TCFD软件在螺旋桨分析的应用

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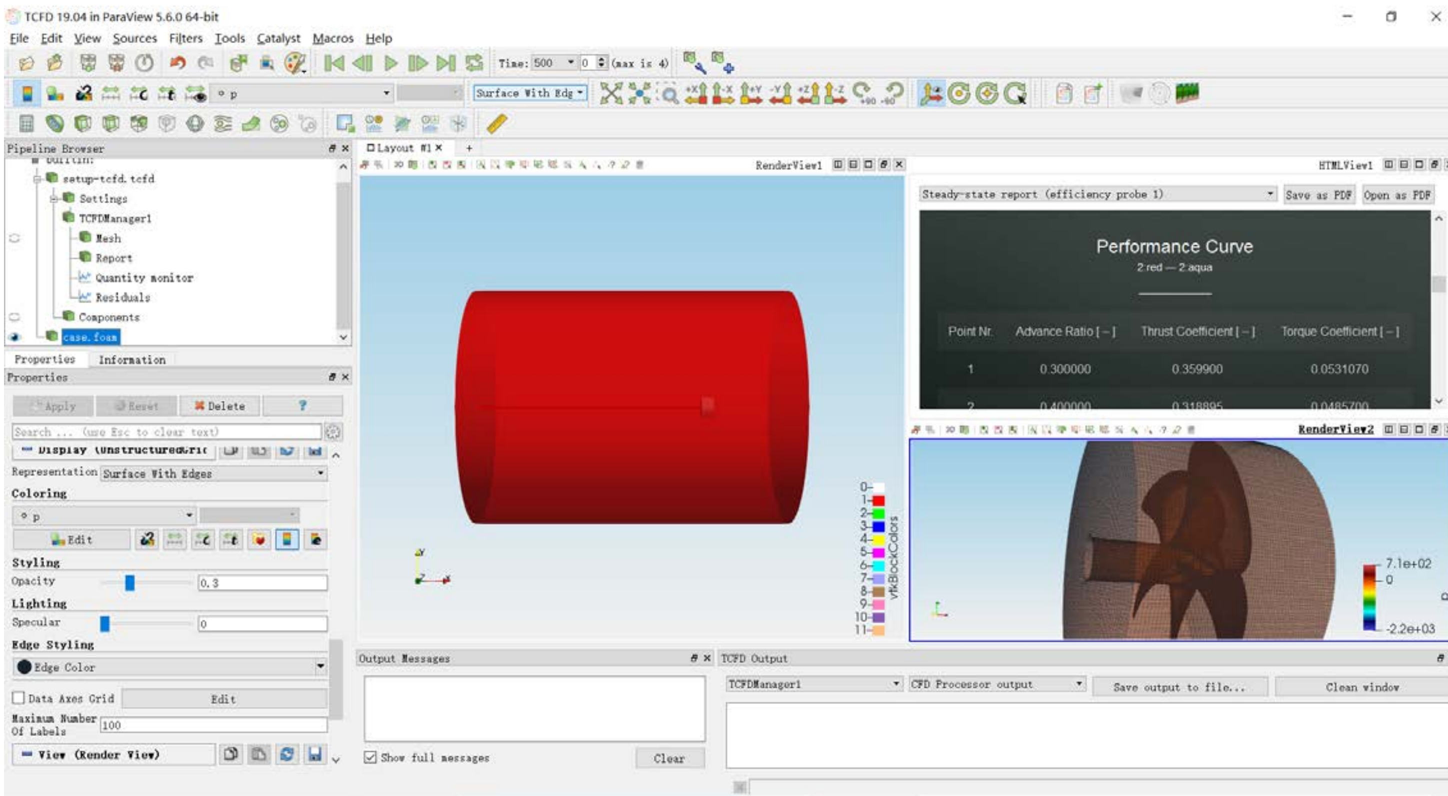
软件概述

Turbomachinery CFD（ 简称TCFD）是一款通用的计算流体力学软件，在开源CFD求解工具OpenFOAM基础上，针对旋转机械进行了深度定制开发，因此特别适用于各类旋转机械产品的流动性能分析，其中包括螺旋桨的敞水性能预报。



主要功能

- 全自动化、模板化设置流程，高效便捷；
- 可同时设置多转速多工况计算，并自动生成性能曲线；
- 自动生成结构化六面体网格；
- 自动生成 HTML 、PDF版本后处理结果报告；

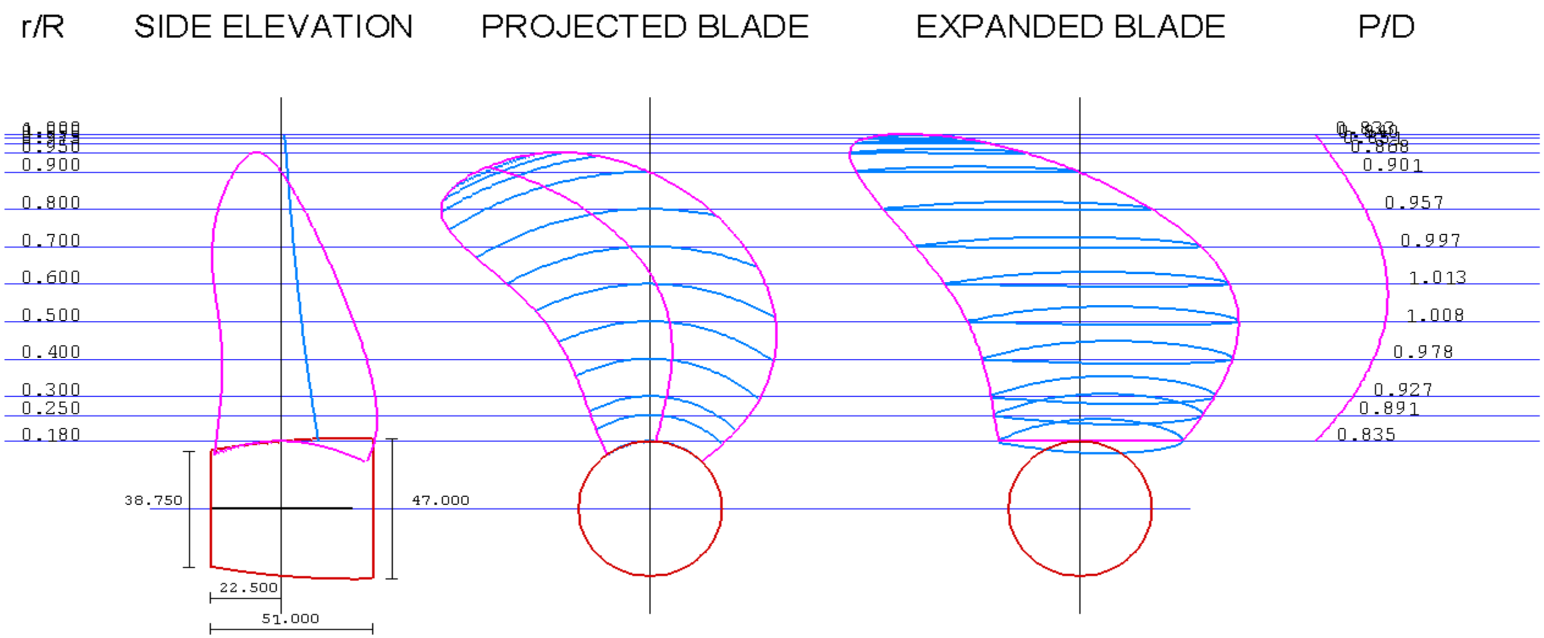
适用范围：

- 各类轴流/径流旋转机械及静止部件
- 可压/不可压流质
- 稳态/瞬态计算

功能对比

	TCFD	标准的OpenFOAM	其他商业软件
开源代码	√	√	X
无用户、工作节点等限制	√	√	X
快速的计算能力	√	X	√
前/后处理	√	X	√
图像交互界面	√	X	√
自动化、模块化工作流程	√	X	X
HTML、PDF格式的报告	√	X	X
真实的案例指导	√	X	√
适用于Linux和Windows	√	X	√
方便的深度二次开发	√	√	X

