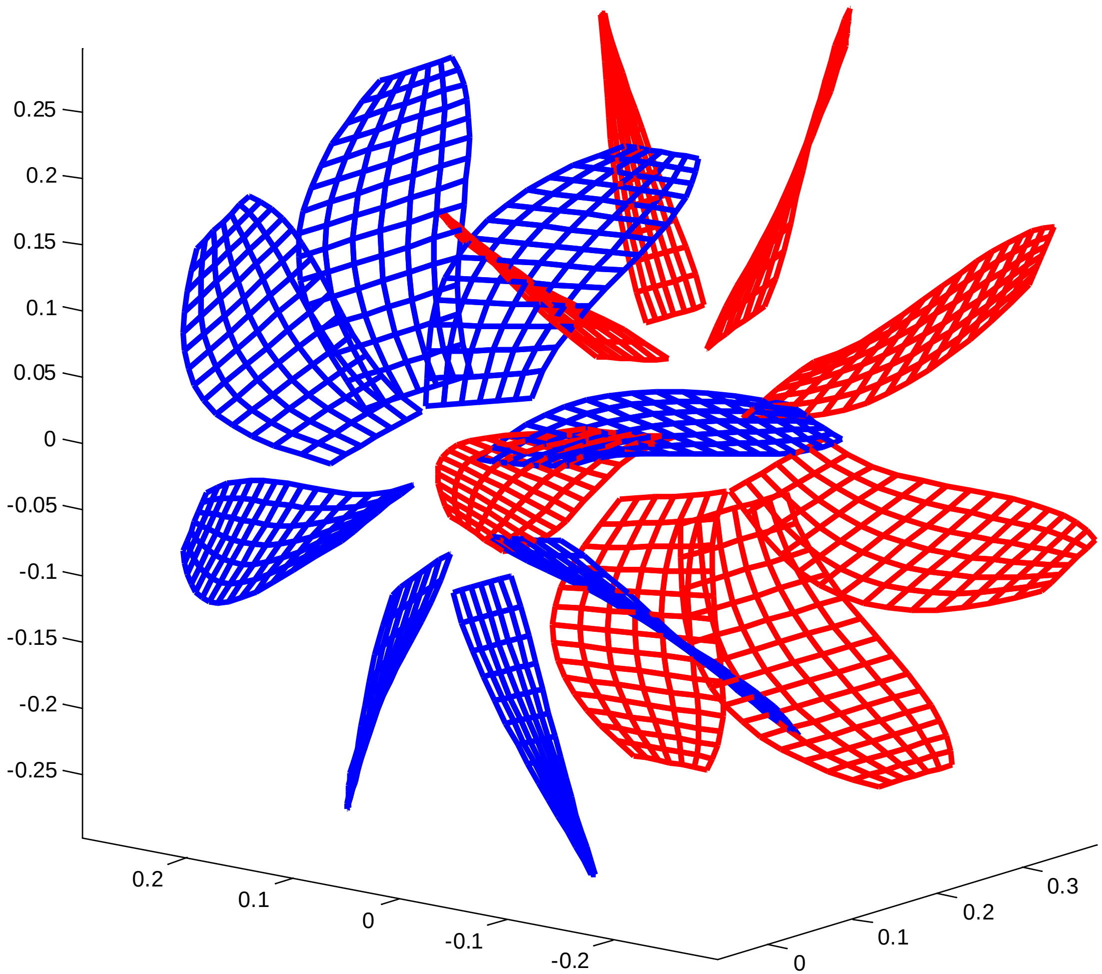


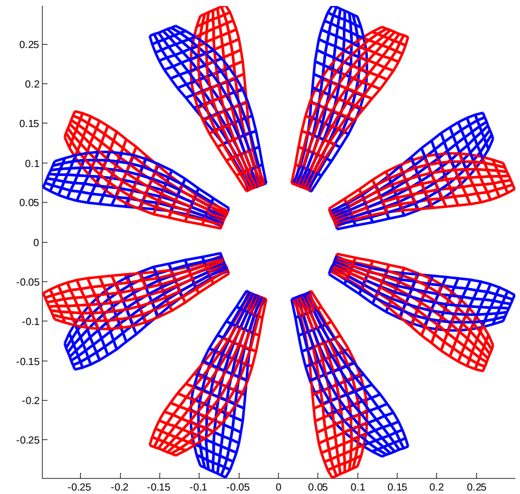
Wind turbine aeroelastic simulation

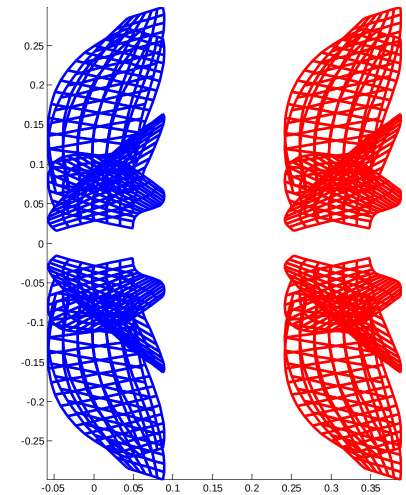


Aeroelastic analysis of Helicopter rotor

CRP Geometry in GENUVP (based on SR-7A)







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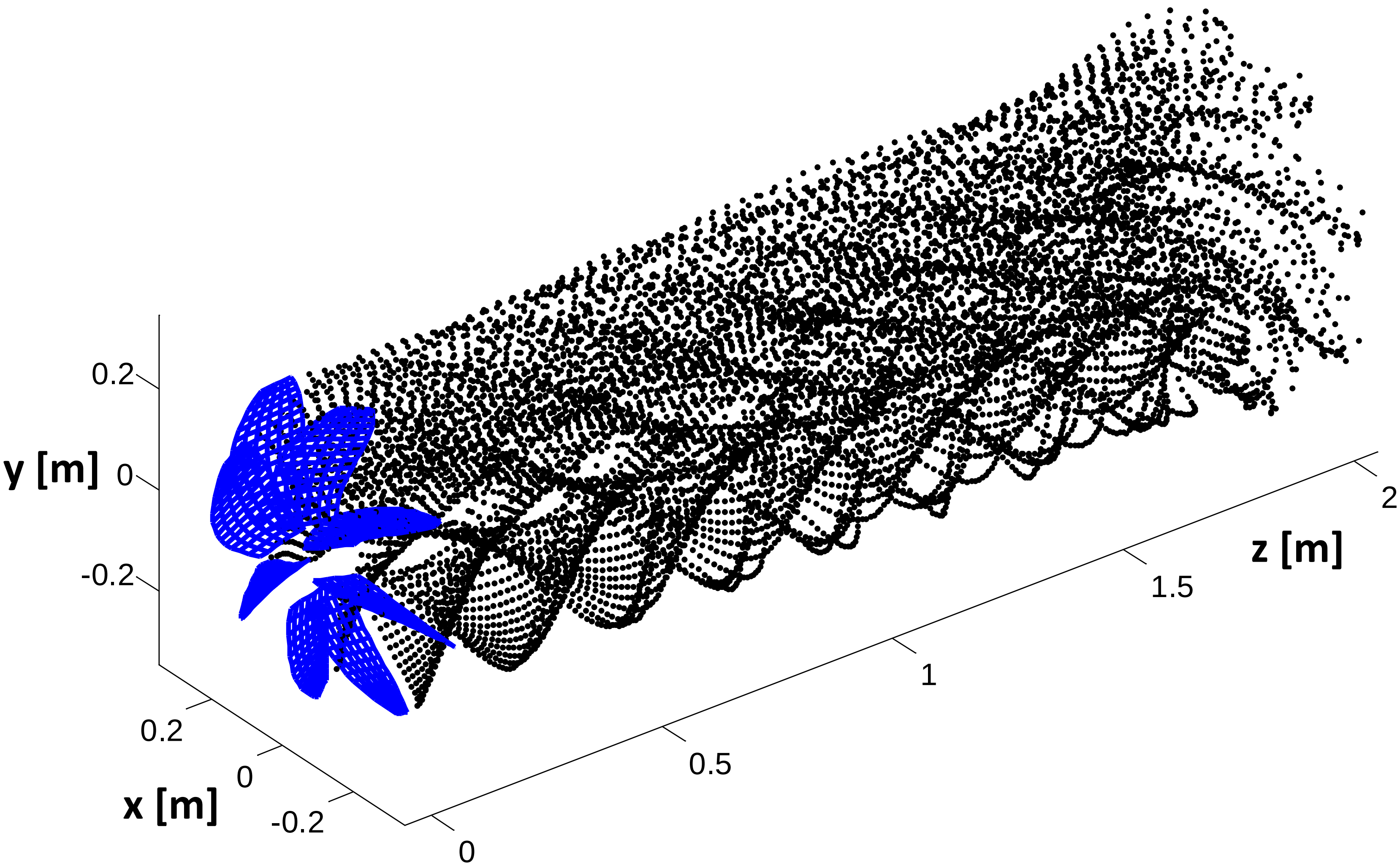
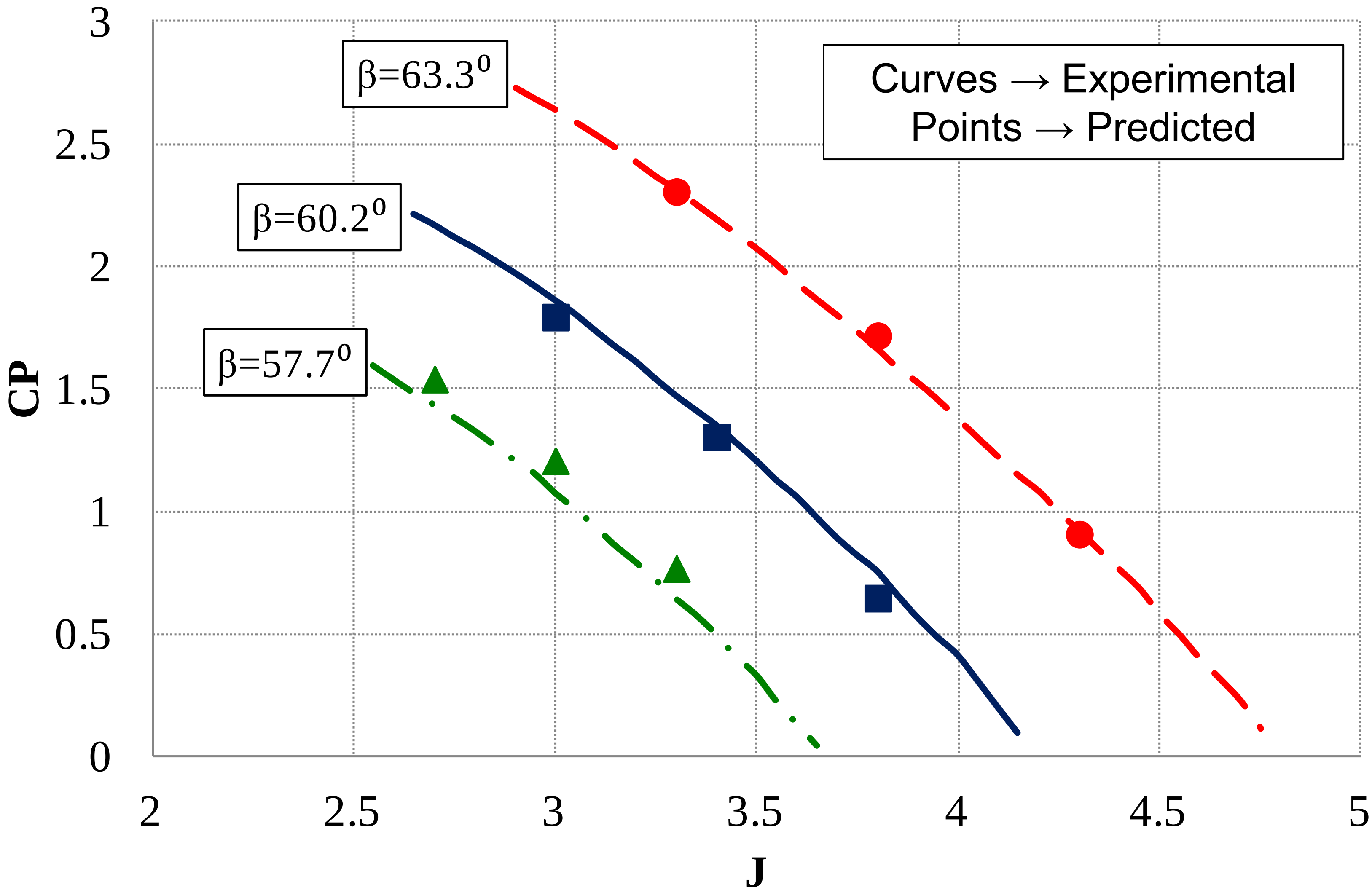
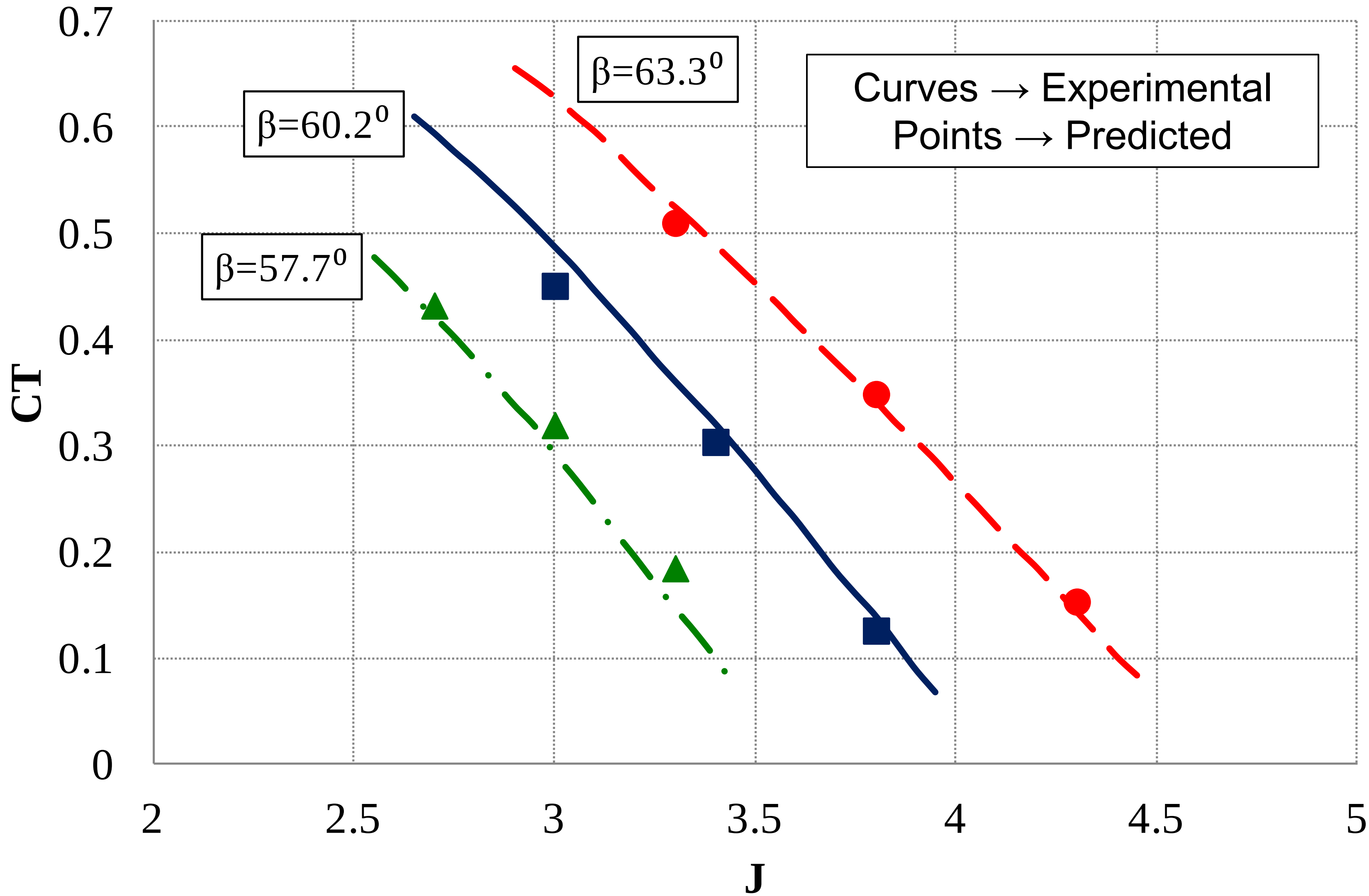
Single Propeller Wake – Panoramic View



