COPROPEL project: Composite propeller design considering fluid-structure interaction

E-Lass Seminar Day
LAS PALMAS - 03/05/2023

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Co-funded by the European Union

This project has received funding from Horizon Europe Grant agreement 101056911.
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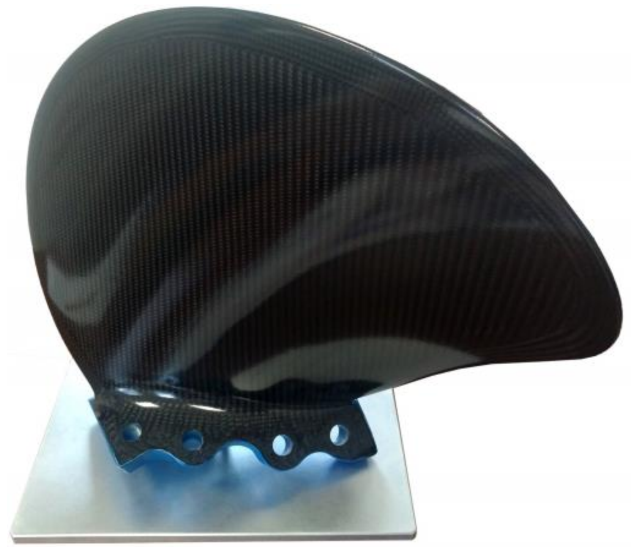
CoPropel Project - Background & motivation



FABHELI project (2016 – 2018)

Loiretech, Méca, Naval Group + BV, AML

Proved the potential of using composite materials for propellers

Manufacturing with the RTM process

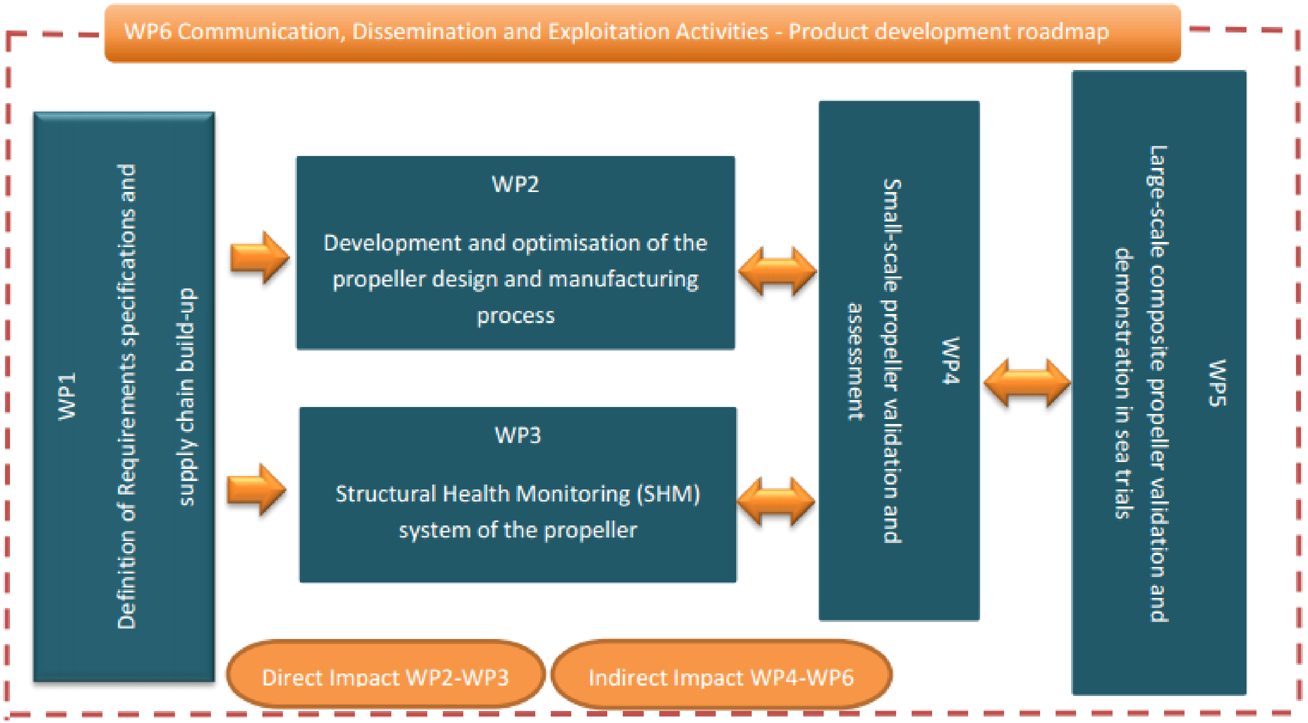
Validation in sea conditions

- **Low vibration** : High damping performance absorbs vibration and reduces underwater radiated noise (URN)
- **Lightweight**: 50-60% lighter than current solutions
- **High performance**: Lower energy consumption creating a reduced environmental footprint
- **High Strength**: Improved reliability due to greater fatigue resistance

CoPropel Project - Partners

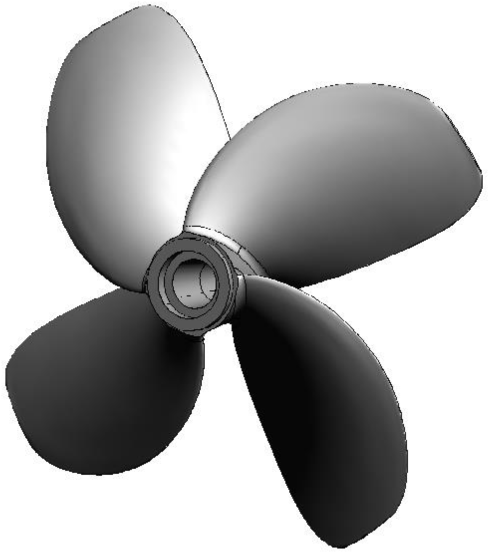
CoPropel Project - Objectives

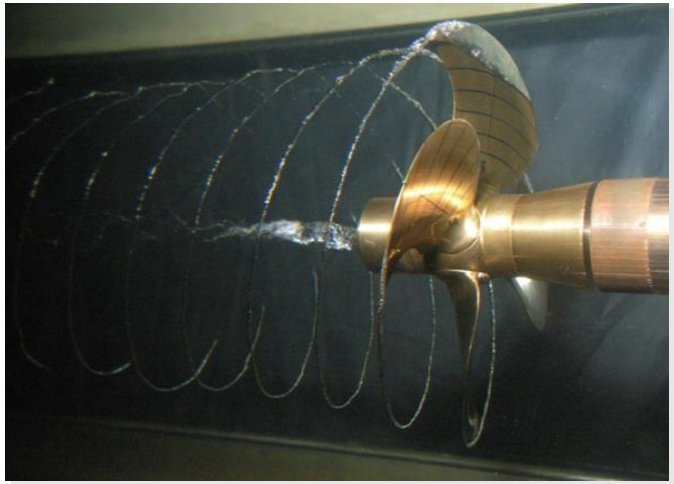
- **Design a composite propeller** to achieve optimum propulsive efficiency
- Optimize the **manufacturing process** based on closed mold resin infusion techniques
- Develop a **condition and structural health monitoring system** that will be embedded within the propeller
- Validation of the composite propeller with **small-scale and full-scale trials**
- Assist in the formulation of new **guidelines**
- **Communication and dissemination** of the project outcomes
- Define roll out strategy and develop a **business plan**