KP505桨标模几何参数

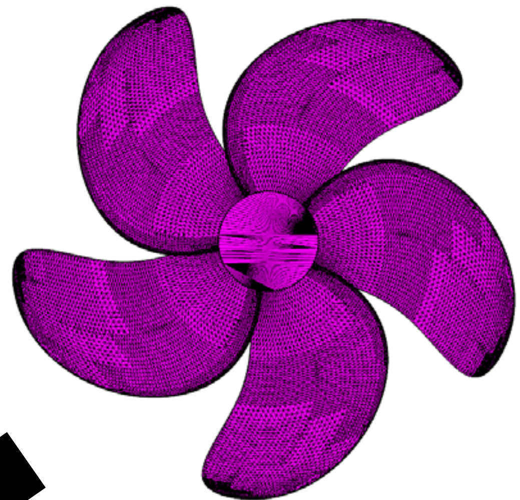


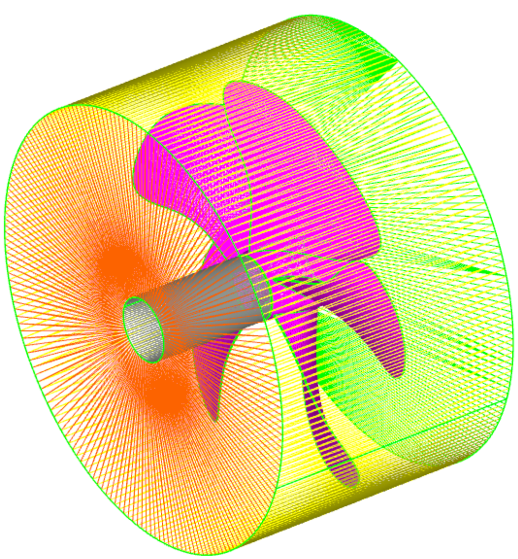
Propeller Principal Particulars					
Diameter(mm)	7900.0	Model Diam(mm)	250.000	Scale Ratio	31.6000
(P/D)mean	0.9500	(Rake/D) Tip	0.0000	Prop. Type	FPP
Ae/Ao	0.8002	Eff. skew(Deg)	32.00	Drawing Scale	1.80556
Hub Ratio	0.1800	(C/D) 0.7R	0.3590	Comment	
No. of Blade	5	(fo/C) 0.7R	0.0140	Prop. Number	KP505
Section	NACA66	(t/D) 0.7R	0.0149		

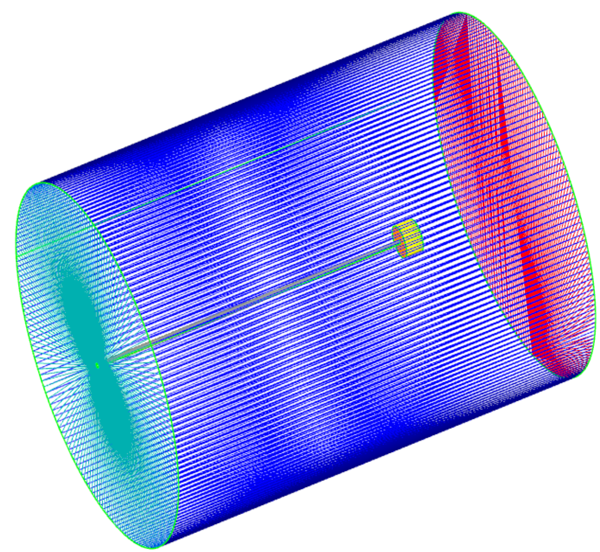
模型文件

STL格式文件
- 桨叶+桨毂（D=0.25m）
- 旋转域（-0.4D，0.24D）
- 静止域（-12D，4D）

颜色区分表面







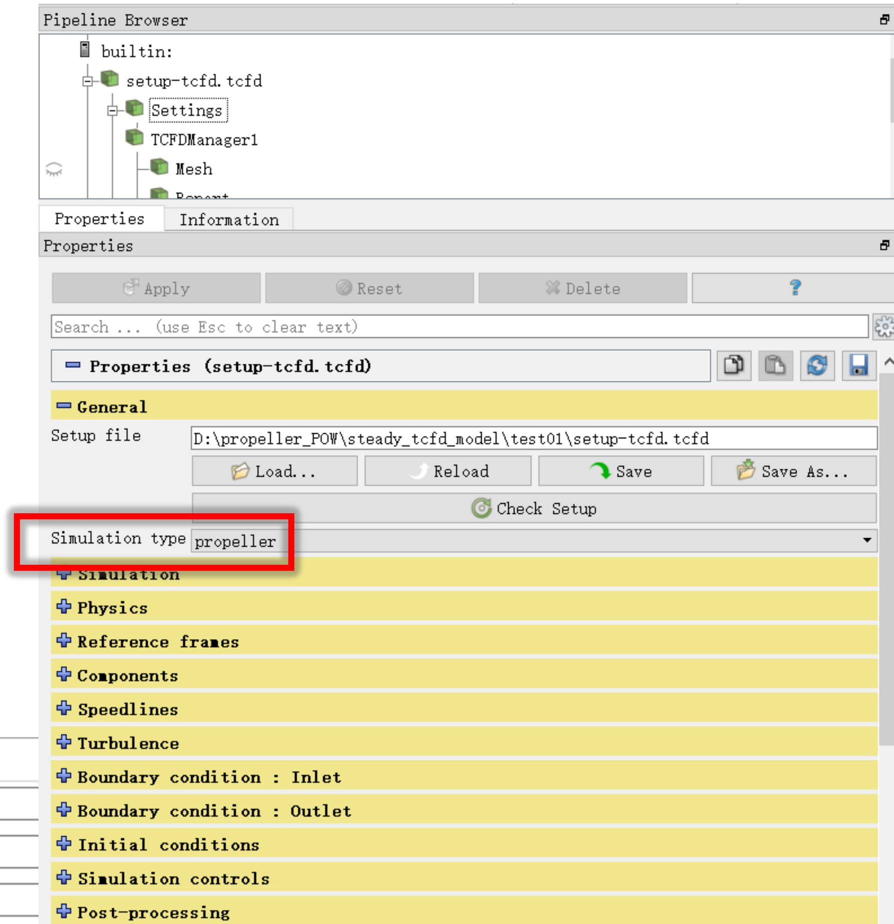
仿真设置

模拟设置：

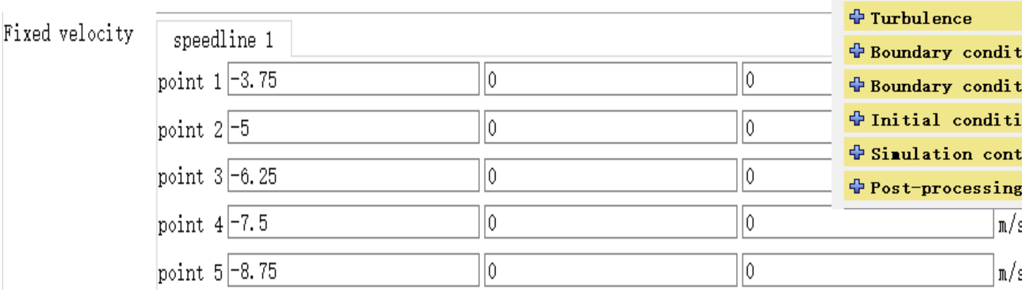
- 稳态计算
- 不可压流质
- 湍流模型（kOmegaSST）

计算工况：

- 转速50rps
- 进速系数J取5个点 (0.3,0.4,0.5,0.6,0.7)



导航式设置



旋转域网格设置

旋转坐标系

Reference frames

Number of reference frames: 2

frame1 | frame2

Name: rotor

Axis: 1 | 0 | 0

Origin: 0 | 0 | 0

☑ Rotating

Rotation speed speedline 1: 3000 RPM

Components

Scale factor: 1 mm

Number of components: 2

☐ Bounding box

component1 | component2

Geometry source: One multi-solid STL file

STL file: D:/propeller_POW/steady_tcfd_model/sub1.stl ...