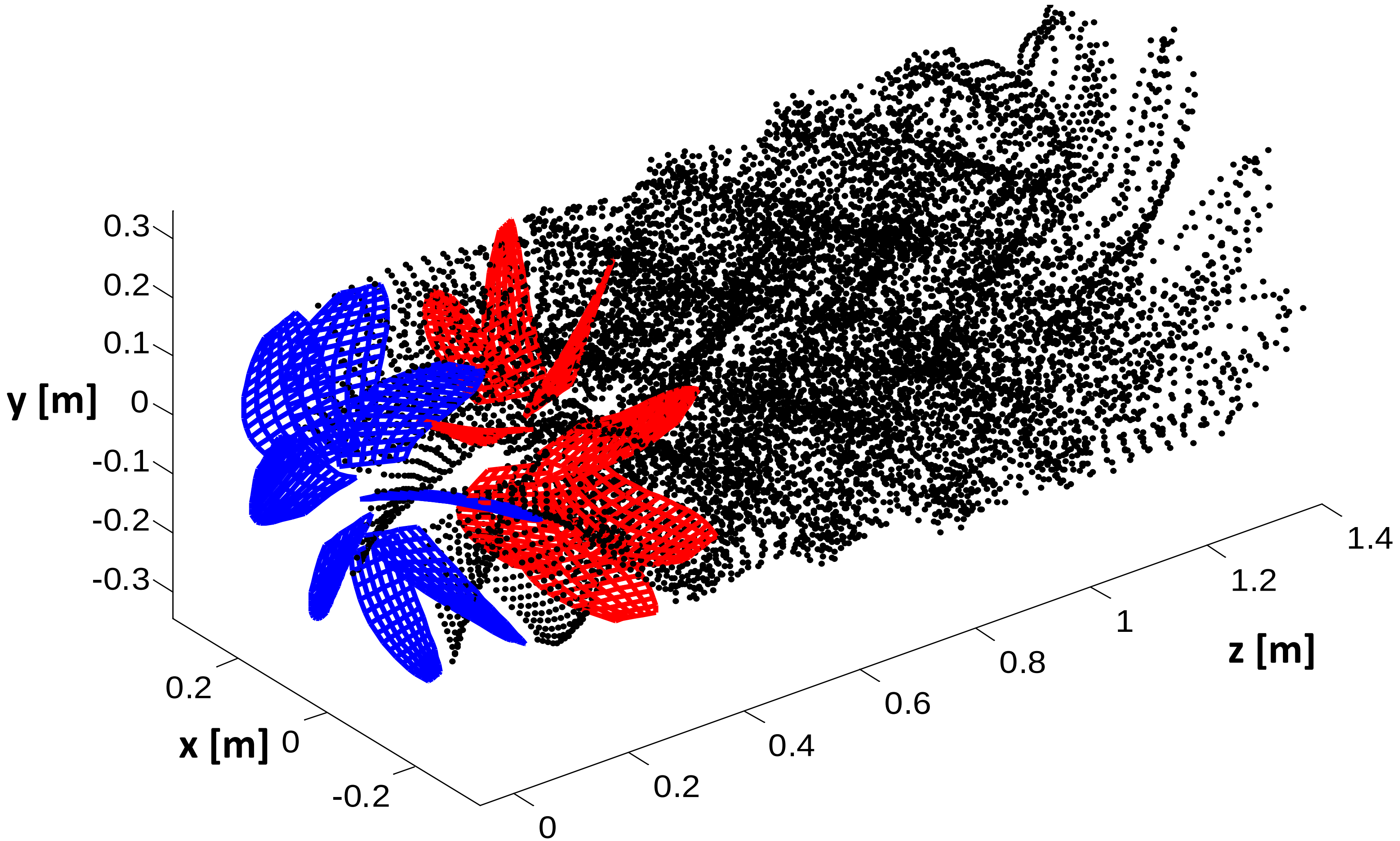
SP Power Coefficient: M=0.7



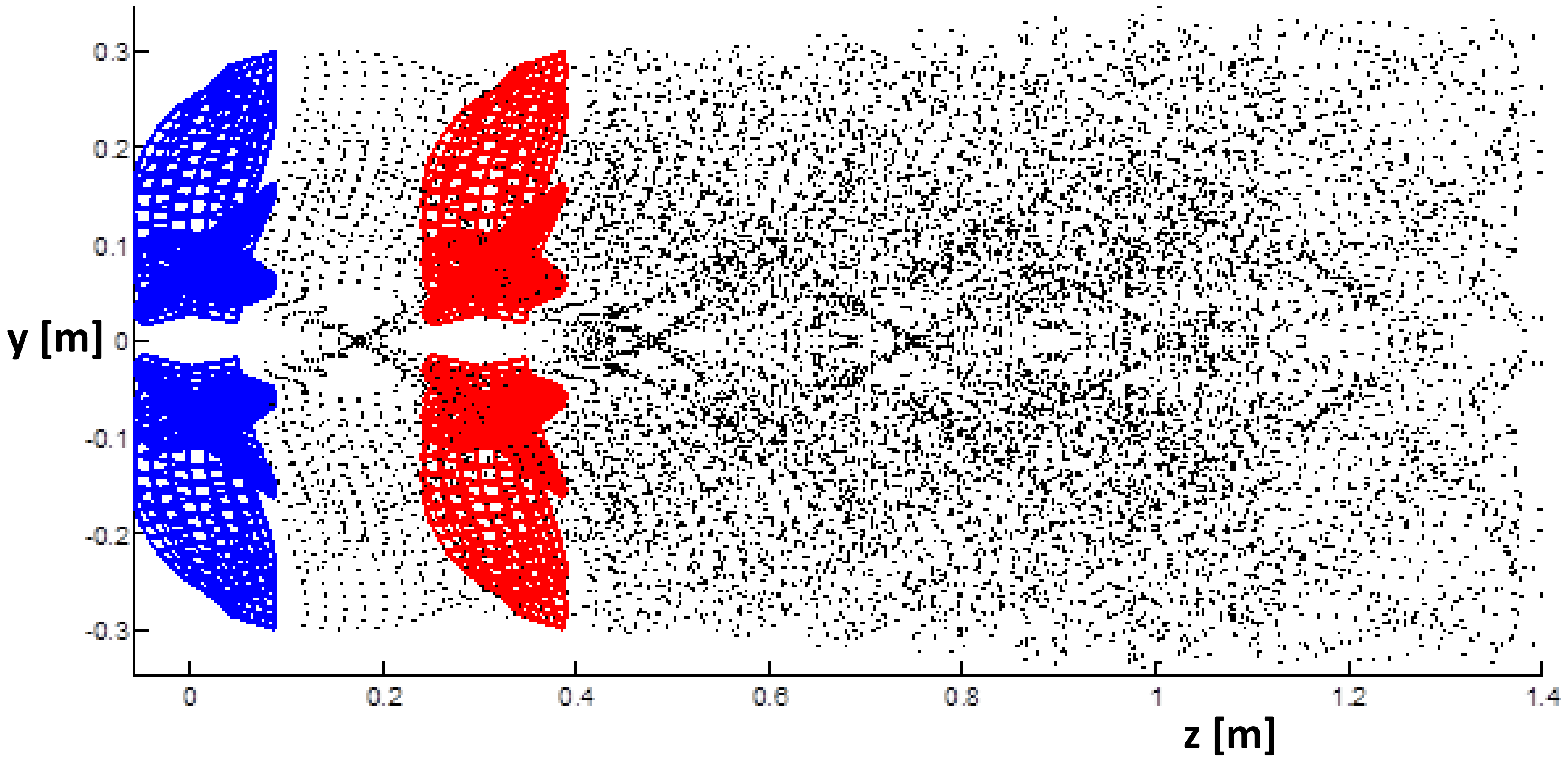
SP Thrust Coefficient: M=0.7



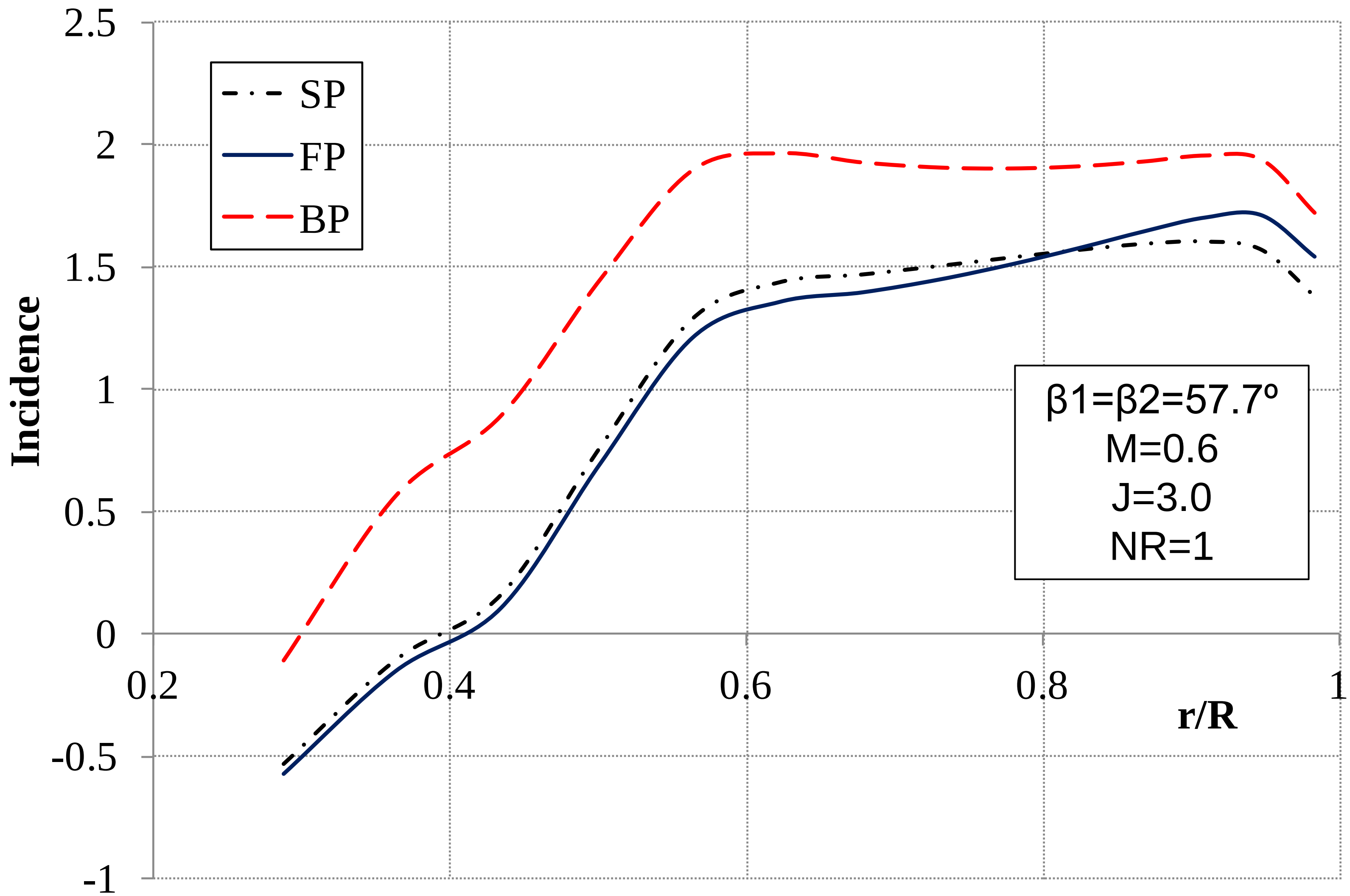
CR Propeller Wake – Panoramic View



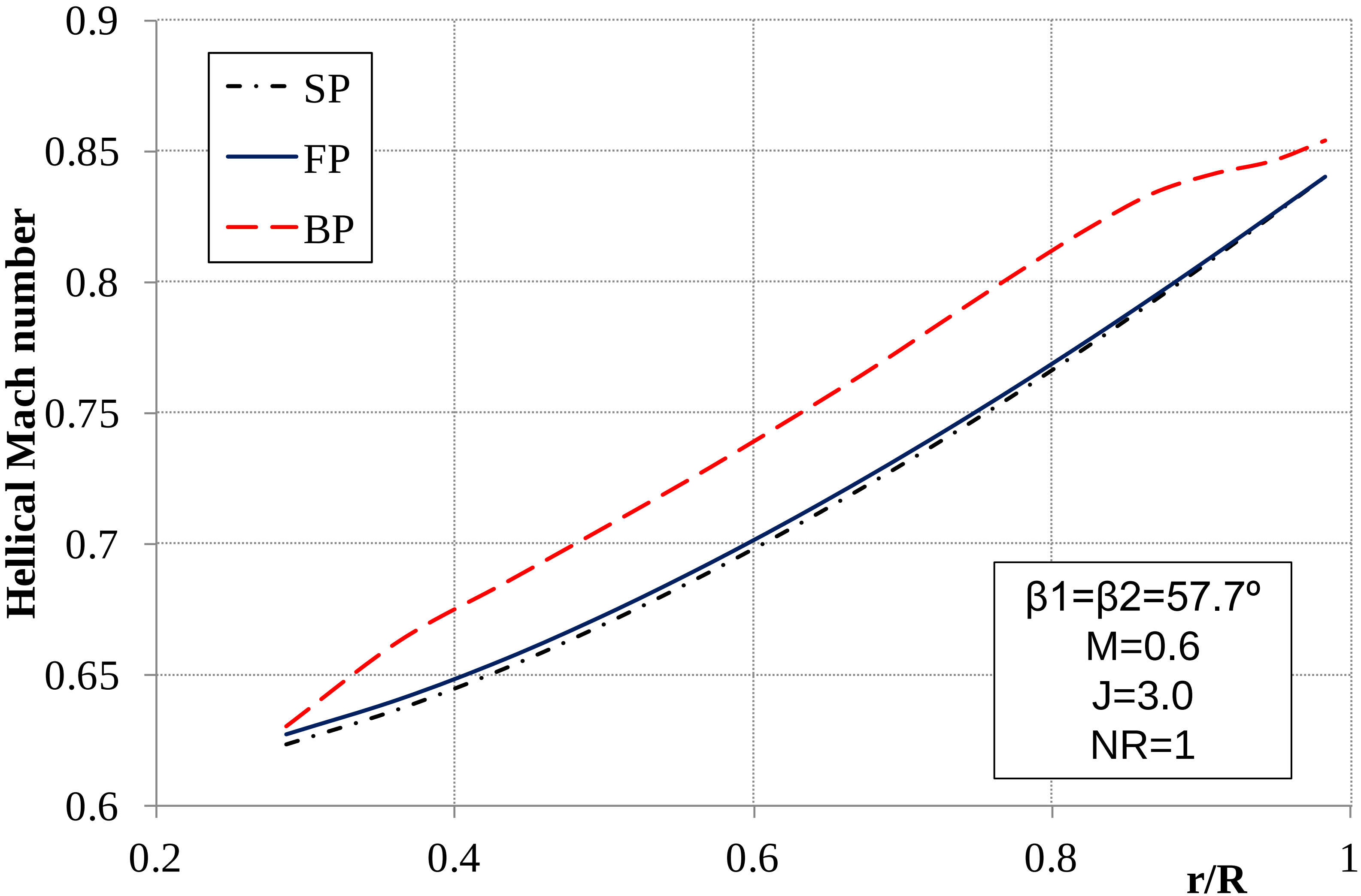
CR Propeller Wake – Meridional View