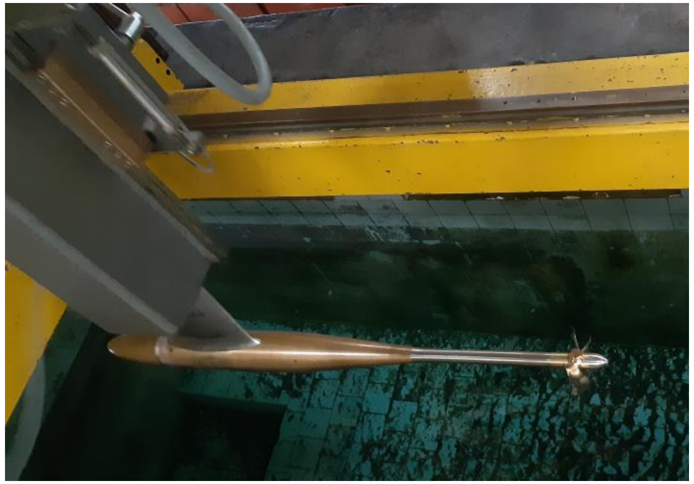


CoPropel Project – Madara vessel

MADARA propeller (Danube river pusher)	
Number of engines	2
Number of propellers	2 *(symmetrical)*
Number of blades	4
Diameter of the propellers	1 960 mm *(full-scale)* 250 mm *(small-scale tests)*





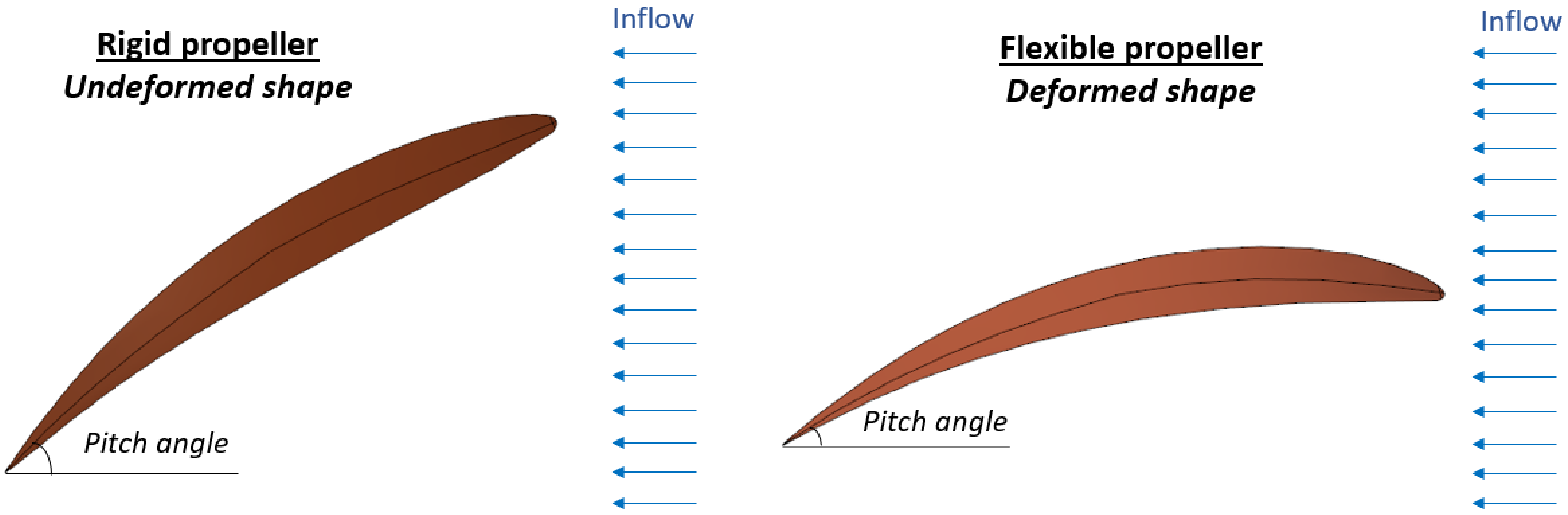


Flexibility of composite propeller

Metallic propeller *(rigid)* : optimal for one operating condition

Composite propeller *(flexible)* : orientation of the blade profile adapts with the changing flow, increased efficiency over a range of operating conditions

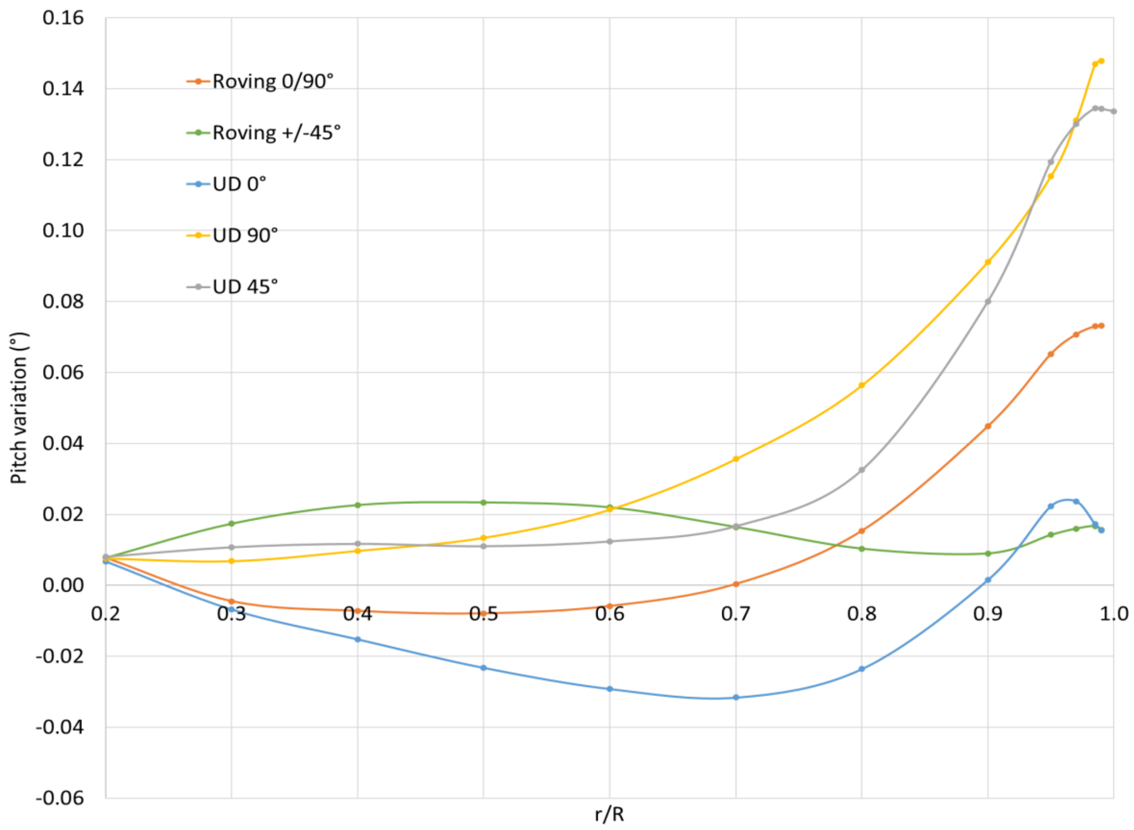
Technology based on **bend-twist coupling** characteristic of composites
Anisotropy of the propeller created by the **optimization of the stacking angles** for expected loads
Difference of deflection between the trailing edge and the leading edge, the **pitch changes with loading**