Component name: propeller

Reference frame: rotor

No. periodic segments: 1

Patches

边界类型

旋转部件

name	type	frame	grp	min ref	max ref	layers	mxp
chocolate	inletInterface	static	🔒	1	1	0	0
default_color	hub	rotor	🔒	2	2	0	?
fuchsia	blade	rotor	🔒	2	4	3	?
olive	outletInterface	static	🔒	1	1	0	0
yellow	freestreamInterface	static	🔒	1	1	0	?

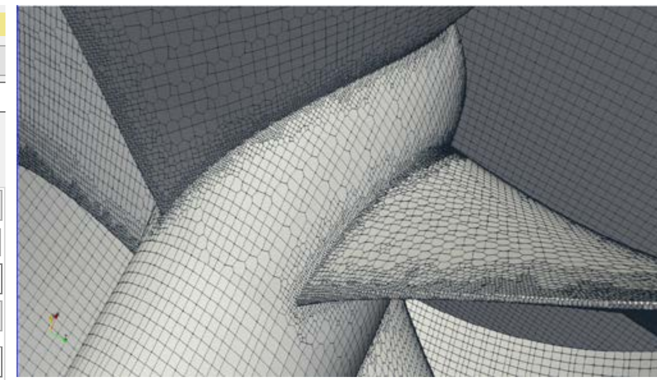
Background mesh size: 5 | 5 | 5

☐ show background mesh wireframe

Internal point: -54.7456 | 38.0399 | -88.0848

☐ show internal point as sphere with radius 10

Wheel diameter: 250



网格设定：

- 网格细化次数
- 边界层数

背景网格尺寸

静止域网格设置

component1 | component2

Geometry source: One multi-solid STL file

STL file: D:/propeller_POW/steady_tcfd_model/sub2.stl ...

Component name: flowDomain

Reference frame: static

No. periodic segments: 1

Patches

name	type	frame	grp	min ref	max ref	layers	mxp
aqua	outlet	static	🔒	0	0	0	?
blue	wallSlip	static	🔒	0	0	0	?
chocolate	outletInterface	static	🔒	4	4	0	0
default_color	hub	static	🔒	3	3	0	?
olive	inletInterface	static	🔒	4	4	0	0
red	inlet	static	🔒	0	0	0	?

Background mesh size: 40 | 40 | 40

☐ show background mesh wireframe

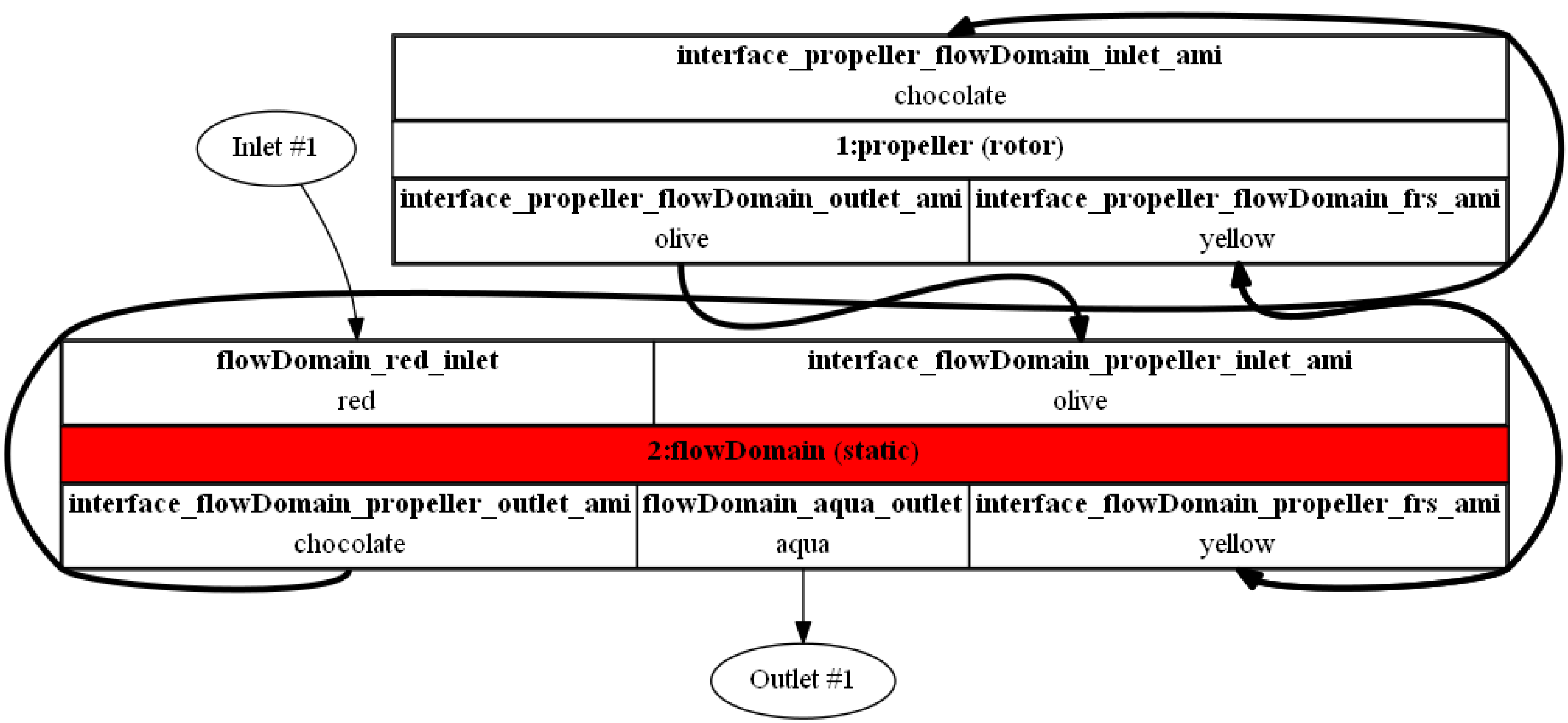
Internal point: -1367.08 | -395.067 | -355.696