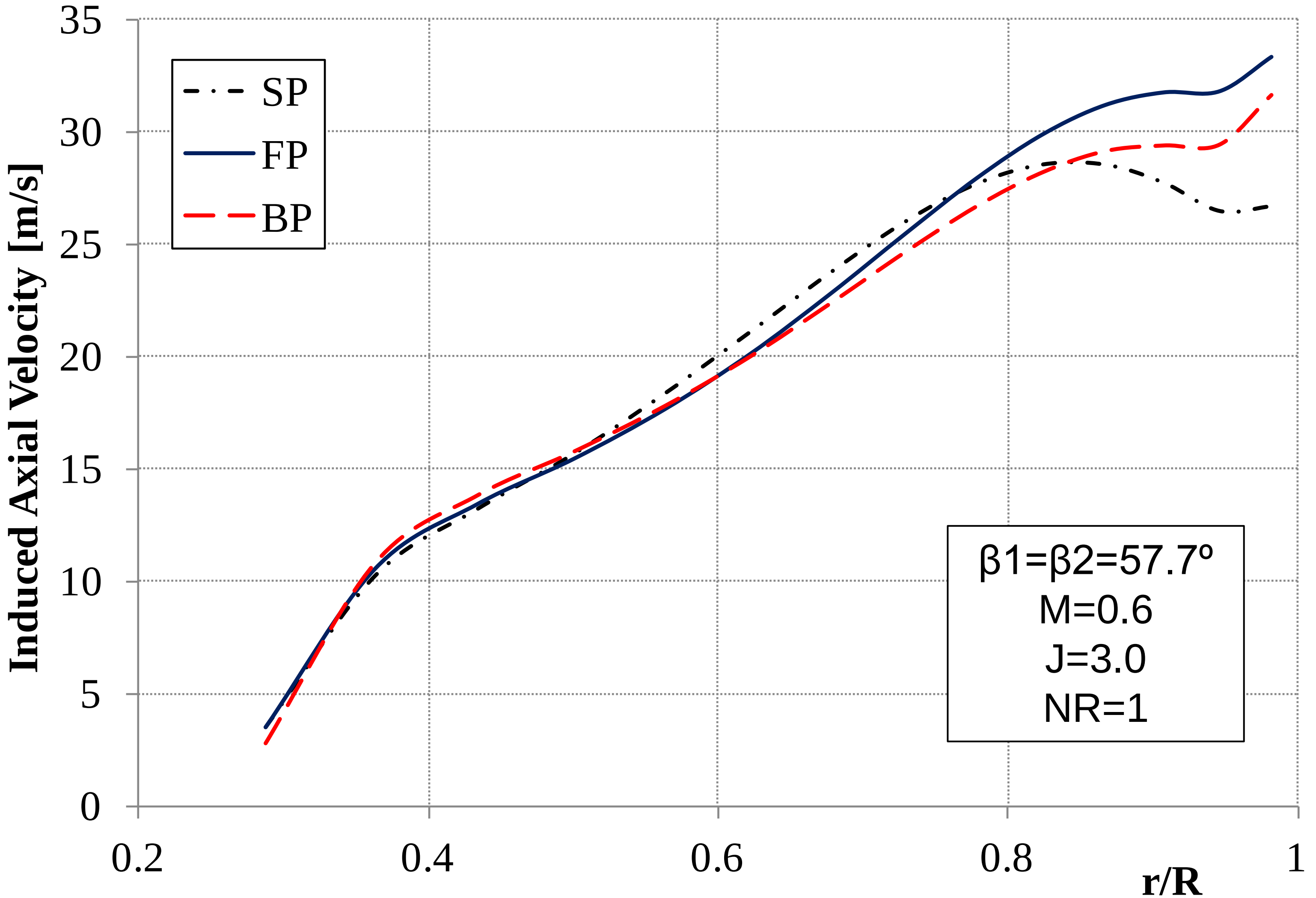
Radial distribution of incidence angle



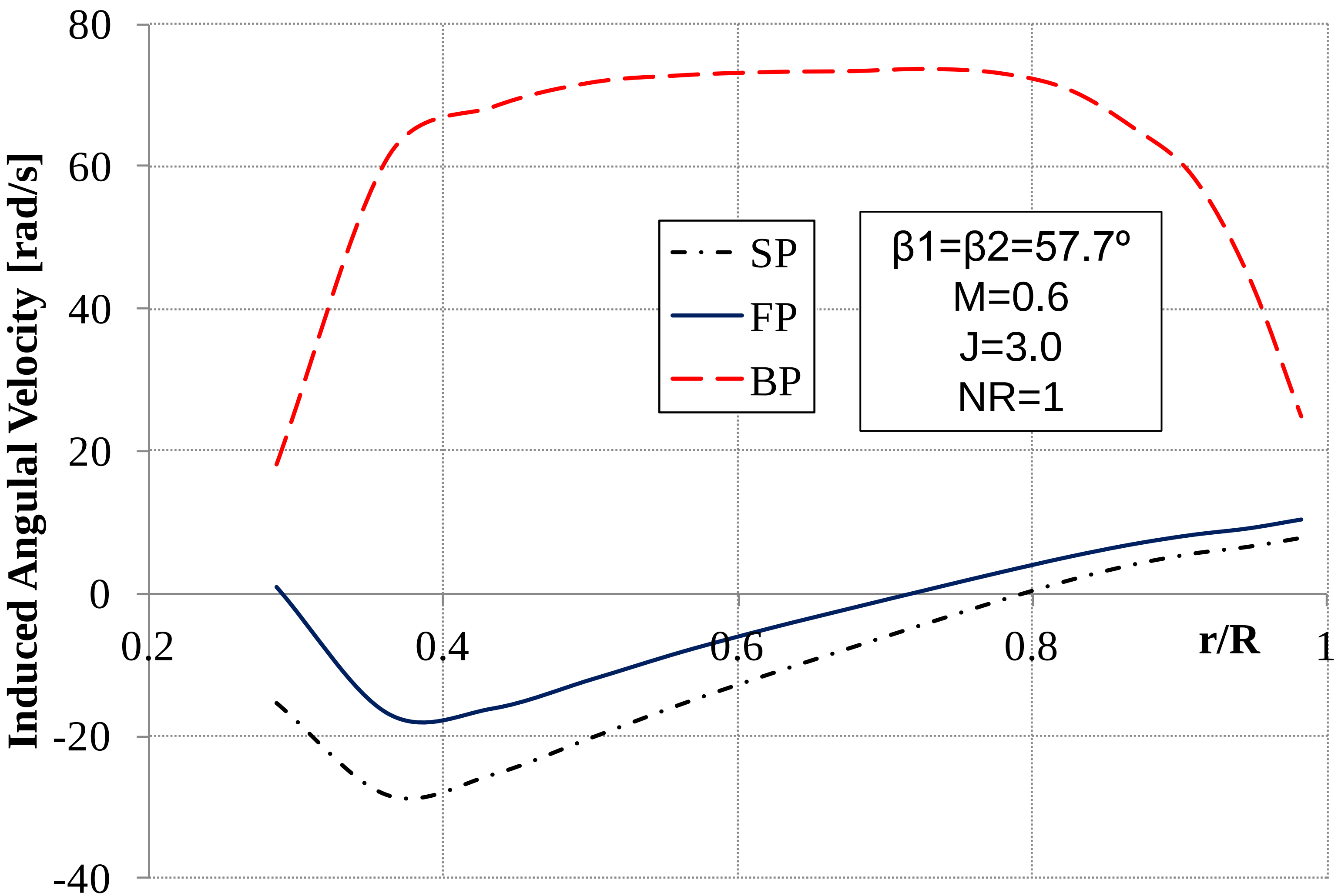
Radial distribution of Helical Mach number



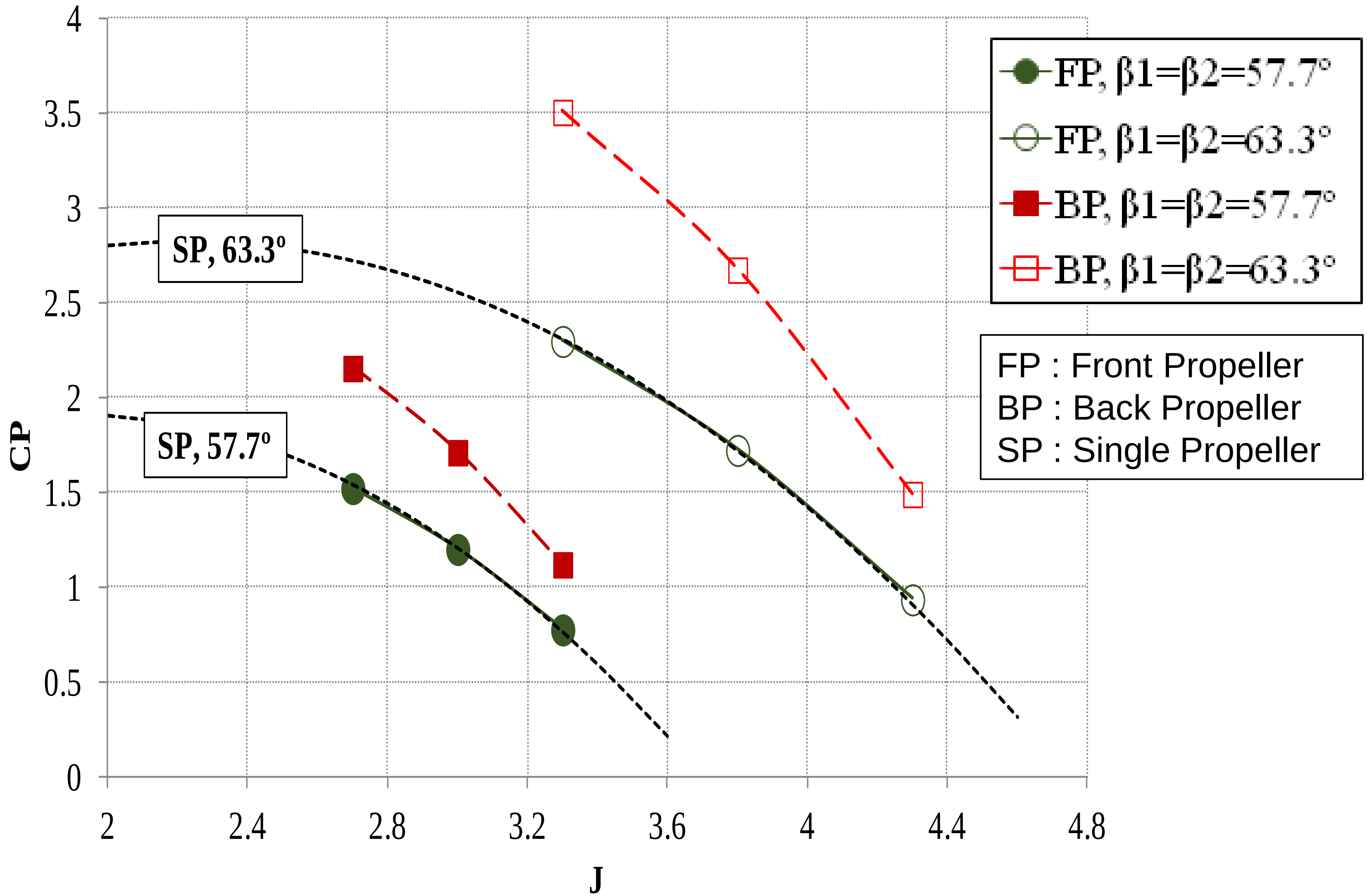
Radial distribution of Induced Axial Velocity



Radial distribution of Induced Angular Velocity