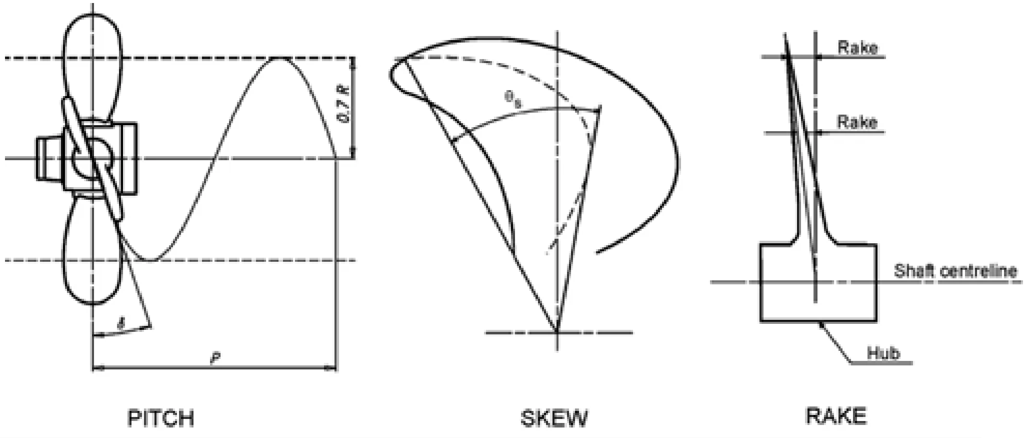


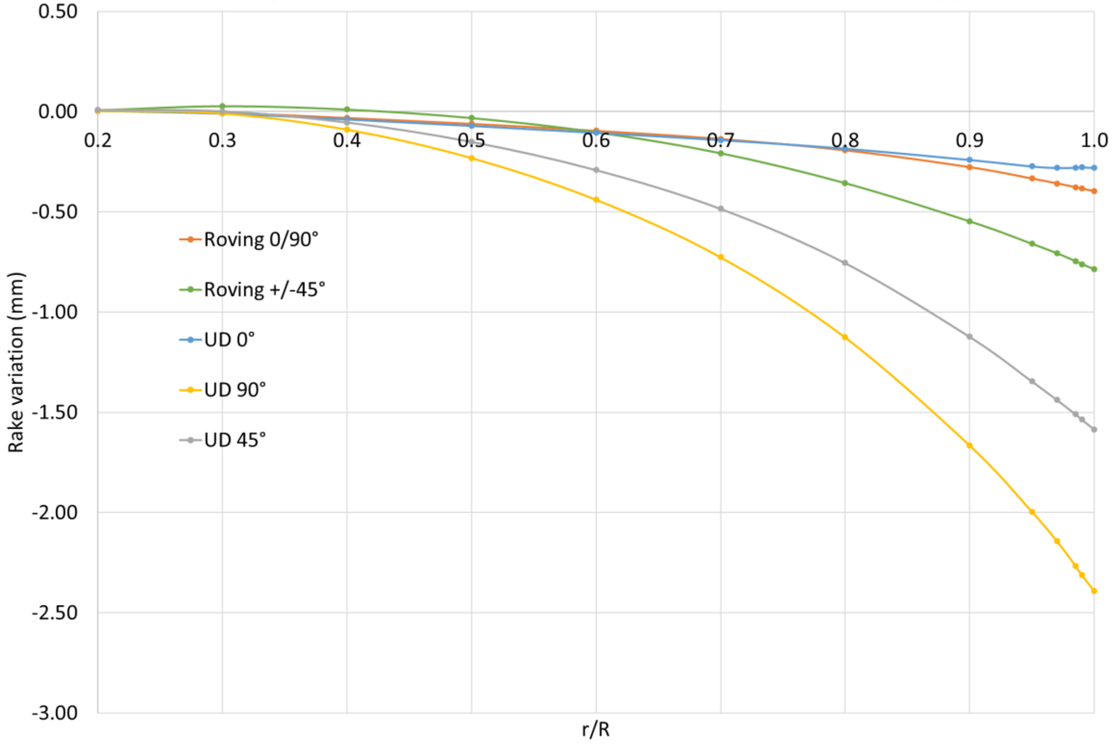
Flexibility of composite propeller

Example – Influence of fiber orientation on a 3D homogeneous model of the small-scale Madara blade

Carbon fiber / epoxy resin
0° direction = reference line of the blade





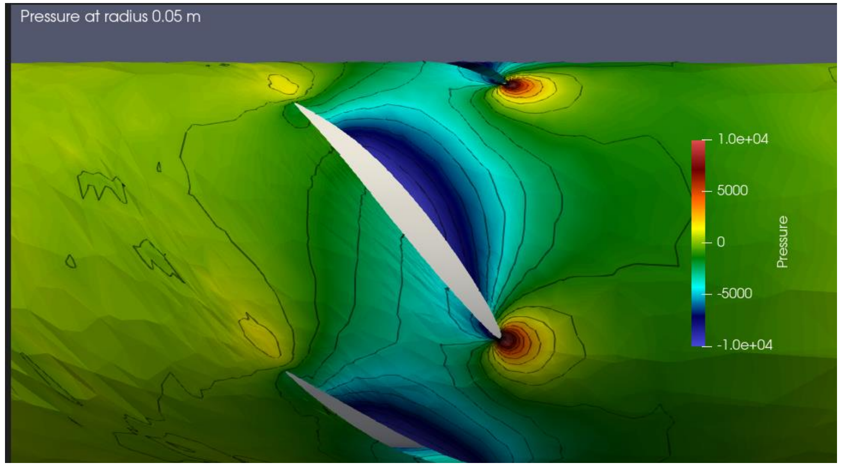


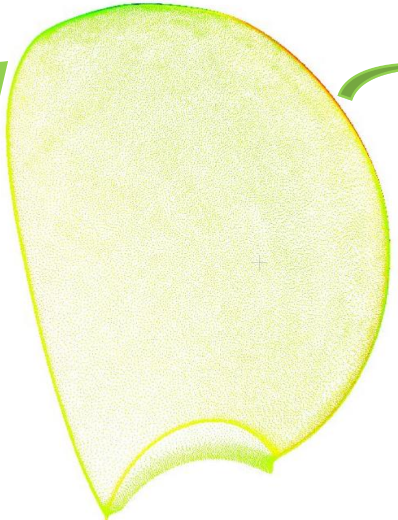
Fluid Structure Interaction – Two-Way Coupling Optimization Oriented