☐ show internal point as sphere with radius: 10

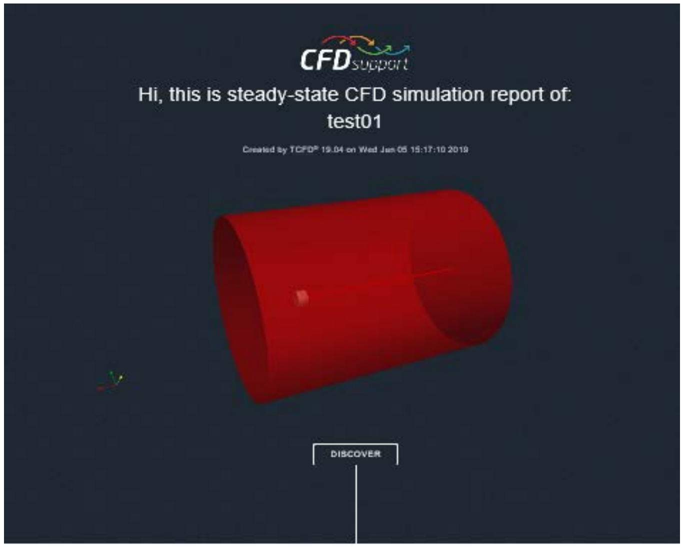
Wheel diameter: 0

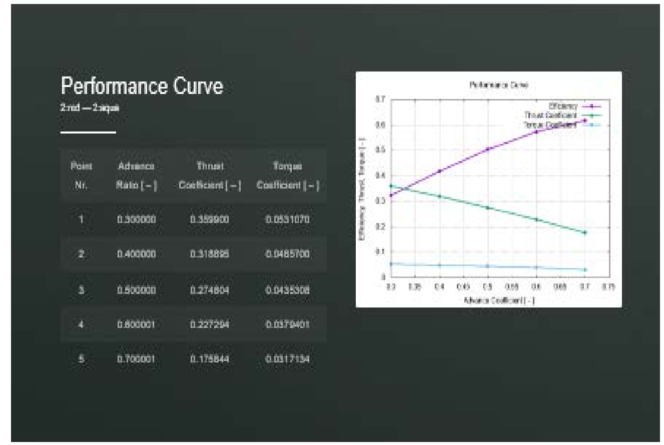
流程图

自动清晰的显示目前设置下的介质流通过程，从进口流经各个部件到从出口流出，可以直接醒目的判断设置流程的对错。



计算报告生成

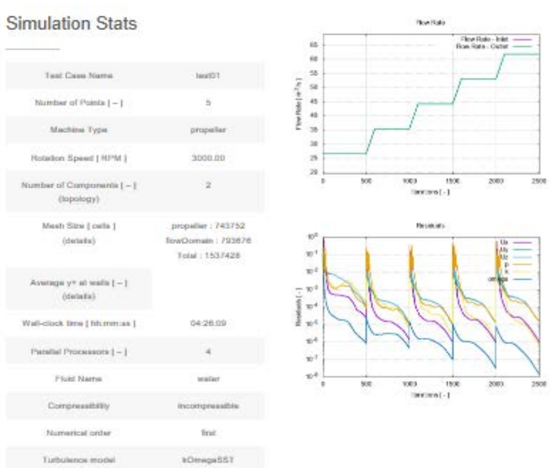




Performance Curve

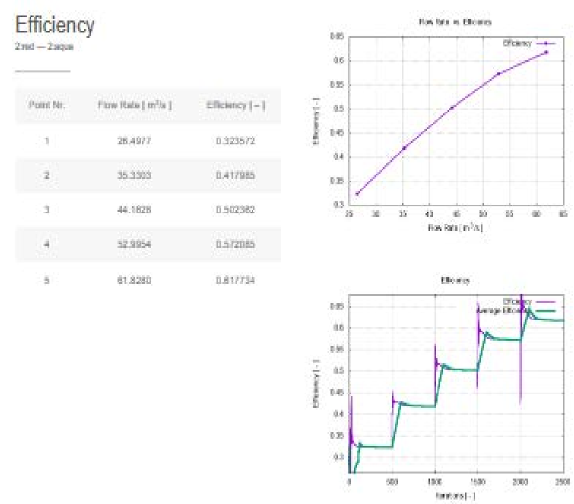
2rnd — 2aqua

Point Nr.	Advance Ratio [–]	Thrust Coefficient [–]	Torque Coefficient [–]
1	0.300000	0.359900	0.0531070
2	0.400000	0.318895	0.0485700
3	0.500000	0.274804	0.0435308
4	0.600001	0.227204	0.0379401
5	0.700001	0.175844	0.0317134



Simulation Stats

Test Case Name	test01
Number of Points [–]	5
Machine Type	propeller
Rotation Speed [RPM]	3000.00
Number of Components [–] (topology)	2
Mesh Size [cells] (details)	propeller : 743752 flowDomain : 793676 Total : 1537428
Average y+ at walls [–] (details)	
Wall-clock time [hh:mm:ss]	04:28:09
Parallel Processors [–]	4
Fluid Name	water
Compressibility	incompressible
Numerical order	first
Turbulence model	kOmegaSST



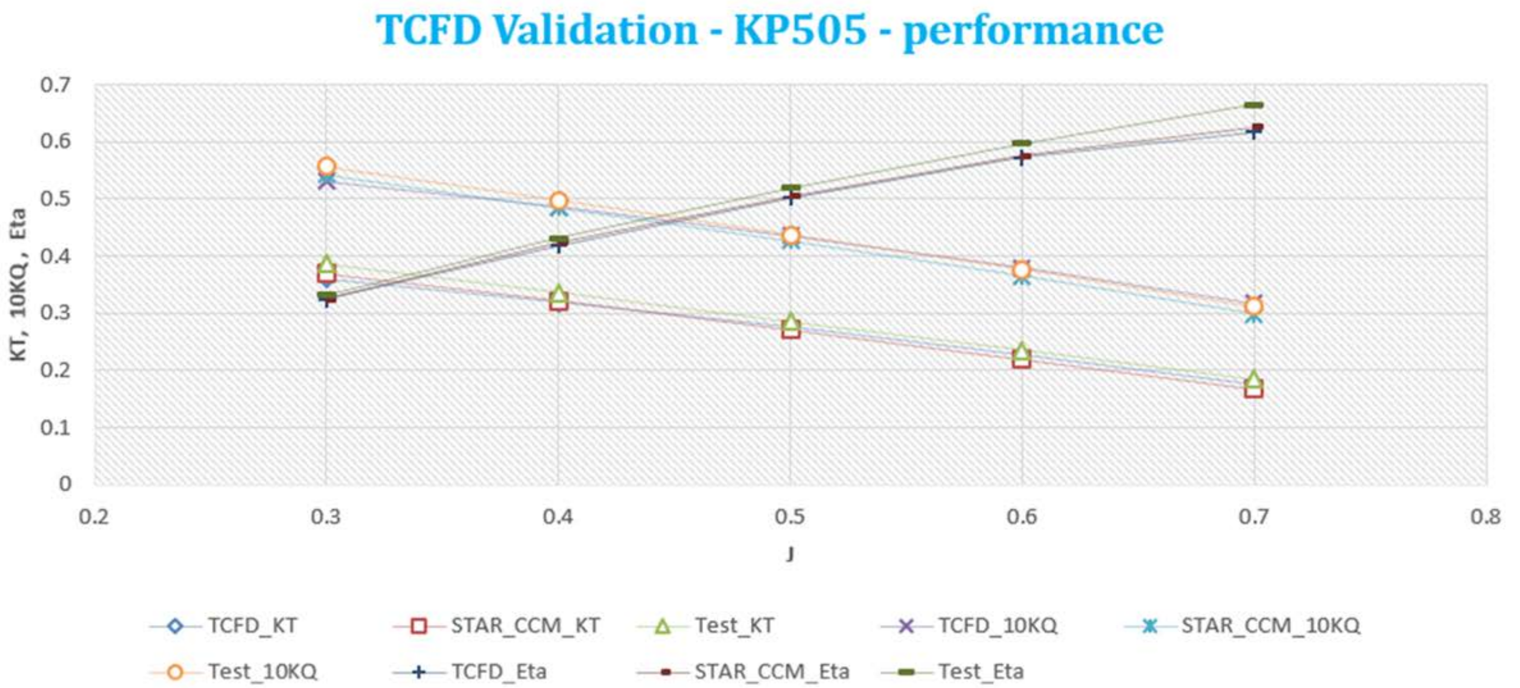
Efficiency

2rnd — 2aqua

Point Nr.	Flow Rate [m³/s]	Efficiency [–]
1	26.4977	0.323572
2	35.3303	0.417985
3	44.1828	0.502382
4	52.9954	0.572085
5	61.8280	0.617734

结果验证

J	TCFD_KT	TCFD_10KQ	TCFD_Eta	STAR_CCM_KT	STAR_CCM_10KQ	STAR_CCM_Eta	Test_KT	Test_10KQ	Test_Eta
0.3	0.36	0.531	0.324	0.369	0.542	0.325	0.387	0.557	0.332
0.4	0.319	0.486	0.418	0.322	0.484	0.424	0.336	0.497	0.431
0.5	0.275	0.435	0.502	0.271	0.427	0.505	0.285	0.437	0.519
0.6	0.227	0.379	0.572	0.22	0.365	0.576	0.235	0.376	0.597
0.7	0.176	0.317	0.618	0.168	0.299	0.626	0.185	0.311	0.665