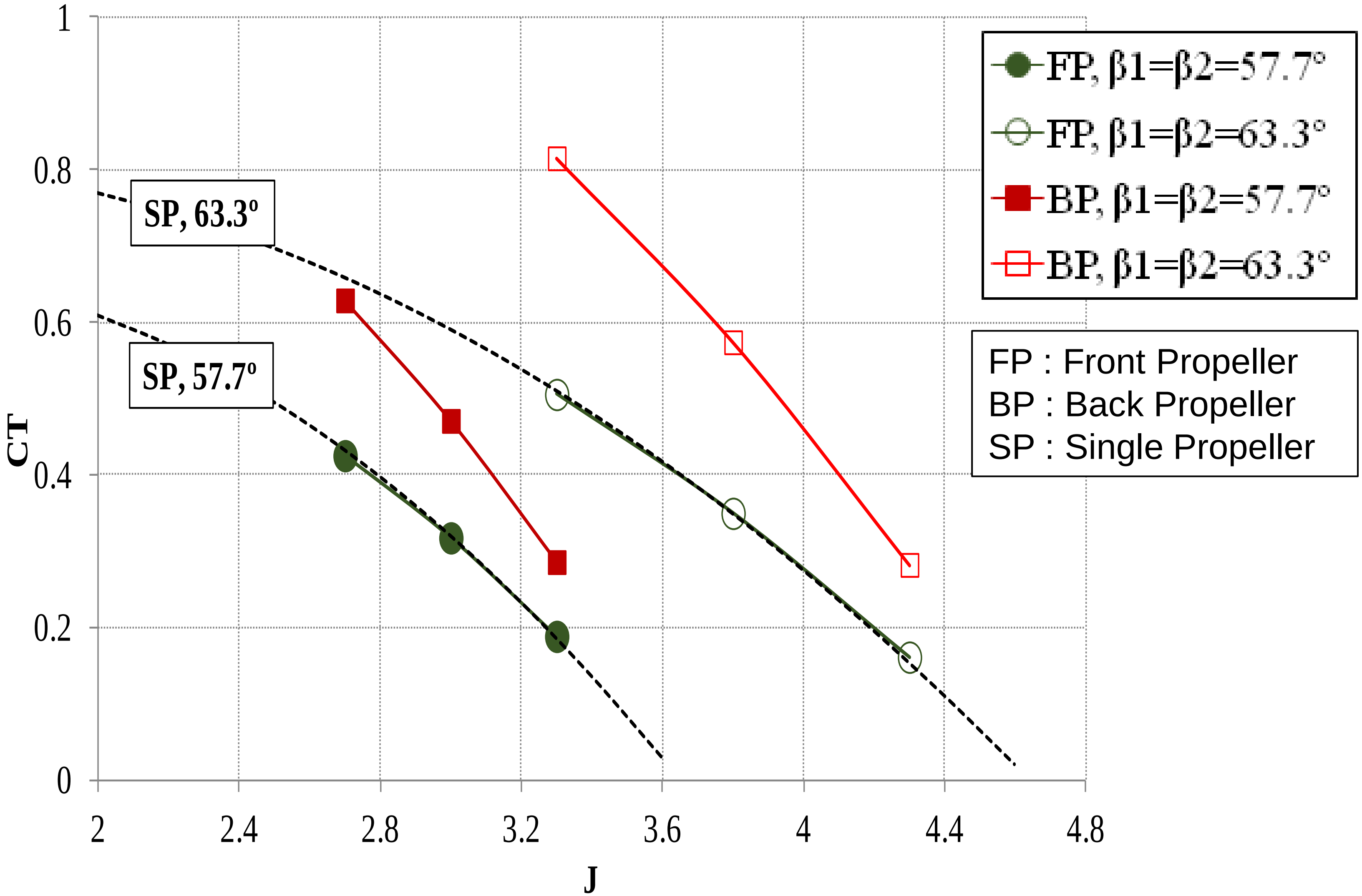


CRP Power Coefficient: M=0.7, NR=1



FP : Front Propeller
BP : Back Propeller
SP : Single Propeller

CRP Thrust Coefficient: M=0.7, NR=1



FP : Front Propeller
BP : Back Propeller
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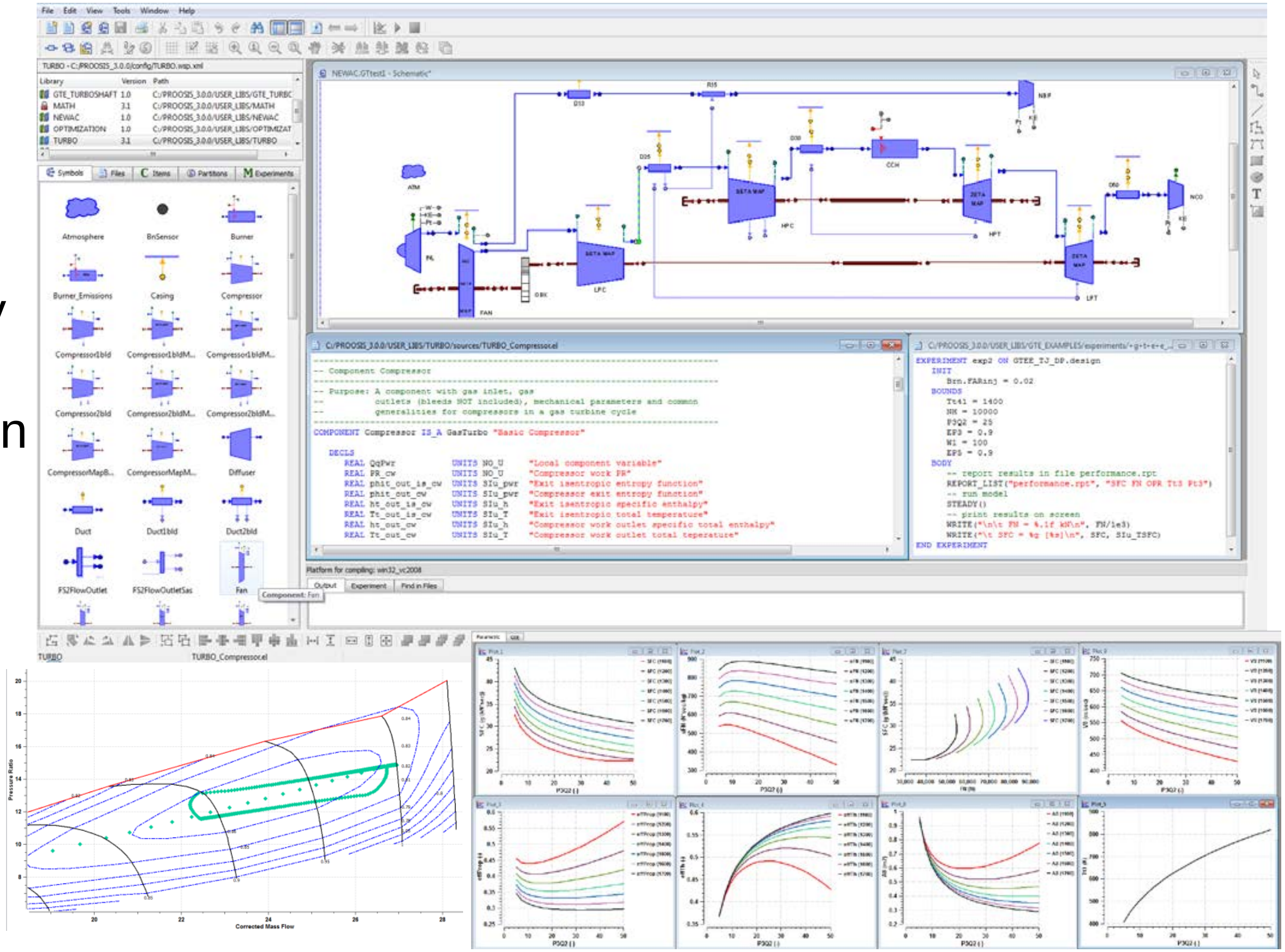
Contents