Deformation of composite propeller under fluid loads influences the hydrodynamic performance

Need to develop representative structural and hydrodynamic models for design, that allow the transfer of data

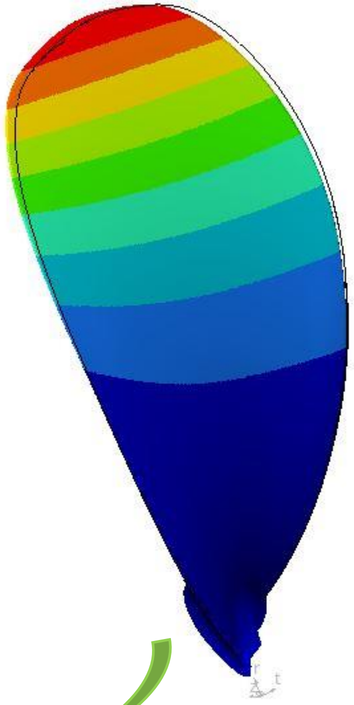
CFD calculation

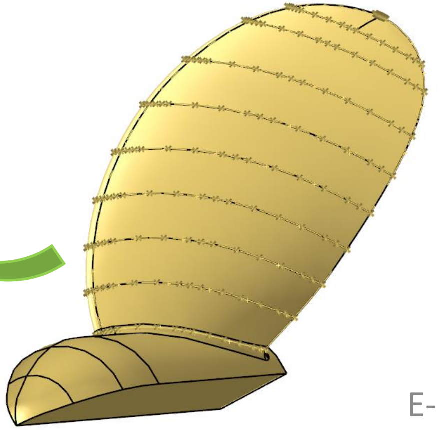




Pressure field

FEM calculation



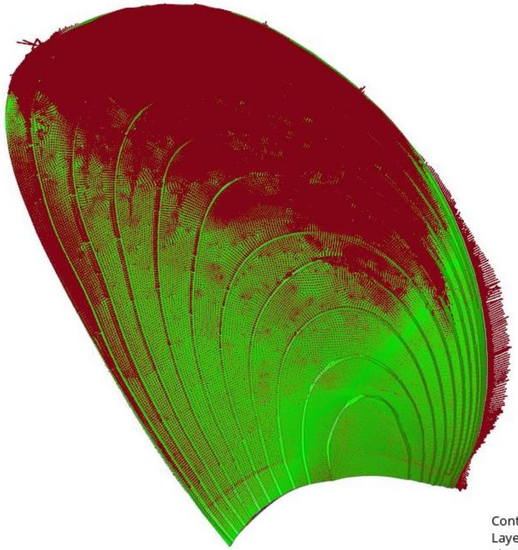


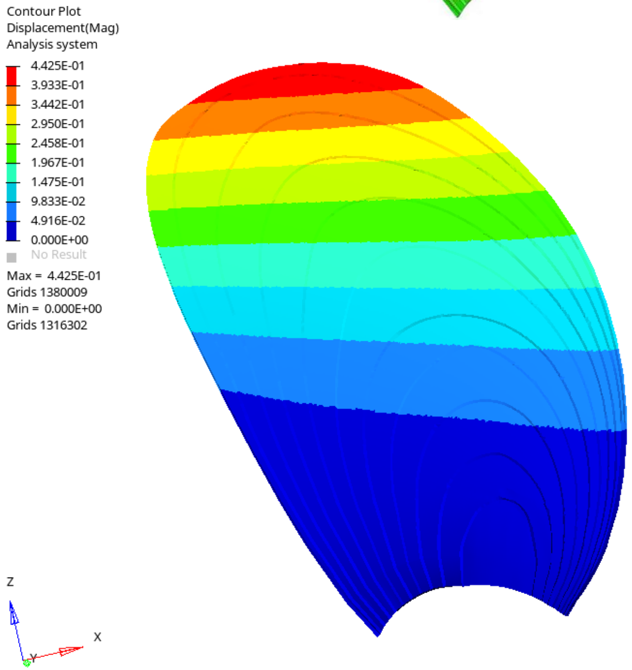
Deformed shape

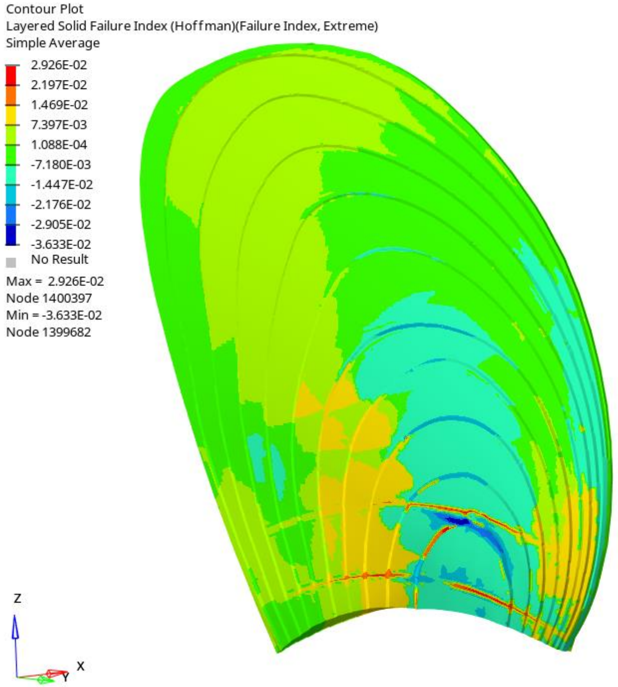
r/R	r	Pitch	C	C_LE	P_angle	tmax	RAKE
-	mm	mm	mm	mm	deg	mm	mm
0.20	199.00	1145.00	524.10	321.90	42.48	71.50	20.00
0.30	298.50	1231.00	595.30	364.70	33.28	64.20	30.00
0.40	398.00	1300.00	648.60	390.20	27.47	55.80	40.00
0.50	497.50	1346.00	681.50	399.00	23.30	47.50	50.00
0.60	597.00	1376.00	692.70	388.50	20.14	39.20	60.00
0.70	696.50	1379.00	681.50	356.10	17.49	30.90	70.00
0.80	796.00	1365.00	623.50	288.50	15.27	22.20	80.00
0.90	895.50	1329.00	510.40	181.50	13.29	13.80	90.00
0.95	945.25	1302.00	411.90	104.10	12.36	10.10	95.00
0.97	965.15	1290.00	349.00	59.20	12.01	8.50	97.00
0.985	980.08	1285.00	256.00	15.00	11.82	7.40	98.50