结果验证

J	Err_KT_TCFD	Err_KT_STAR_CCM	Err_10KQ_TCFD	Err_10KQ_STAR_CCM	Err_Eta_TCFD	Err_Eta_STAR_CCM
0.3	-6.97%	-4.65%	-4.66%	-2.69%	-2.40%	-2.11%
0.4	-5.05%	-4.17%	-2.21%	-2.61%	-3.01%	-1.62%
0.5	-3.50%	-4.91%	-0.45%	-2.28%	-3.27%	-2.70%
0.6	-3.40%	-6.38%	0.79%	-2.92%	-4.18%	-3.52%
0.7	-4.86%	-9.18%	1.92%	-3.85%	-7.06%	-5.87%

通过验证可以看出，TCFD稳态计算结果与试验数据和其他商业软件计算结果趋势一致，精度基本相当。而旋转坐标系法模拟螺旋桨运动会导致推力普遍较小，误差偏大。

TCFD刚体运动法的瞬态计算结果

J	KT_MRF	KT_Motion	KT_test	Err_KT_Motion
0.3	0.36	0.366	0.387	-5.42%
0.7	0.176	0.179	0.185	-3.24%

CAESES参数化模型

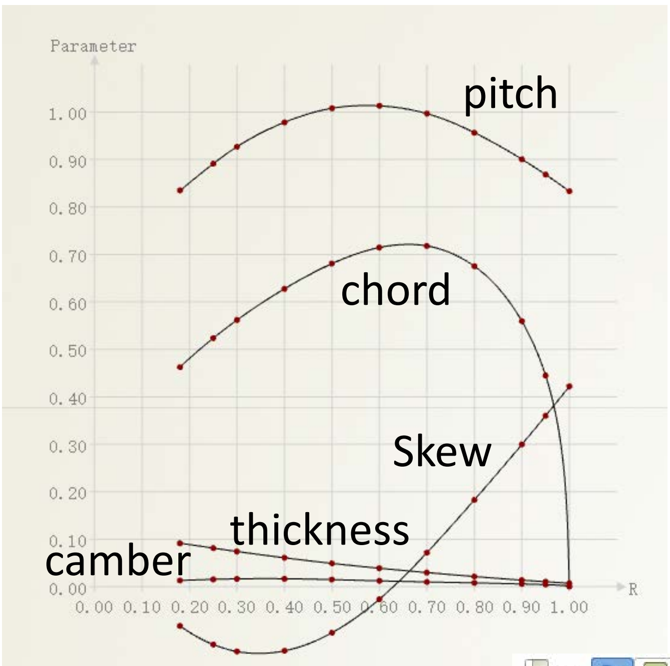
通过参数化定义二维切面翼型，以及螺距，侧斜及纵倾的空间位置变化规律，实现对螺旋桨的参数化建模。

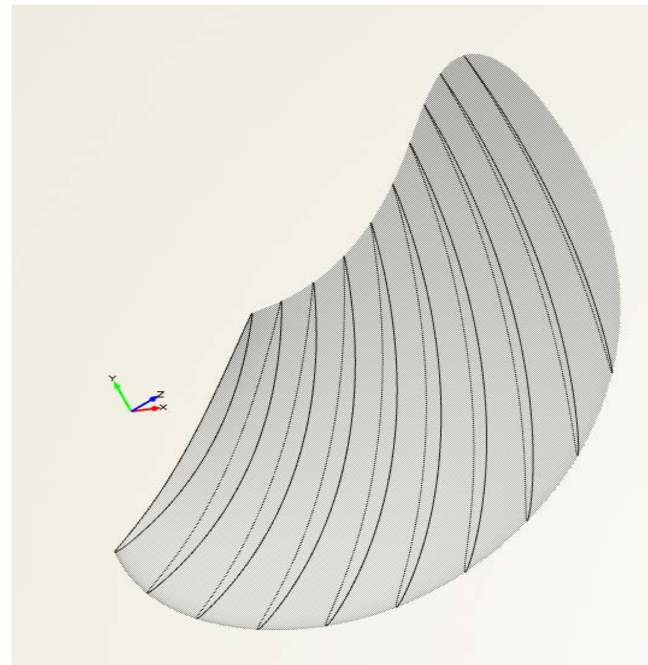
KP505螺旋桨特征参数沿径向分布

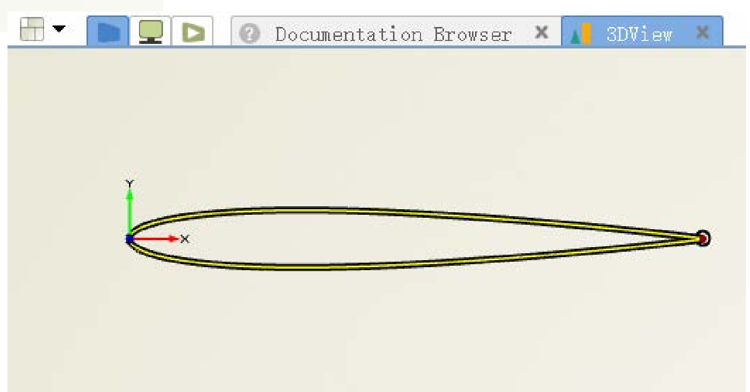
r/R	P/D	Rake	Skew(。)	C/D	fo/C	to/D
0.180	0.834700	0.0000	-4.720	0.231300	0.028448	0.045850
0.250	0.891200	0.0000	-6.980	0.261800	0.029641	0.040710
0.300	0.926900	0.0000	-7.820	0.280900	0.029477	0.037120
0.400	0.978300	0.0000	-7.740	0.313800	0.026769	0.030470
0.500	1.007900	0.0000	-5.560	0.340300	0.022010	0.024590
0.600	1.013000	0.0000	-1.500	0.357300	0.017324	0.019470
0.700	0.996700	0.0000	4.110	0.359000	0.014039	0.014920
0.800	0.956600	0.0000	10.480	0.337600	0.011996	0.010730
0.900	0.900600	0.0000	17.170	0.279700	0.010440	0.006930
0.950	0.868300	0.0000	20.630	0.222500	0.010067	0.005280
1.000	0.833100	0.0000	24.180	0.000100	8.700000	0.003690