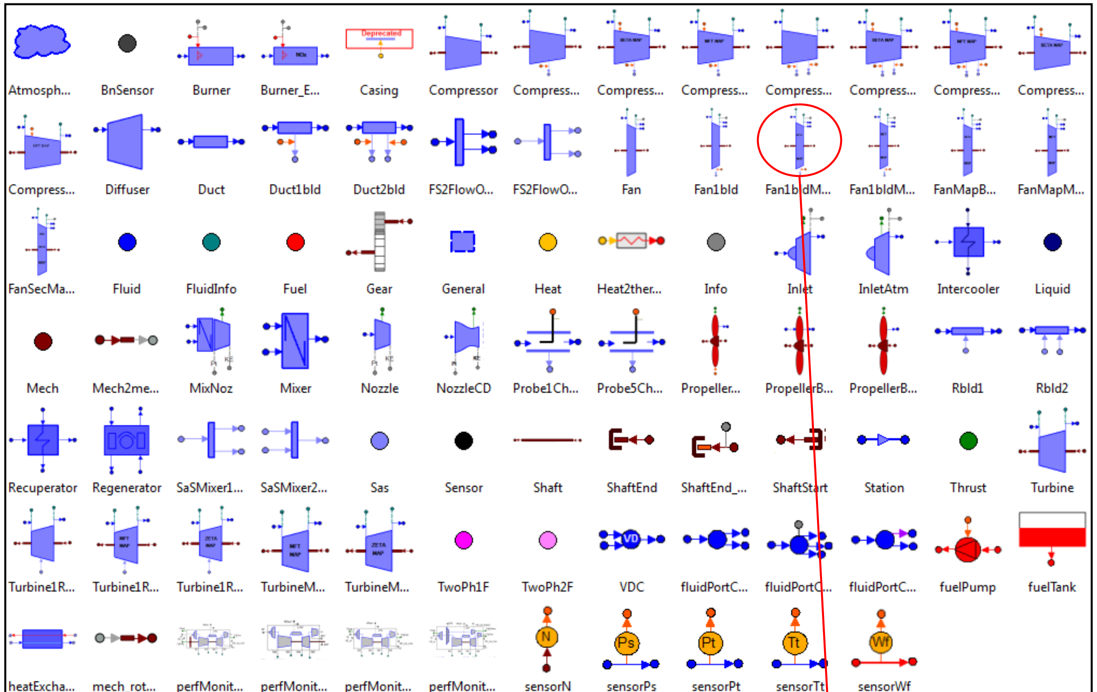
Simulation Platform

PROOSIS (PRopulsion Object-Oriented SImulation Software)

- Object-Oriented
- Steady State
- Transient
- Mixed-Fidelity
- Multi-Disciplinary
- Distributed
- Multi-point Design
- Off-Design
- Test Analysis
- Diagnostics
- Parametric
- Sensitivity
- Optimisation
- Deck Generation

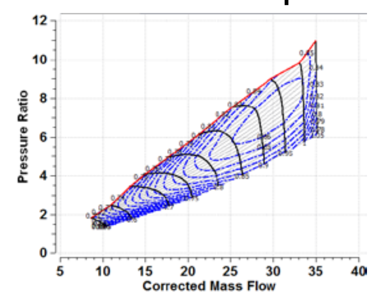


Model Construction

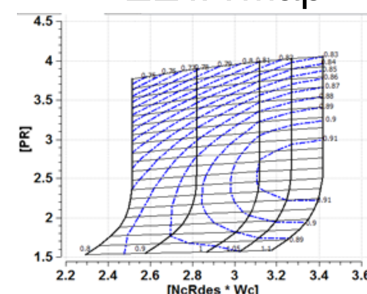


TURBO library of Gas Turbine Engine Components

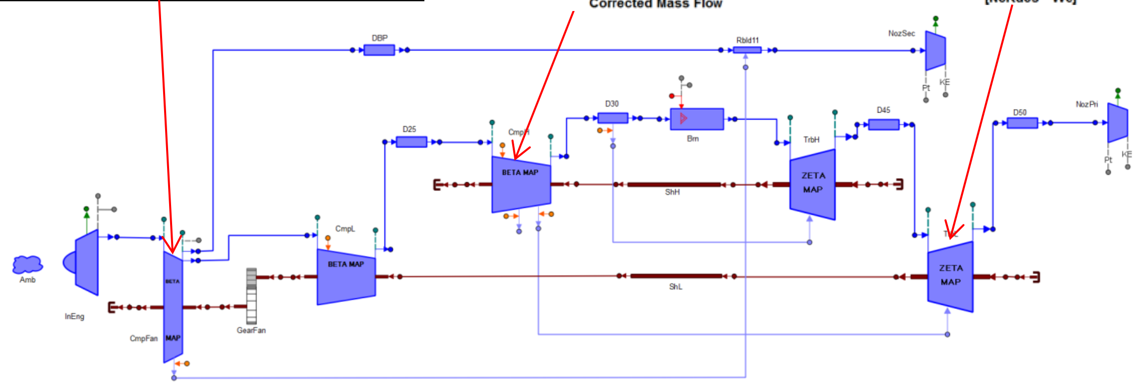
Compressor BETA map



Turbine ZETA map

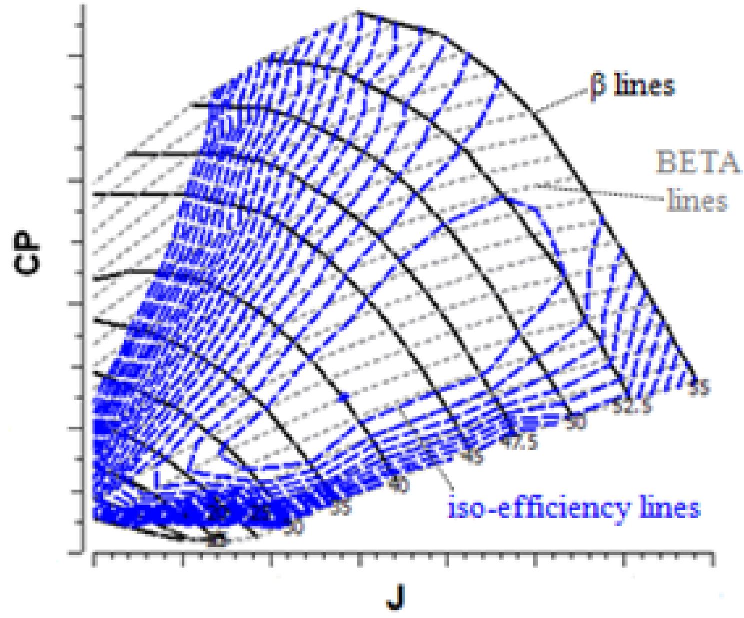


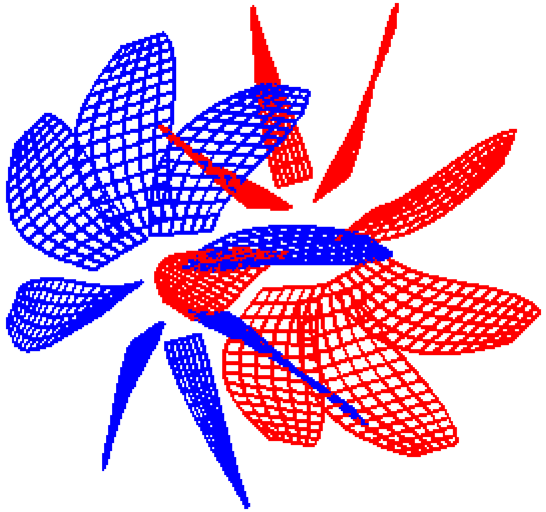
Engine configuration constructed graphically



Generation of Propeller Maps

PROOSIS Propeller Map



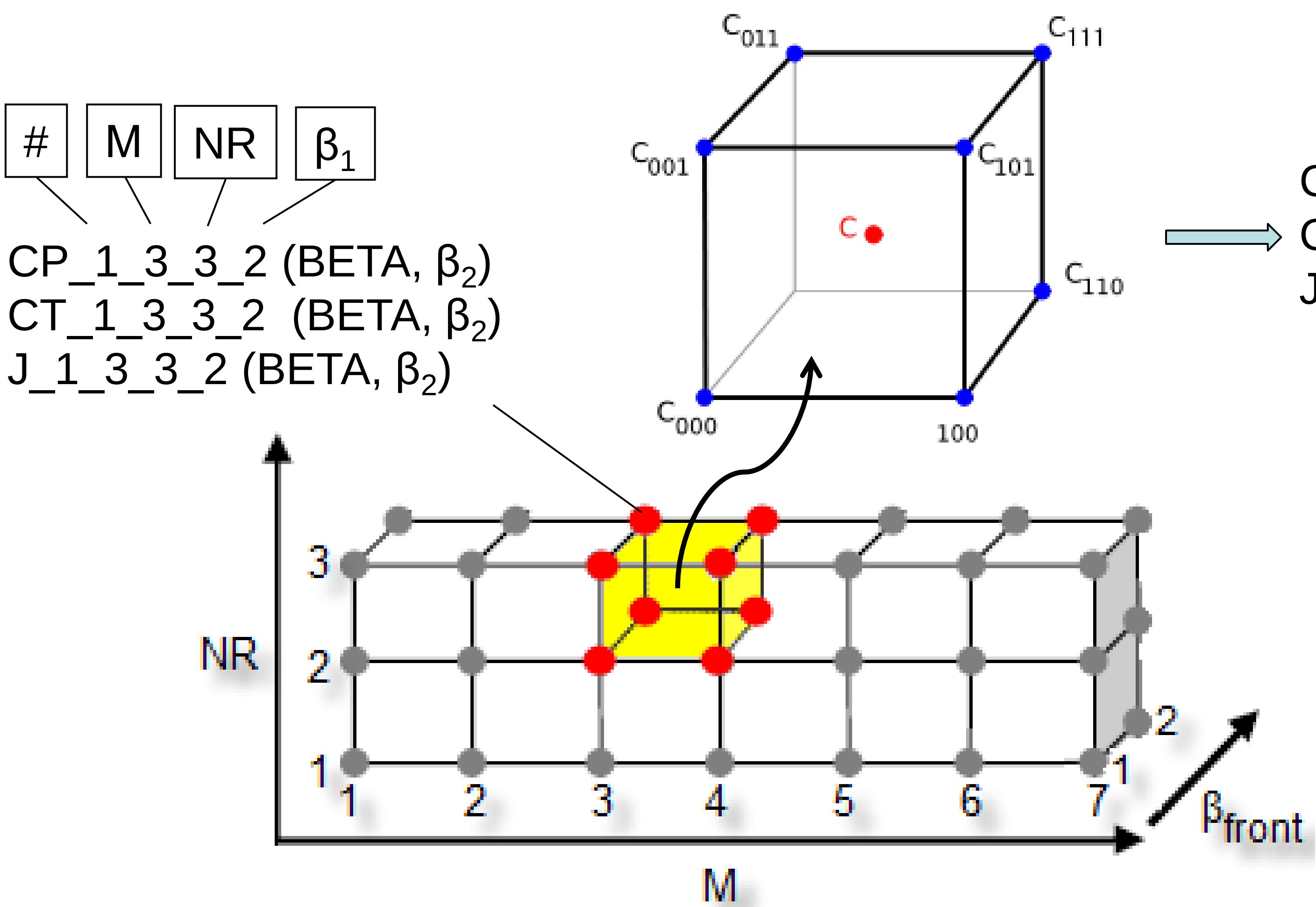


CP (BETA, β)
CT (BETA, β)
J (BETA, β)