Fluid Structure Interaction - FEM model

- Thickness discretization, ply drop-off
- Blade deformation control
- Multi-layers approach
- Ply-by-ply stresses, strain evaluation
- Verification of criteria with BV rules
- Parametrized model for optimization
- Integration of SHM system, assembly to the hub, manufacturing limitations
- Frequency calculation in water
- Validation with small-scale and full-scale testing

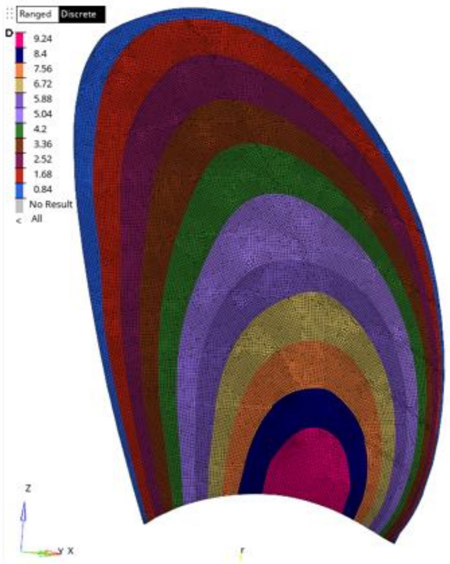


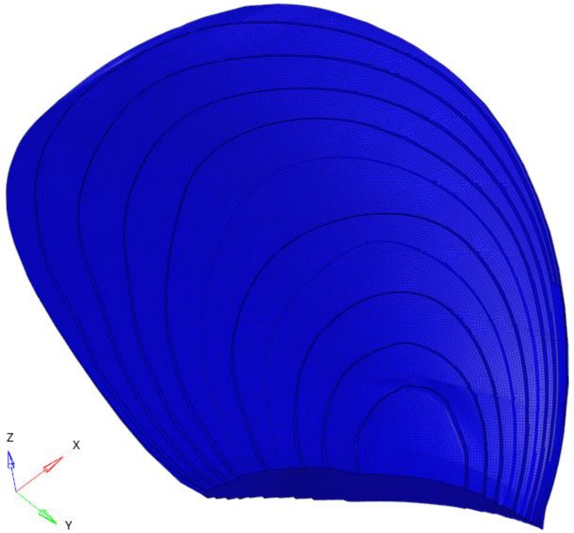


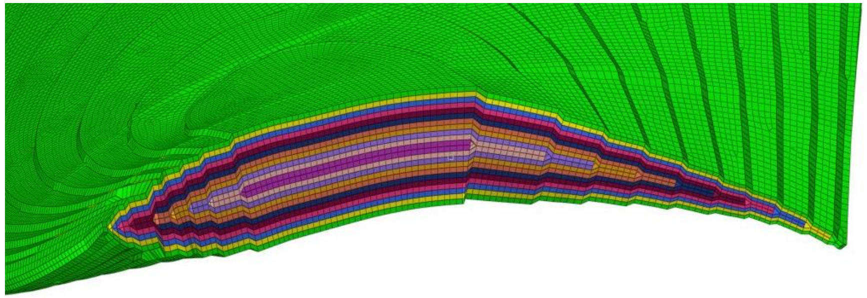


Fluid Structure Interaction - FEM model

Benchmark of element types



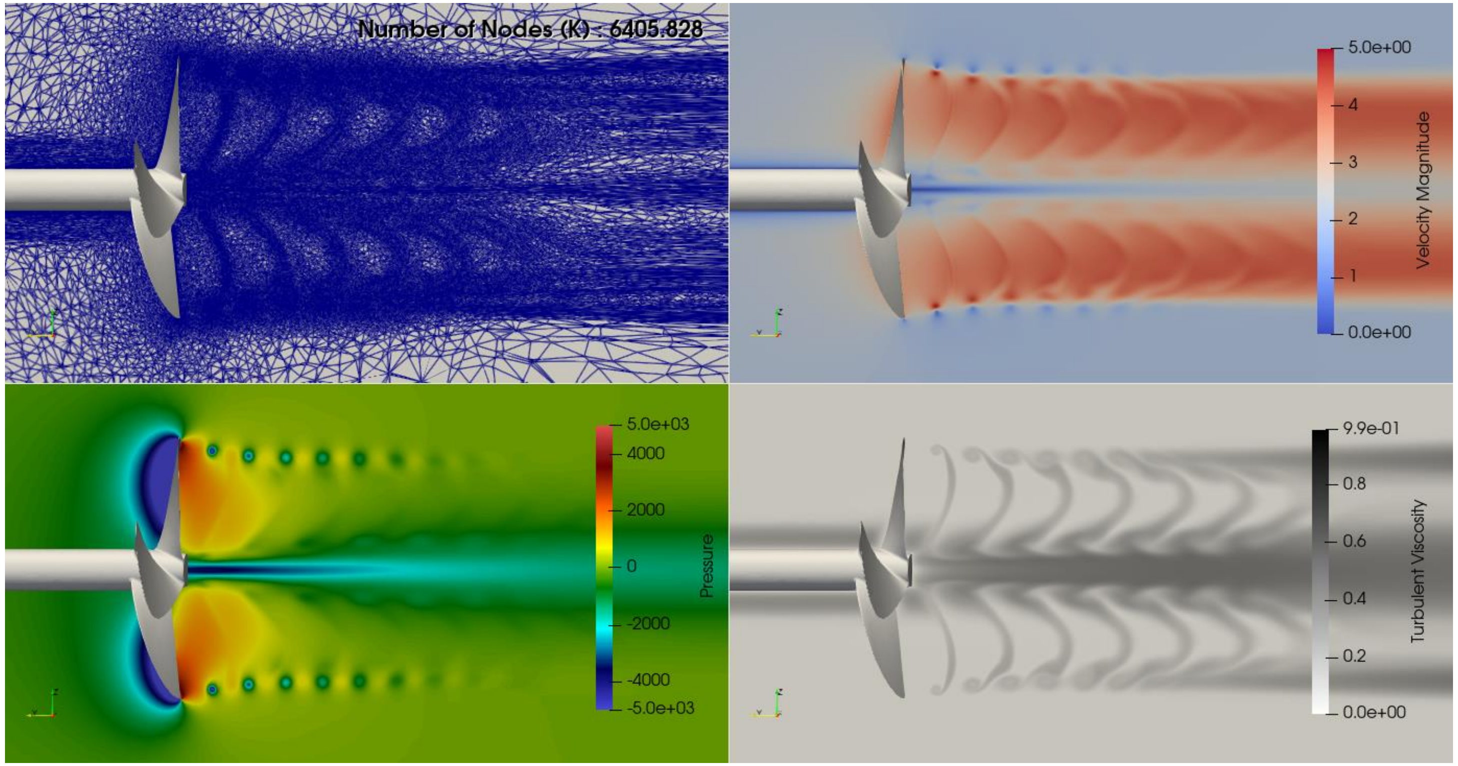


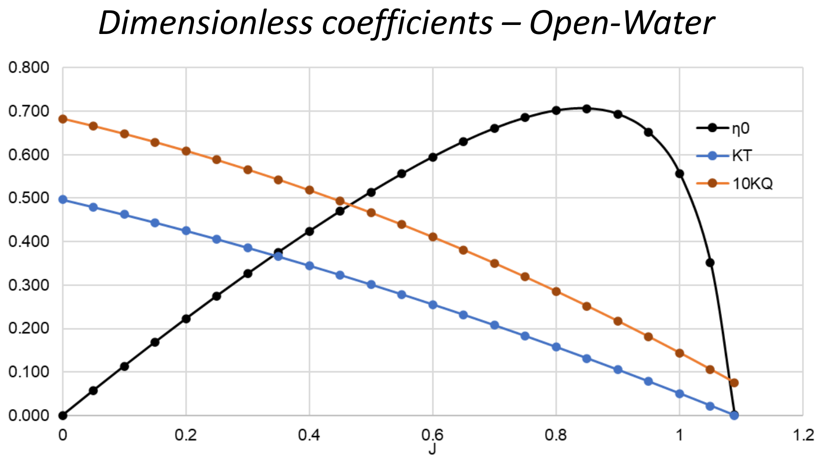


Model type	2D multilayer shell	3D Solid with homogeneous properties	3D Solid Laminate 1EL in thickness	3D Solid Laminate >1EL in thickness
Reliability of the results (FE formulation)	- -	-	+	+
Time to develop model and meshing	+ +	+	-	-
Load application – data transfer with CFD	-	+	+	+
Calculation time	+ +	+	-	- -
Material orientation	+	-	-	-
Modification of the stacking sequence	++	-	+	-
Failure criterion, type of outputs	+	- -	+	+
Visual validation	++	-	+	++

Fluid Structure Interaction - CFD model

- Performance evaluation
- Load pressure distribution
- Computation of thrust, torque and efficiency
- Adaptive meshing software, convergence study
- Influence of the hull
- Validation with experiments and other calculation methods





- Advance ratio: $J = V_a/(nD_p)$
- Thrust coefficient: $K_T = T/(\rho n^2 {D_p}^4)$
- Torque coefficient: $K_Q = Q/(\rho n^2 {D_p}^5)$
- Efficiency : $\eta_0 = JK_T/(2\pi K_Q)$

ComPropApp – Hydro-Structure coupling

ComPropApp, a Fluid-Structure Interaction tool for flexible propeller