CAESES参数化模型

2D，3D参数沿径向变化方程





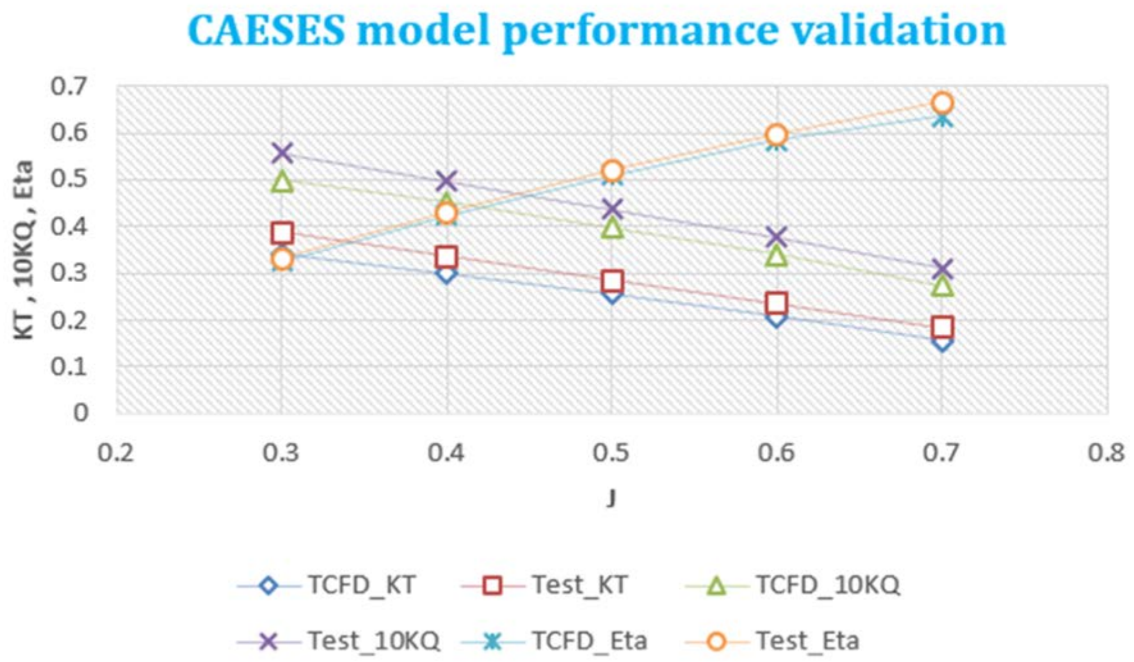


参数化叶切面

参数化模型计算结果

模拟设置，网格划分和标模计算一致

J	TCFD_KT	TCFD_10KQ	TCFD_Eta	Test_KT	Test_10KQ	Test_Eta
0. 3	0. 34	0. 499	0. 326	0. 387	0. 557	0. 332
0. 4	0. 3	0. 451	0. 423	0. 336	0. 497	0. 431
0. 5	0. 256	0. 399	0. 51	0. 285	0. 437	0. 519
0. 6	0. 208	0. 34	0. 585	0. 235	0. 376	0. 597
0. 7	0. 157	0. 275	0. 635	0. 185	0. 311	0. 665



参数化模型计算结果

J	Err_KT_CAESES	Err_KT_KP505	Err_10KQ_CAESES	Err_10KQ_KP505	Err_Eta_CAESES	Err_Eta_KP505
0. 3	12. 14%	6. 97%	10. 41%	4. 66%	1. 81%	2. 40%
0. 4	10. 71%	5. 05%	9. 25%	2. 21%	1. 86%	3. 01%
0. 5	10. 17%	3. 50%	8. 69%	0. 45%	1. 73%	3. 27%
0. 6	11. 48%	3. 40%	9. 57%	0. 79%	2. 01%	4. 18%
0. 7	15. 13%	4. 86%	11. 57%	1. 92%	4. 51%	7. 06%

从验证结果可以看出，CAESES参数化模型计算结果趋势与试验数据一致，和标模计算结果的对比显示，尽管效率得到了提升，但不可忽视的是推力的显著下降。由此说明CAESES参数化建模所用的NACA 4DS切面形状和标模所采用的NACA 66(mod)切面形状的差异对于螺旋桨性能产生了很大的影响。

自定义叶切面翼型

切面拱度沿弦长分布

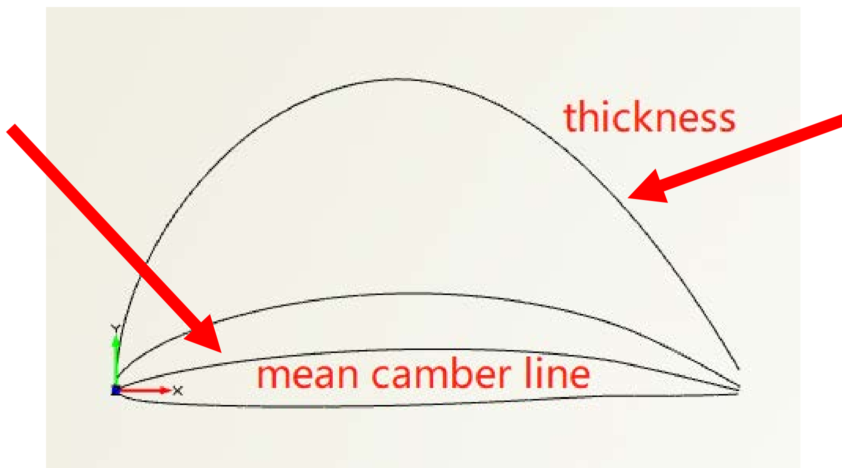
x_c (% c)	y_c (% c)
0	0
0.5	0.281
0.75	0.396
1.25	0.603
2.5	1.055
5.0	1.803
7.5	2.432
10	2.981
15	3.903
20	4.651
25	5.257
30	5.742
35	6.120
40	6.394
45	6.571
50	6.651
55	6.631
60	6.508
65	6.274
70	5.913
75	5.401
80	4.673
85	3.607
90	2.452
95	1.226
100	0

Feature参数化自定义叶切面

$$y_c = \begin{cases} m\dfrac{x}{p^2}\left(2p - \dfrac{x}{c}\right), & 0 \le x \le pc \\[2ex] m\dfrac{c-x}{(1-p)^2}\left(1 + \dfrac{x}{c} - 2p\right), & pc \le x \le c \end{cases}$$

General | Feature Definitions | Arguments | Create Function | Attributes

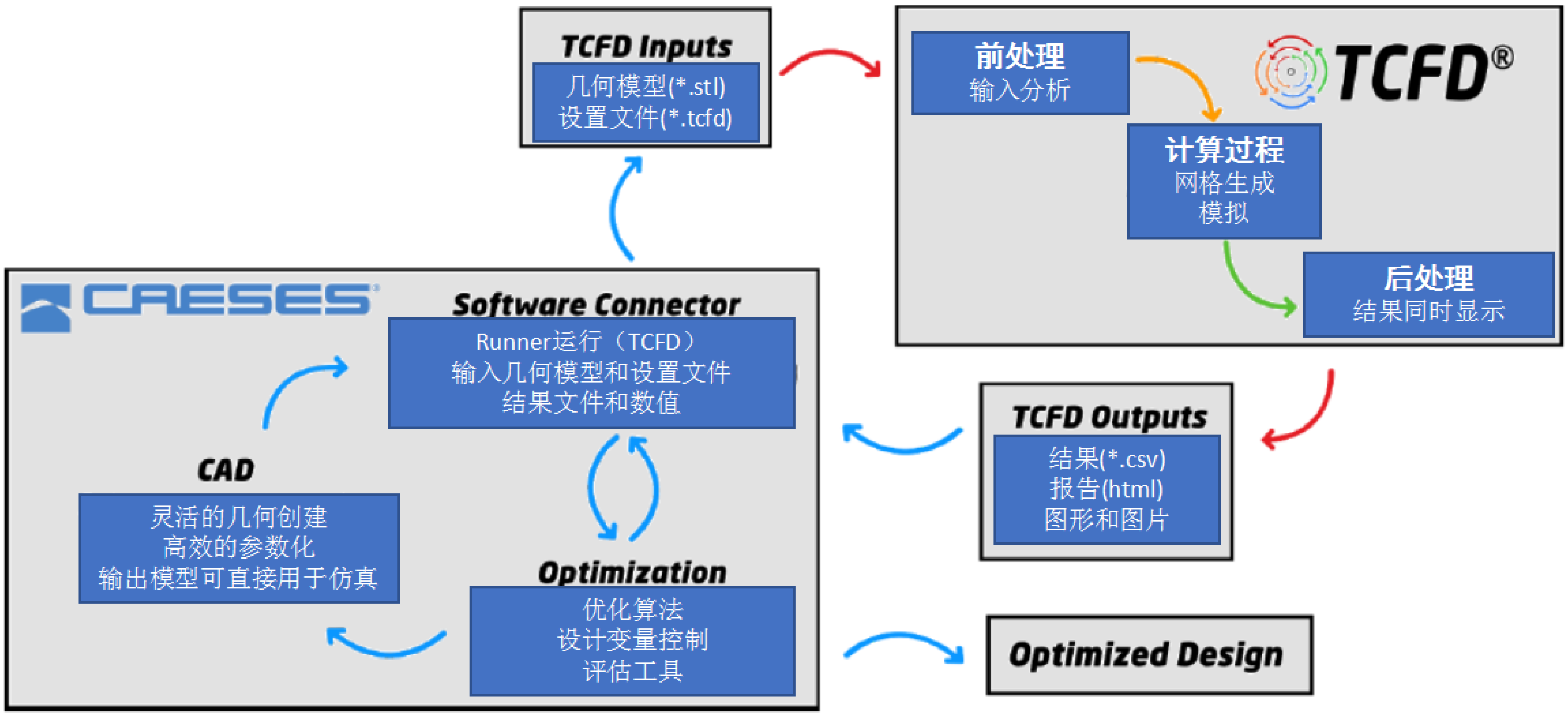
```
parameter tc(t*c)
parameter pc(p*c)

genericcurve mean()

mean.setX(t*c)
mean.sety( if( tc<=pc, m*tc/(p*p)*(2*p-tc/c), m*(c-tc)/(1-p)^2*(1+tc/c-2*p)) )