M → 0.45, 0.60, 0.70, 0.75, 0.80, 0.85, 0.90
NR → 0.95, 1.00, 1.05
$\boldsymbol{\beta_1}$ → 57.7º, 63.3º
$\boldsymbol{\beta_2}$ → 54.7º/57.7º (β_1=57.7º) & 60.3º/63.3º (β_1=63.3º)

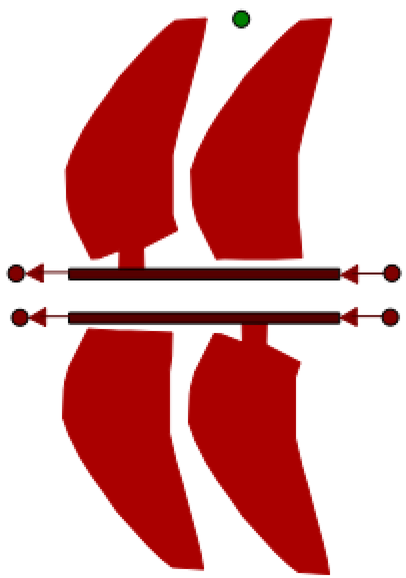
× 3 **J** = 252 GENUVP runs

CRP Propeller Map Reading



CP (M NR, β_1)
CT (M NR, β_1)
J (M NR, β_1)

PROOSIS CRP Component



CRP Map file
Front & Back Propeller Diameters
CRP system inertia

DATA

β_1, β_2 CONTROL

Flight Conditions: Pamb, Tamb, WAR, M
N1, N2

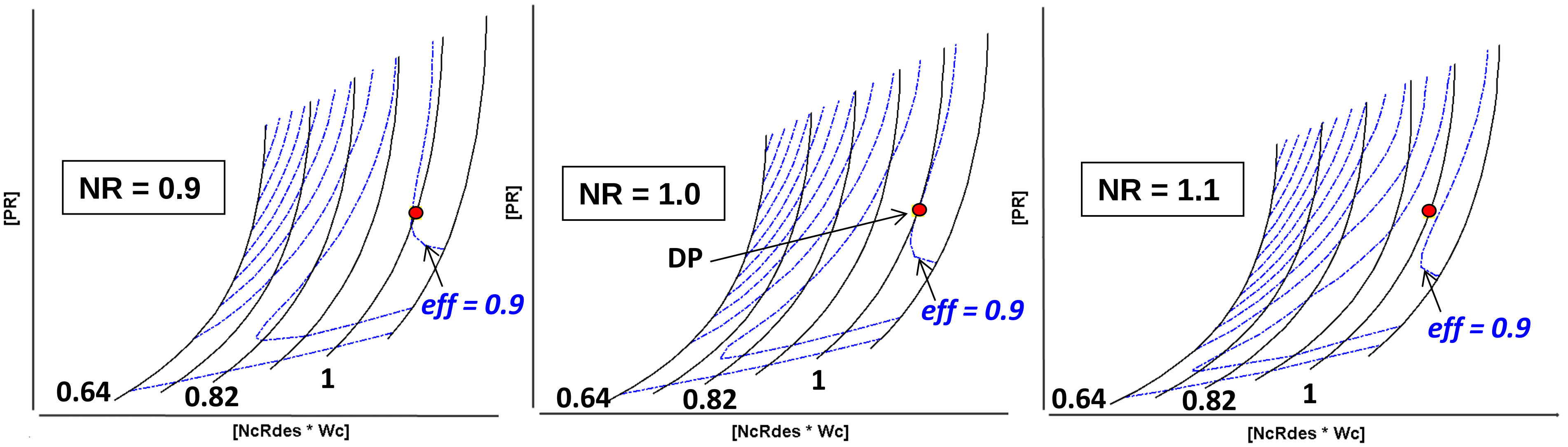
BOUNDS

BETA ALGEBRAIC

NR
J, CP, CT (BETA, M, NR, β_1, β_2)
Thrust, Power, Efficiency

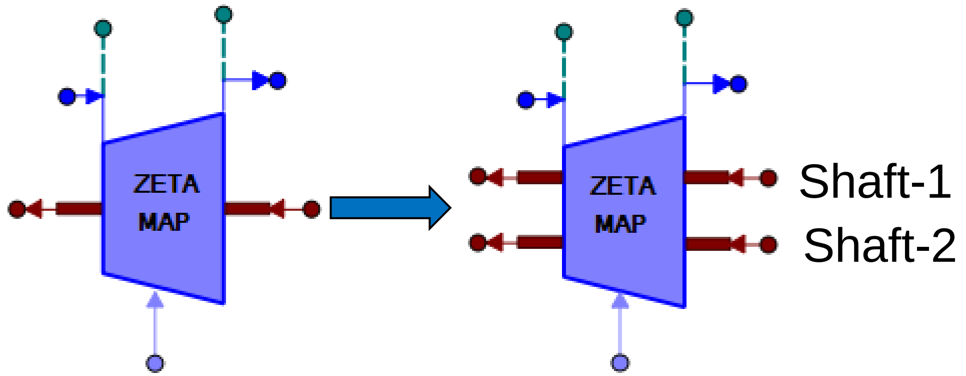
CALCULATED

Contra-Rotating Turbine Modelling



Wc (NR, NcRdes, ZETA)
eff (NR, NcRdes, ZETA)
trqR (NR, NcRdes, ZETA)

Speed ratio NR = N1 / N2
Torque ratio trqR = trq1 / trq2



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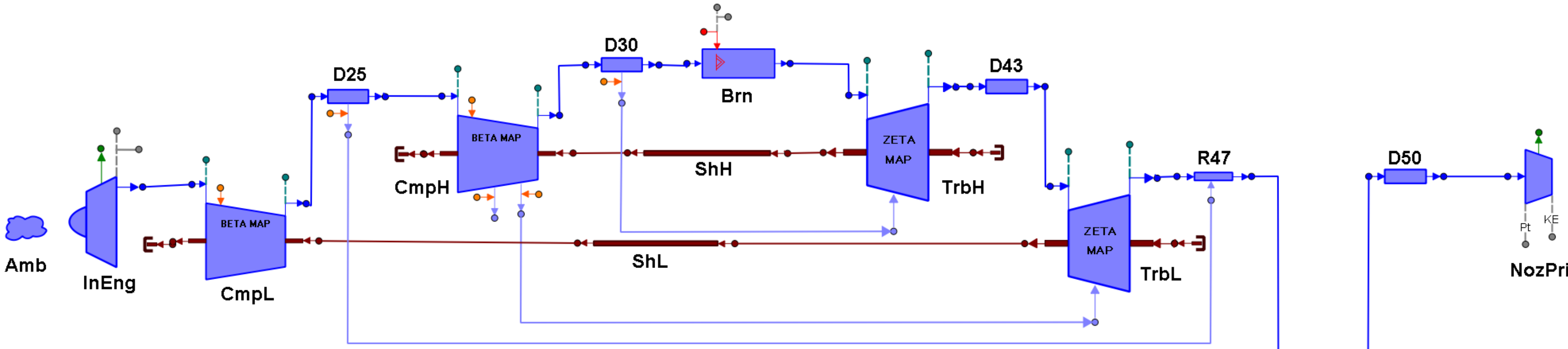
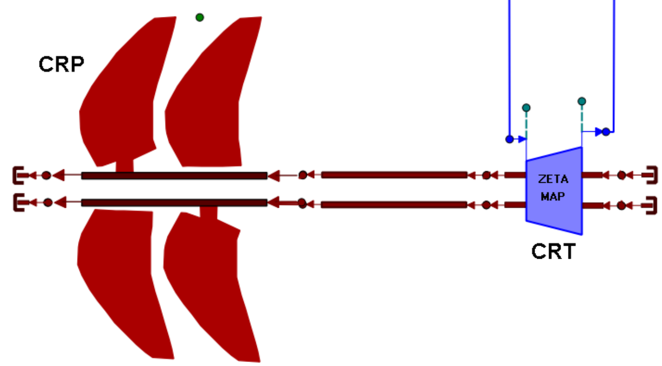
CROR Engine PROOSIS Model



D_{t1} [m]	3.56
D_{t2} [m]	3.39
β_1 [º]	59
β_2 [º]	59
$effP_1$ [-]	0.77
$effP_2$ [-]	0.85
N_1 [rpm]	1275
D_h/D_{t1} [-]	0.425



eff [-]	0.91
power ratio	1

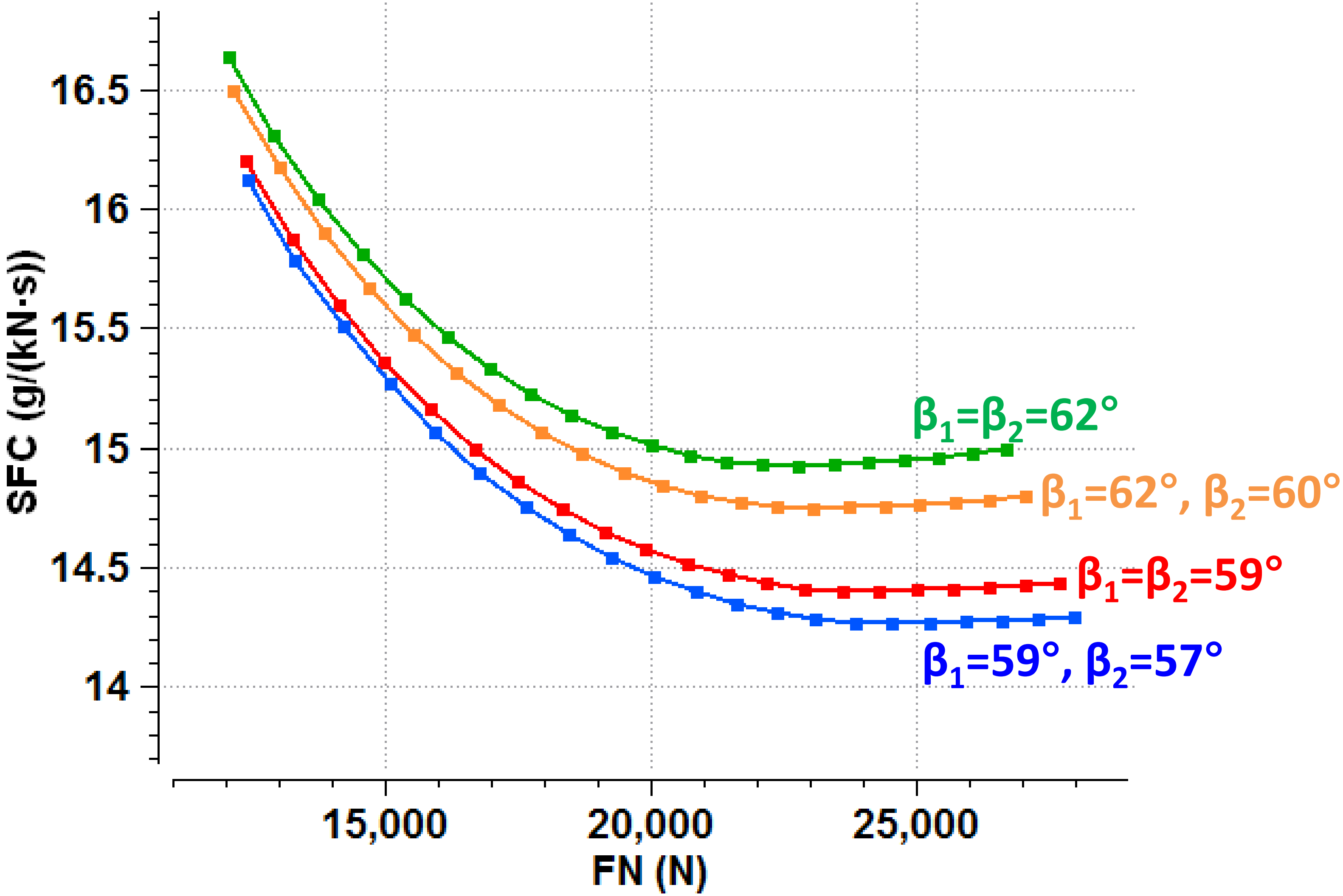
Design Point Definition (ToC)

Component	Parameter [units]	Value
InEng	W [kg/s]	17.5
CmpL	PR [-]	4.16
	eff [-]	0.88
CmpH	PR [-]	4.46
	eff [-]	0.87
Brn	TET [K]	1500
	effB [-]	0.995
	Pressure loss [%]	6
TrbH	eff [-]	0.843
TrbL	eff [-]	0.87