- Developed within Comprop & Comprop2 and ORCA projects
- Cooperative Research Ship (CRS), organisation led by MARIN

Coupling of:

- Fluid model: Boundary Element Method (BEM)
  - ➔ Procal
  - Inviscid/Isovolume/Irrotational fluid flow
- Structural model: Finite Element Model (FEM)
  - ➔ Trident/VAST solvers
  - Homogenized anisotropic materials properties

Validation of ComPropApp: 4 methods investigated

1	2	3	4
BEM-FEM One-way	**BEM-FEM** One-way	**RANS-FEM** One-way	**RANS-FEM** Two-way
• ComPropApp	• Procal • FEMAP & Nastran	• StarCCM+ • FEMAP & Nastran	• StarCCM+ • FEMAP & Nastran

Application case: FabHeli Propeller[1]

- Diameter: 1.10 m
- Number of blades: 5
- Materials: Carbon fibres
- Process: RTM (Resin Transfer Molding)
- Connection to the hub: Bolted

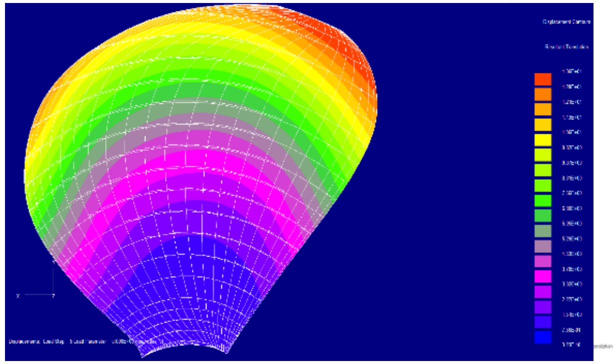
[1] ***FabHeli: French research project (2017-2020)***
DGA (French Department of Defense), LoireTech, Meca, Naval Group, AML, BV

Comparison of results

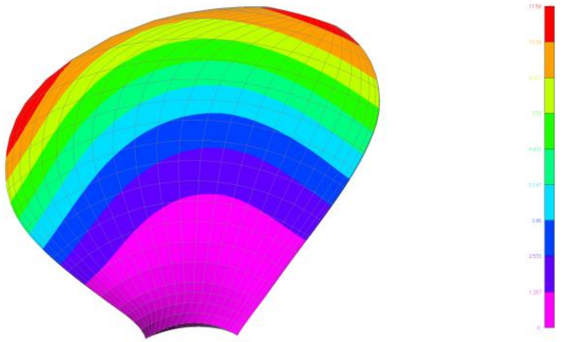
1	2	3	4
BEM-FEM One-way	**BEM-FEM** One-way	**RANS-FEM** One-way	**RANS-FEM** Two-way
• ComPropApp	• Procal • FEMAP & Nastran	• StarCCM+ • FEMAP & Nastran	• StarCCM+ • FEMAP & Nastran

Thrust	**0%**	**1.08%**	**-0.44%**
Torque	0%	-0.91%	-2.07%
Max. displ.	-14.85%	-4.93%	-6.32%

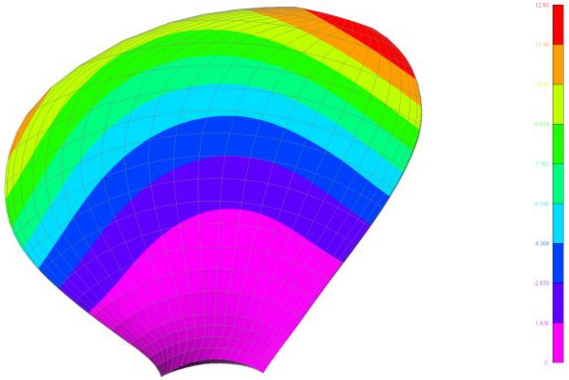
Difference with Method 1 - ComPropApp



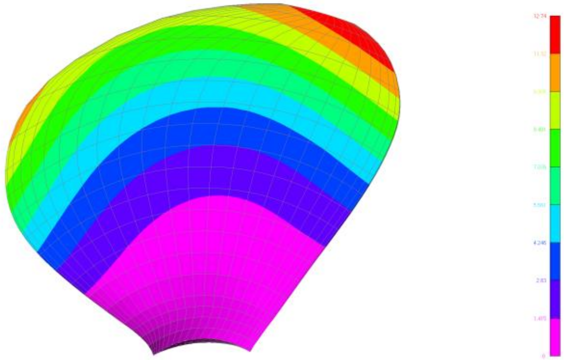
Method 1: max displacement 13.6 mm



Method 2: max displacement 11.58mm



Method 3: max displacement 12.93 mm



Method 4: max displacement 12.74 mm

Paboeuf et al, *Validation of a Fluid Structure Interaction Tool for Flexible Propeller in Composite Materials*, Proceedings of the PRADS 2022 Conference, Dubrovnik, Croatia, October 2022.