```



	x/c	NACA 16 y/t_{max}	NACA 66 (mod) y/t_{max}
LE	0	0	0
	0.005	–	0.0665
	0.0075	–	0.0812
	0.0125	0.1077	0.1044
	0.0250	0.1504	0.1466
	0.0500	0.2091	0.2066
	0.0750	0.2527	0.2525
	0.1000	0.2881	0.2907
	0.1500	0.3445	0.3521
	0.2000	0.3887	0.4000
	0.2500	–	0.4363
	0.3000	0.4514	0.4637
	0.3500	–	0.4832
	0.4000	0.4879	0.4952
	0.4500	–	0.5000
	0.5000	0.5000	0.4962
	0.5500	–	0.4846
	0.6000	0.4862	0.4653
	0.6500	–	0.4383
	0.7000	0.4391	0.4035
	0.7500	–	0.3612
	0.8000	0.3499	0.3110
	0.8500	–	0.2532
	0.9000	0.2098	0.1877
	0.9500	0.1179	0.1143
TE	1.0000	0.0100	0.0333

Section t_{max}/c	0.06	0.09	0.12	0.15	0.18	0.21	
LE radius/c (%)	0.176	0.396	0.703	1.100	1.584	2.156	$\rho_L = 0.448c\left(\frac{t_{max}}{c}\right)^2$

软件耦合

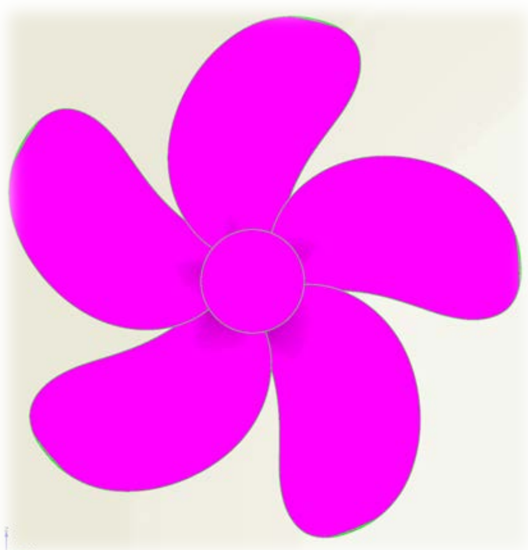

TCFD Inputs
几何模型(*.stl)
设置文件(*.tcfd)
TCFD®
前处理
输入分析
计算过程
网格生成
模拟
后处理
结果同时显示
CAESES
Software Connector
Runner运行（TCFD）
输入几何模型和设置文件
结果文件和数值
CAD
灵活的几何创建
高效的参数化
输出模型可直接用于仿真
Optimization
优化算法
设计变量控制
评估工具
TCFD Outputs
结果(*.csv)
报告(html)
图形和图片
Optimized Design

优化应用

优化目标：探索在不改变叶切面形状的情况下，是否存在螺旋桨特征参数的搭配组合可以弥补切面形状差异性所带来的性能损失。以0.7进速系数下的性能数据和试验数据绝对误差为优化目标。

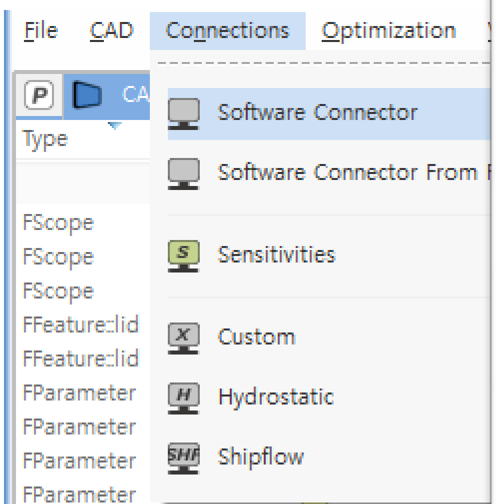
设计变量：桨叶侧斜角度，切面最大拱度位置

blade_Skew_factor



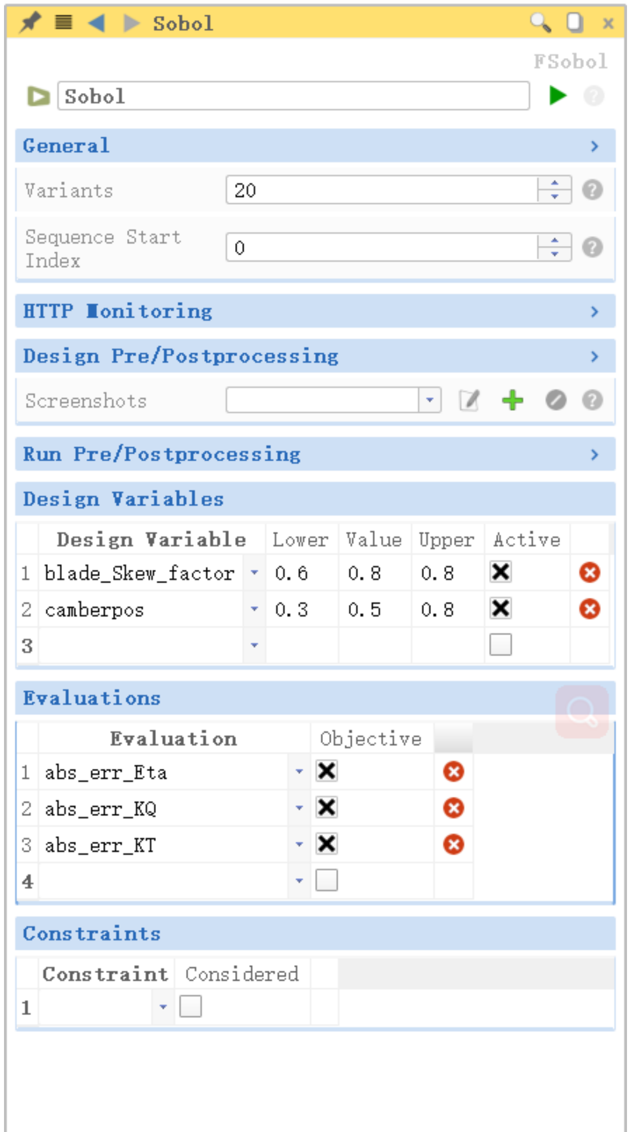
camberpos

链接设置



	Value	Type	
Eta	0.634875	FD…	
KT	0.15693	FD…	
KQ	0.0275383	FD…	

优化设置



Sobol
FSobol
Sobol
General
Variants 20
Sequence Start Index 0
HTTP Monitoring
Design Pre/Postprocessing
Screenshots
Run Pre/Postprocessing
Design Variables
Design Variable Lower Value Upper Active
1 blade_Skew_factor 0.6 0.8 0.8
2 camberpos 0.3 0.5 0.8
3
Evaluations
Evaluation Objective
1 abs_err_Eta
2 abs_err_KQ
3 abs_err_KT
4
Constraints
Constraint Considered
1