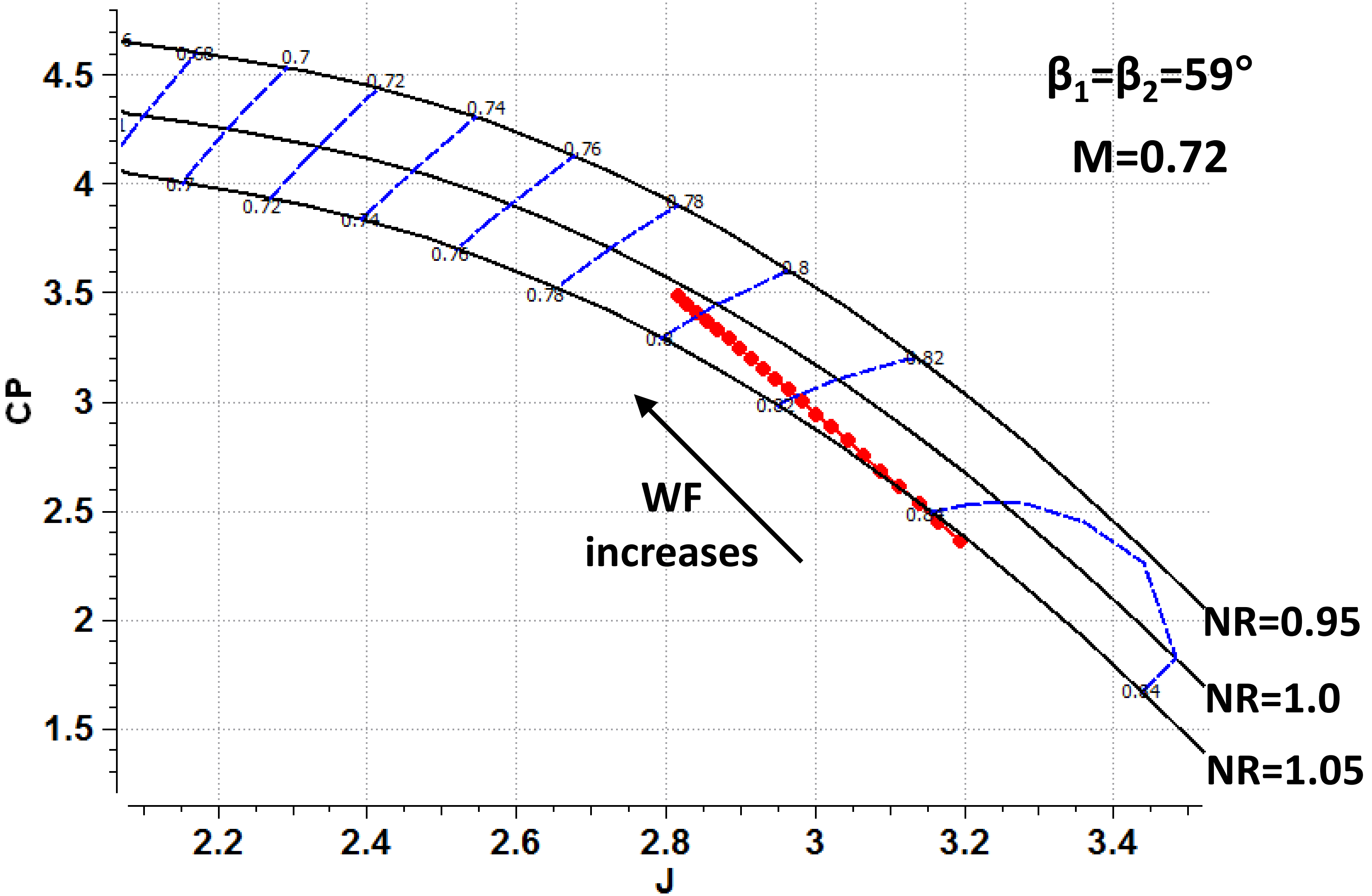
Design Point Results

Parameter [units]	Value
Front propeller thrust [kN]	10.55
Back propeller thrust [kN]	11.65
Nozzle Thrust [kN]	1.05
Net Thrust [kN]	23.3
Specific Fuel Consumption [g/(kN·s)]	14.4
Nozzle pressure ratio [-]	1.22
Propeller speed ratio [-]	1.02
Propeller torque ratio [-]	0.977
J_1 [-] | J_2 [-]	2.9 | 3.1
CP_1 [-] | CP_2 [-]	1.6 | 2.2
CT_1 [-] | CT_2 [-]	0.43 | 0.60
CRT PR	4.95

OD Performance for Different Blade Settings



Operating line on CRP map



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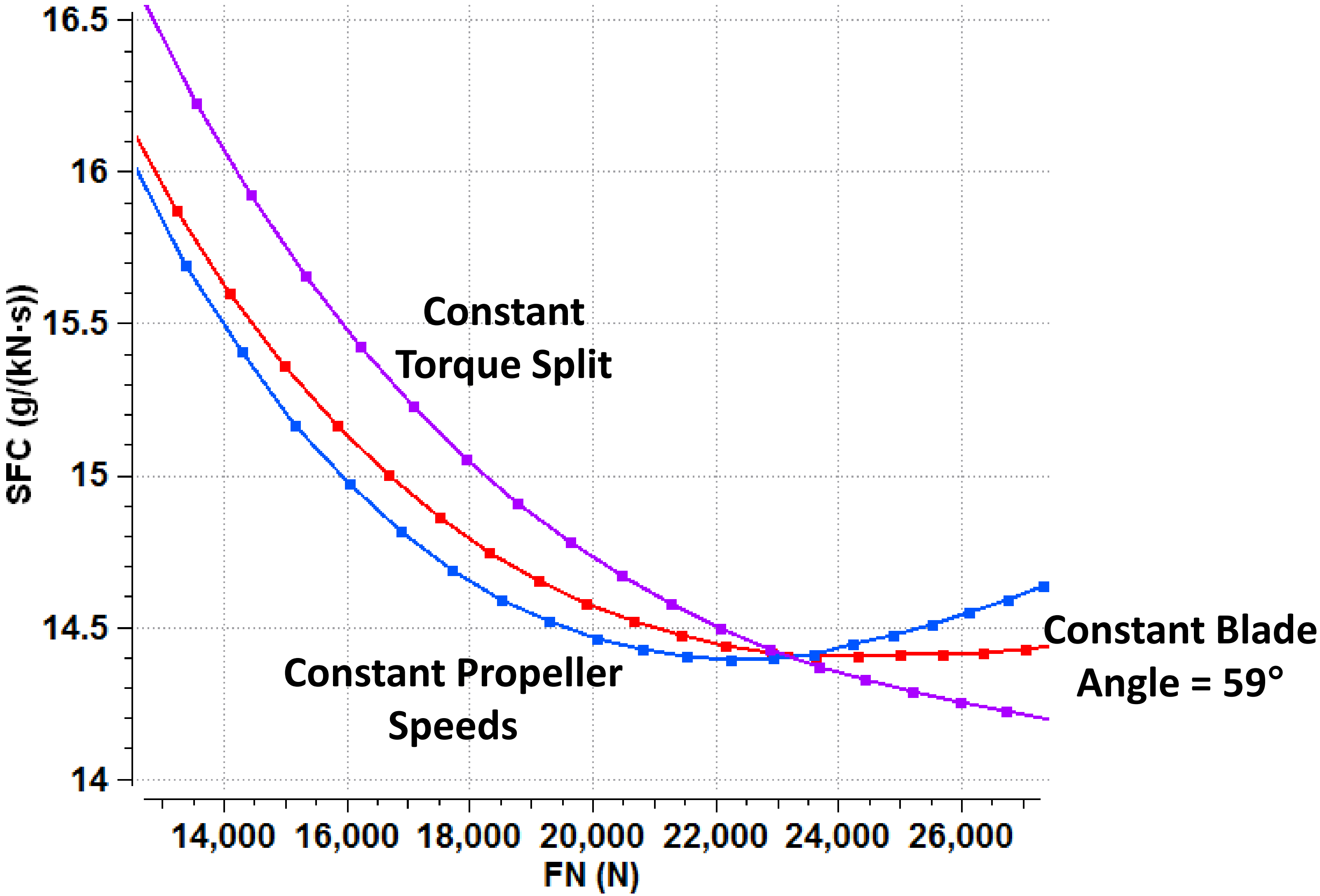
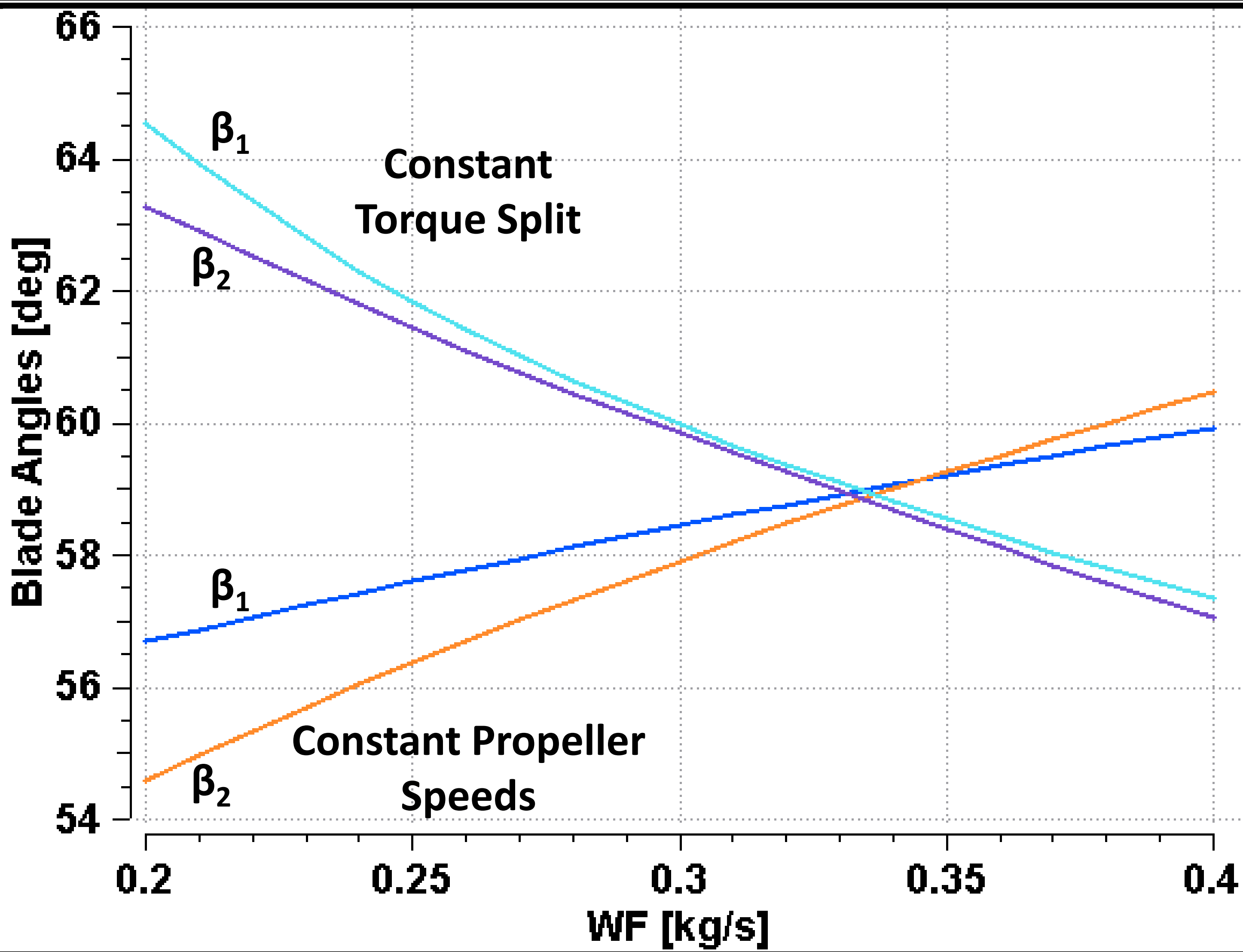
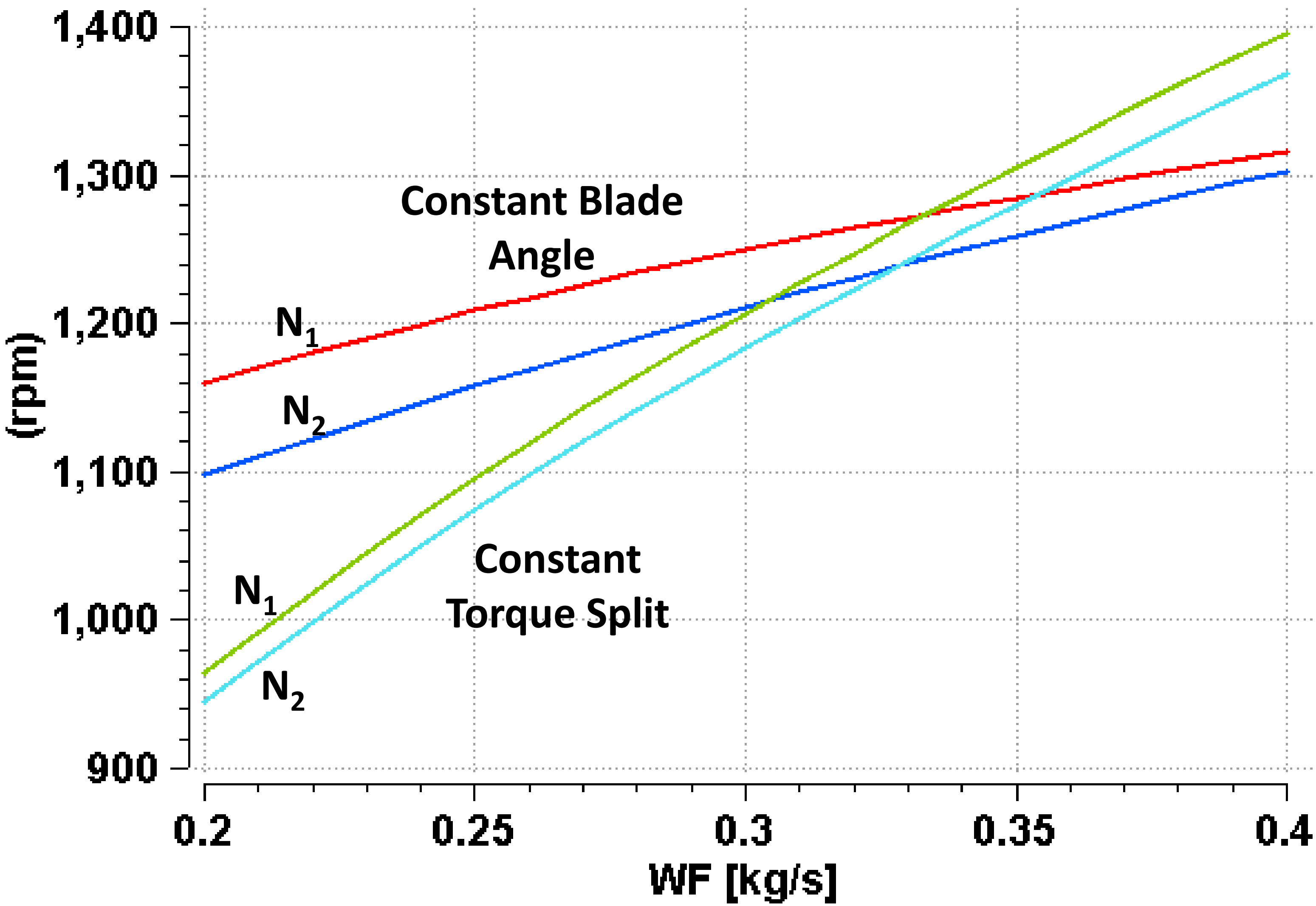
OD Performance for Different Control Strategies