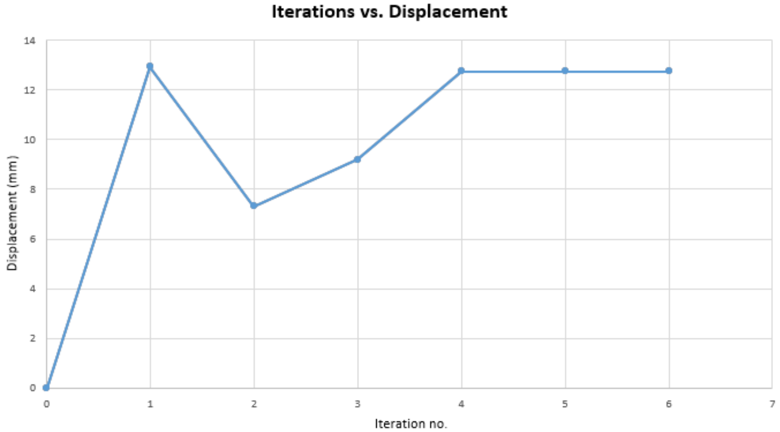
ComPropApp – Hydro-Structure coupling

1	2	3	4
BEM-FEM One-way	**BEM-FEM** One-way	**RANS-FEM** One-way	**RANS-FEM** Two-way
• ComPropApp	• Procal • FEMAP & Nastran	• StarCCM+ • FEMAP & Nastran	• StarCCM+ • FEMAP & Nastran

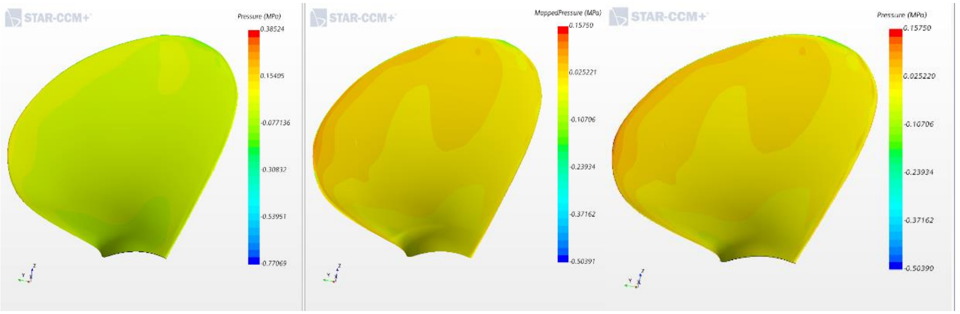
Analysis of results

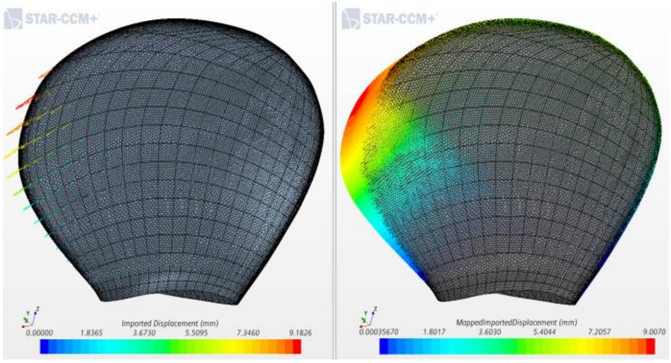
Method 4 – RANS-FEM Two-way

- **Pressure and displacement field mapping**
    - StarCCM+ to FEMAP **AND** FEMAP to StarCCM+
    - Fine to coarse mesh **AND** coarse to fine mesh



- **Pressure loss at leading edge ➔ No significant effect**





- **Displacement field mapping ➔ Small percentage of discrepancy**

NI663 Propeller in Composite Materials

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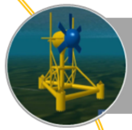


Sabella D10 (2011-2015)
- Fatigue approach
- NI603 Current and Tidal Turbine

COMPROP1 & 2 (2014-2020)
- Cavitation erosion
- Fluid-structure interaction tool

ViComTe (2015-2018)
- Ageing and Fatigue of Tidal Turbine Blade
- Blade hub connections

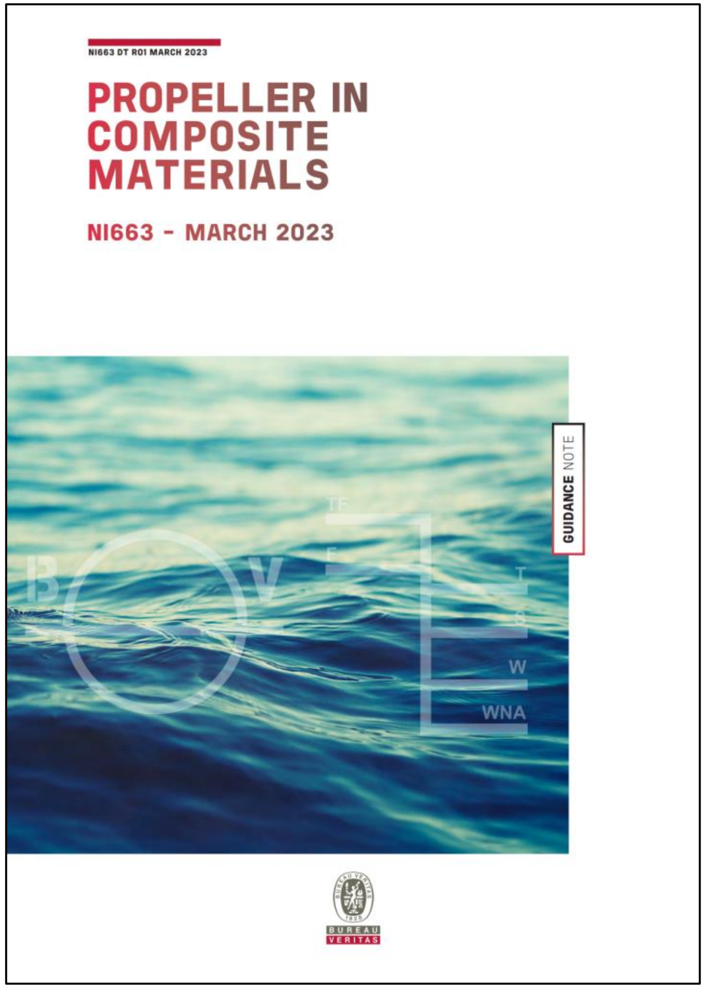
FabHeli (2016-2018)
- Design, construction and test (D=1.1m)
- Develoment of design assessment methodology

REALTIDE (2018-2021)
- StarBlades (BEMT tool)
- Methodology for the fatigue assessment

MEVEF (2018-2021)
- Fatigue and ageing coupling assessment for composite materials blades

ORCA (2021-2023)
- Design of large propeller
- Validation tool

EcoProp (2021-2024)
- Blade design review, Fatigue
- Construction and testing of composite propeller



BV Guidance Note for propellers made in Composite Materials covering:

- Process of certification
  - Design Phase
  - Production Phase
- Design assessment
  - Analytical
  - Numerical
- Testing
  - Coupons
  - Prototype
- Manufacturing
- In-service surveys
  - Periodic survey
  - NDT

Conclusion

- ***Use of composite propellers and optimization of the stacking sequence to improve efficiency***
- ***Design of shape adaptative structure involving two-way fluid-structure interaction (FEM - CFD)***
- ***Development of accurate and efficient structural and hydrodynamical models***
- ***Alternative numerical method for hydro-structure coupling with ComPropApp***
- ***Roadmap for the certification of composite propellers and improvements of NI663***

Thank you for your attention!