FParameter
abs_err_Eta
General
Value not evaluated
abs(eval_Eta - 0.665)
Design Variable
FParameter
abs_err_KQ
General
Value not evaluated
abs(eval_KQ - 0.0311)
Design Variable
FParameter
abs_err_KT
General
Value not evaluated
abs(eval_KT - 0.185)
Design Variable

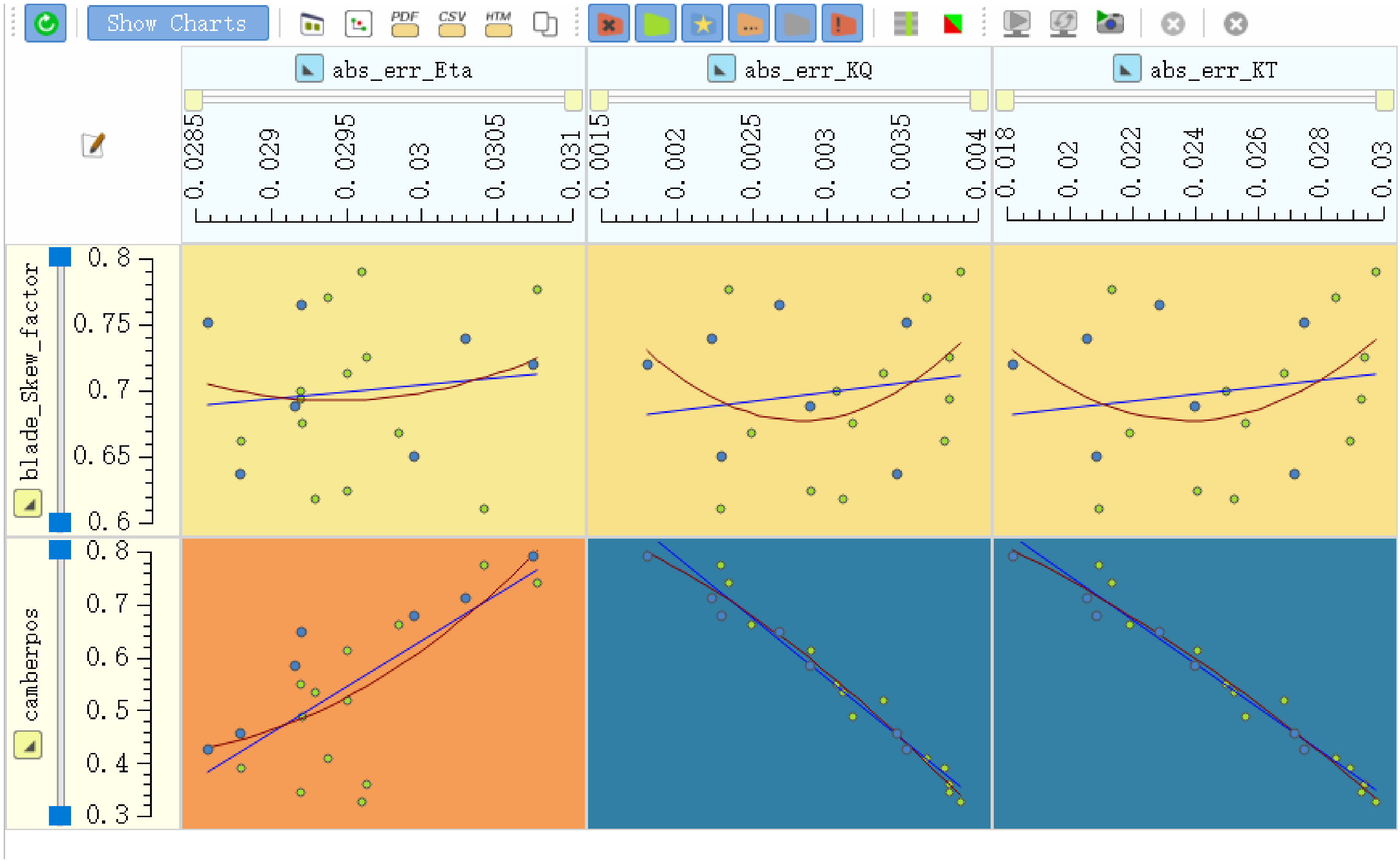
优化计算结果

Show Charts

	blade_Skew_factor	camberpos	abs_err_Eta	abs_err_KQ	abs_err_KT
Sobol_03_des0016	0.71875	0.784375	0.0307413	0.00182333	0.0183253
Sobol_03_des0008	0.7375	0.70625	0.0302968	0.00225197	0.0206505
Sobol_03_des0002	0.65	0.675	0.0299511	0.00231512	0.0209209
Sobol_03_des0014	0.6125	0.76875	0.0304128	0.00230404	0.0209771
Sobol_03_des0004	0.775	0.7375	0.0307612	0.00235696	0.0213685
Sobol_03_des0018	0.66875	0.659375	0.029849	0.00250422	0.0219726
Sobol_03_des0012	0.7625	0.64375	0.0292185	0.00269702	0.022911
Sobol_03_des0010	0.6875	0.58125	0.0291702	0.0028944	0.0240252
Sobol_03_des0006	0.625	0.6125	0.0295074	0.0028885	0.0240769
Sobol_03_des0000	0.7	0.55	0.0292064	0.00305987	0.0249787
Sobol_03_des0015	0.61875	0.534375	0.0293003	0.0031046	0.0252576
Sobol_03_des0003	0.675	0.4875	0.0292199	0.00316493	0.0255817
Sobol_03_des0013	0.7125	0.51875	0.0295129	0.00336911	0.0268197
Sobol_03_des0007	0.6375	0.45625	0.028816	0.00346398	0.0271881
Sobol_03_des0001	0.75	0.425	0.028605	0.00352322	0.0274741
Sobol_03_des0017	0.76875	0.409375	0.0293868	0.00365452	0.0284167
Sobol_03_des0011	0.6625	0.39375	0.0288151	0.003765	0.0289068
Sobol_03_des0019	0.69375	0.346875	0.0292034	0.0038037	0.0292229
Sobol_03_des0005	0.725	0.3625	0.029641	0.00380234	0.0293224
Sobol_03_des0009	0.7875	0.33125	0.0296033	0.00386961	0.0296968

	baseline	des0016	improve
Err_KT	15.13%	9.91%	5.22%
Err_KQ	11.57%	5.86%	5.71%
Err_Eta	4.51%	4.62%	-0.11%

优化计算结果


Show Charts
abs_err_Eta
abs_err_KQ
abs_err_KT
0.0285
0.029
0.0295
0.03
0.0305
0.031
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.018
0.02
0.022
0.024
0.026
0.028
0.03
blade_Skew_factor
0.8
0.75
0.7
0.65
0.6
camberpos
0.8
0.7
0.6
0.5
0.4
0.3

小结

- 通过KP505桨标模数值计算初步验证TCFD软件在螺旋桨敞水性能分析应用的可行性，同等计算条件下，与其他商业软件精度相当，在某几个进速系数下的仿真值更接近试验值。

- 自动化网格生成技术，模块化计算设置，计算报告自动生成等特点，使得工程师在网格划分方面的经验要求得以降低，计算设置出错复查变得更加方便直观，同时大幅缩减计算结果后处理的工作量。

- CAESES+TCFD的软件耦合使得工程师可以突破现有的知识储备的局限，通过CAESES批量自动化地生成变形方案，加上相应的优化算法，能够系统性地探索影响螺旋桨性能的设计参数，对突破原型设计具有一定的指导性作用。

Thanks

谢 谢

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