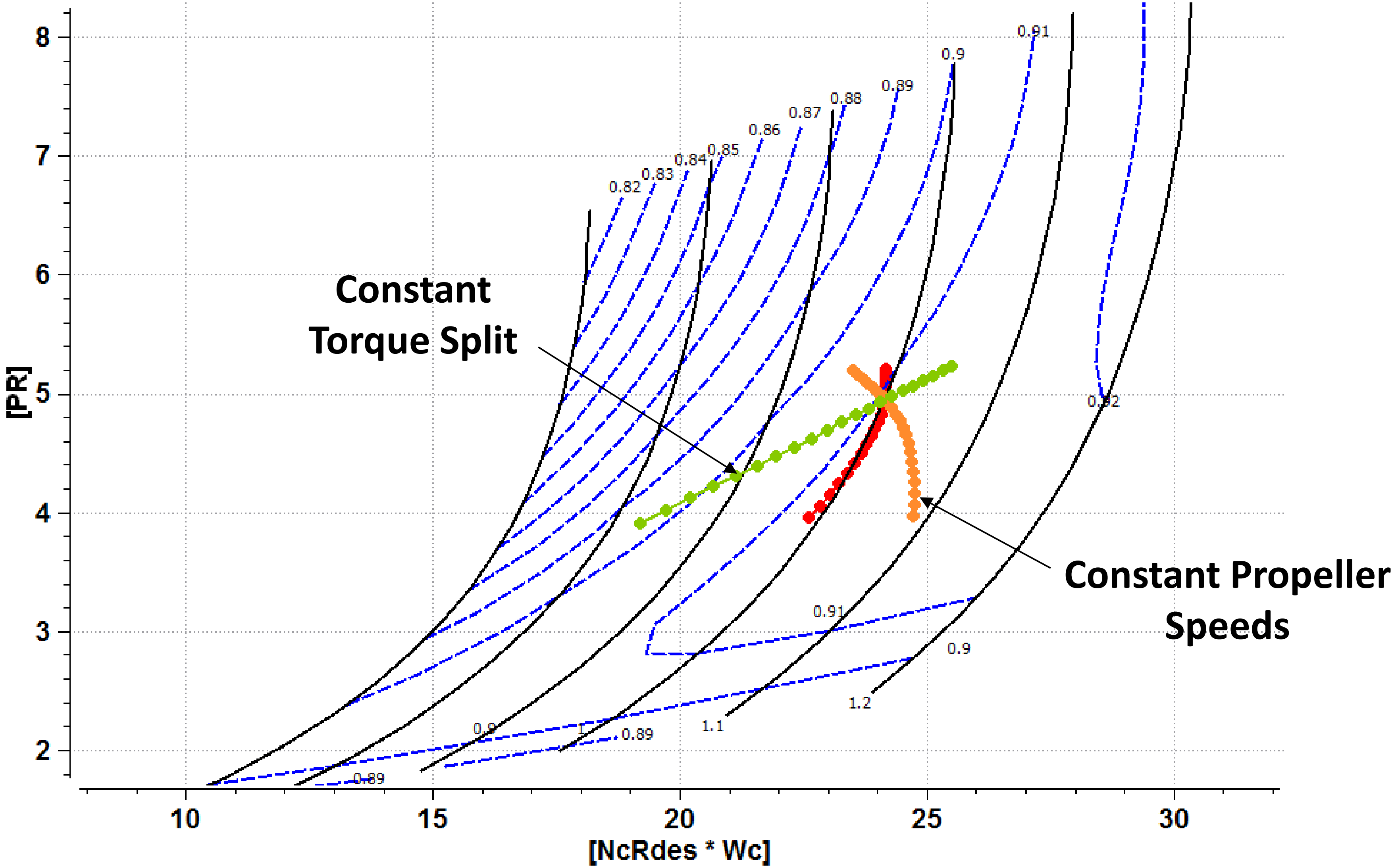
Propeller Blade Angle Variation



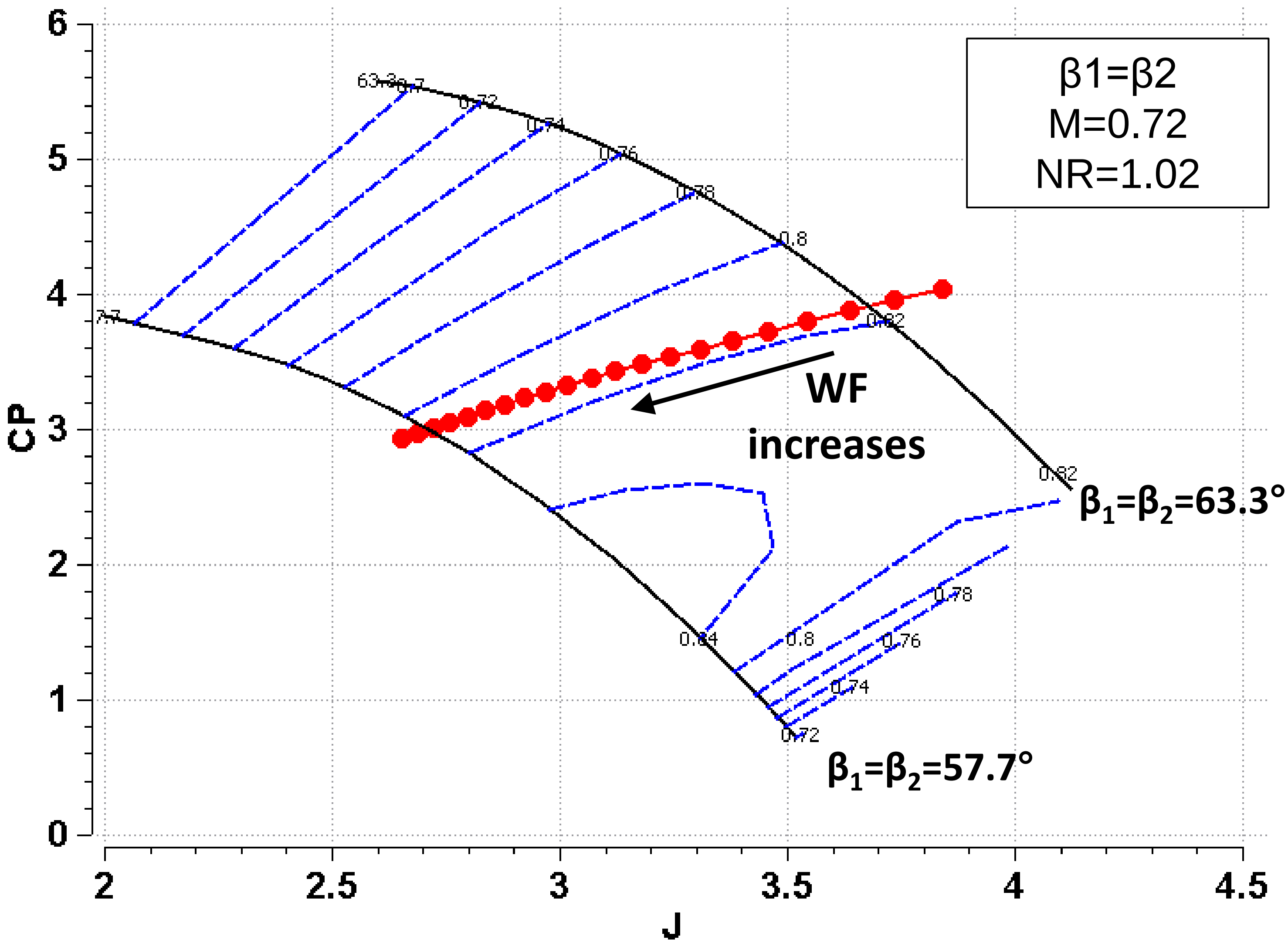
Propeller Speed Variation



Operating lines on CRT map



Operating line on CRP map



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- CRP PERFORMANCE MODEL
  - o Simulation Environment - PROOSIS
  - o CRP Performance Maps
  - o CRP PROOSIS Component
- CROR ENGINE MODEL
- ENGINE CONTROL STUDIES
- **SUMMARY & CONCLUSIONS**

Summary & Conclusions

- An approach to contra-rotating propeller performance modelling has been presented, based on a set of individual propeller maps generated by a free-wake lifting surface model of a specific CRP system for different values of Mach number, speed ratio and blade pitch angles.

- A dedicated CRP component model is developed in an engine performance simulation environment that uses these maps to calculate CRP performance.

- This CRP component is used to create a direct-drive open rotor engine performance model. The capabilities of the approach are demonstrated through design point and off-design engine studies while its flexibility is exemplified with a study of the effects of propeller blade control strategy on engine performance.

Summary & Conclusions

- The accuracy of the presented approach can be further improved through:
  - more accurate values of the aerodynamic coefficients (CL and CD) and
  - extending the range of parameters simulated through the lifting surface model in order to reduce map interpolation and extrapolation errors.

- Significant computer time savings could be achieved through:
  - the use of a particle mesh approach for the far wake part downstream of the BP
  - code optimization and parallelization

Summary & Conclusions

- The CRP component developed can be used to study both DDOR and GOR configurations and is suitable for a variety of performance calculations at component, engine or aircraft mission analysis level.
- Using the lifting surface model, maps for different combinations of propeller designs can be generated thus enabling multi-disciplinary design optimization studies.
- Direct integration of GENUVP in PROOSIS as an external object will offer an advantage to the map approach both in terms of execution speed as well as modelling accuracy.

감사합니다

THANK YOU