Any questions?

>> **Contact:**
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Composite propeller design

General assumptions - Material properties

The mechanical characteristics of raw materials (fiber and resin) are taken from BV NR546 for certification purpose, according to NI663.

		BV Carbon HS	*Toray T300*
Density	kg/m³	1880	*1760*
Tensile modulus	MPa	238000	*230000*
Axial Poisson ratio	-	0.3	/
Transverse Young modulus	MPa	15000	/
Transverse Poisson ratio	-	0.02	/
Shear modulus	MPa	50000	/
Tensile strength	MPa	3600	*3530*
Compressive strength	MPa	2140	/
Shear strength	MPa	1200	/

		BV Epoxy	*Sicomin SR8100*
Density	kg/m³	1250	*1158*
Glass Transition Temperature	°C	80 - 150	*63 - 88*
Tensile modulus	MPa	3100	*2800 - 3200*
Poisson ratio	-	0.39	/
Shear modulus	MPa	1500	/
Tensile strength	MPa	75	*50 - 71*
Compressive strength	MPa	75	/
Shear strength	MPa	80	*41 - 47*

Material properties are to be considered layer by layer according to NR546 requirements. The fiber volume fraction is considered to be 40% (LRT).

		Unidirectional	Twill 2-2
Fiber mass fraction	-	49.3%	49.3%
Volume fiber fraction	-	40.0%	40.0%
Density	kg/m³	1454	1454
Thickness for 100g/m²	g/m²	0.140	0.140
Stiffness			
Young Modulus X	MPa	97118	51087
Young Modulus Y	MPa	4734	51087
Young Modulus Z	MPa	4734	4734
Shear Modulus XY	MPa	2984	2984
Shear Modulus XZ	MPa	2984	2686
Shear Modulus YZ	MPa	2089	2686
Poisson Ratio XY	-	0.280	0.026
Poisson Ratio XZ	-	0.280	0.235
Poisson Ratio YZ	-	0.190	0.235
Strength			
Tensile strength X	MPa	1165	511
Compressive strength X	MPa	971	511
Tensile strength Y	MPa	40	434
Compressive strength Y	MPa	109	434
Tensile strength Z	MPa	40	434
Compressive strength Z	MPa	109	434
Shear strength XY	MPa	48	46
Shear strength XZ	MPa	48	42
Shear strength YZ	MPa	40	42

NI663: Mechanical tests will be performed on test panels representative of the scantling and the manufacturing process used for the propeller manufacturing, and compared with theoretical properties.

Composite propeller design

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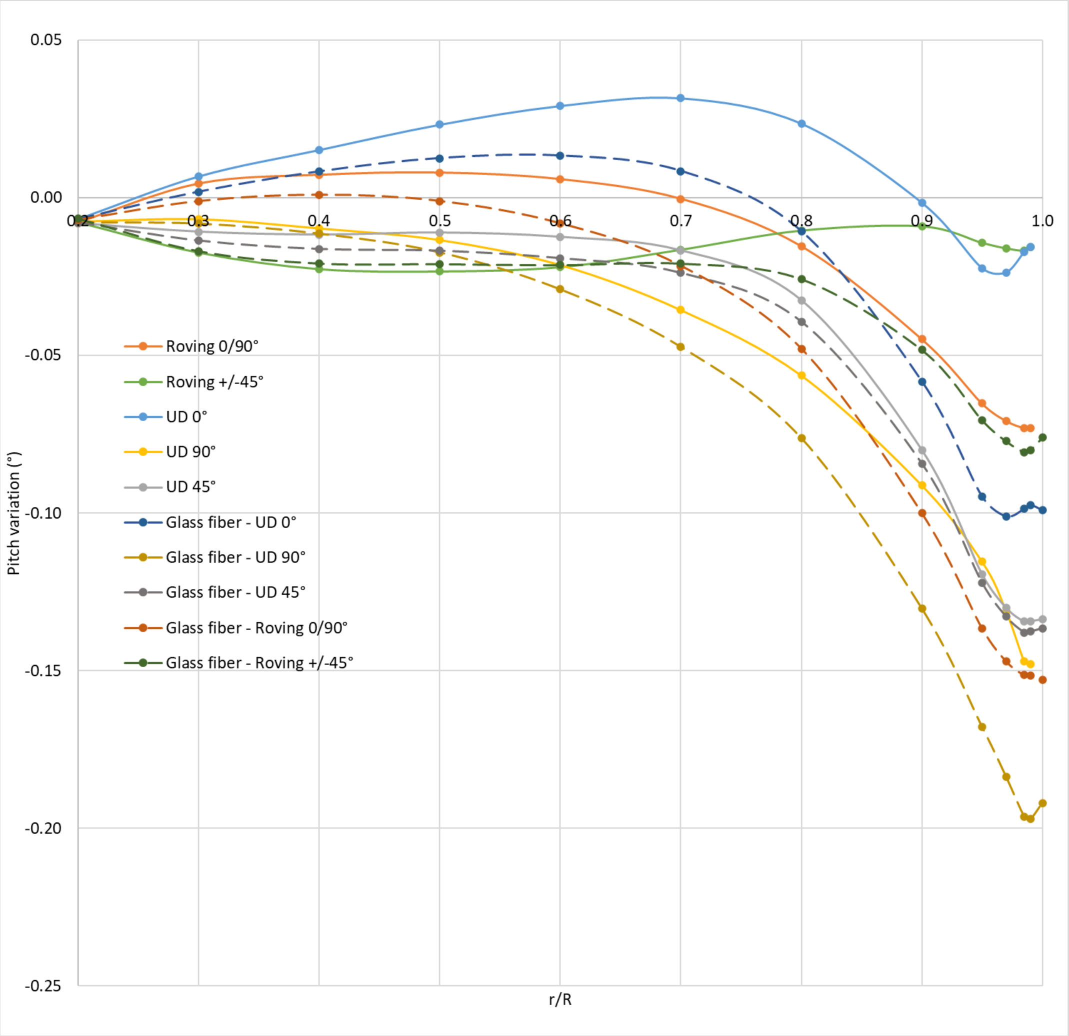
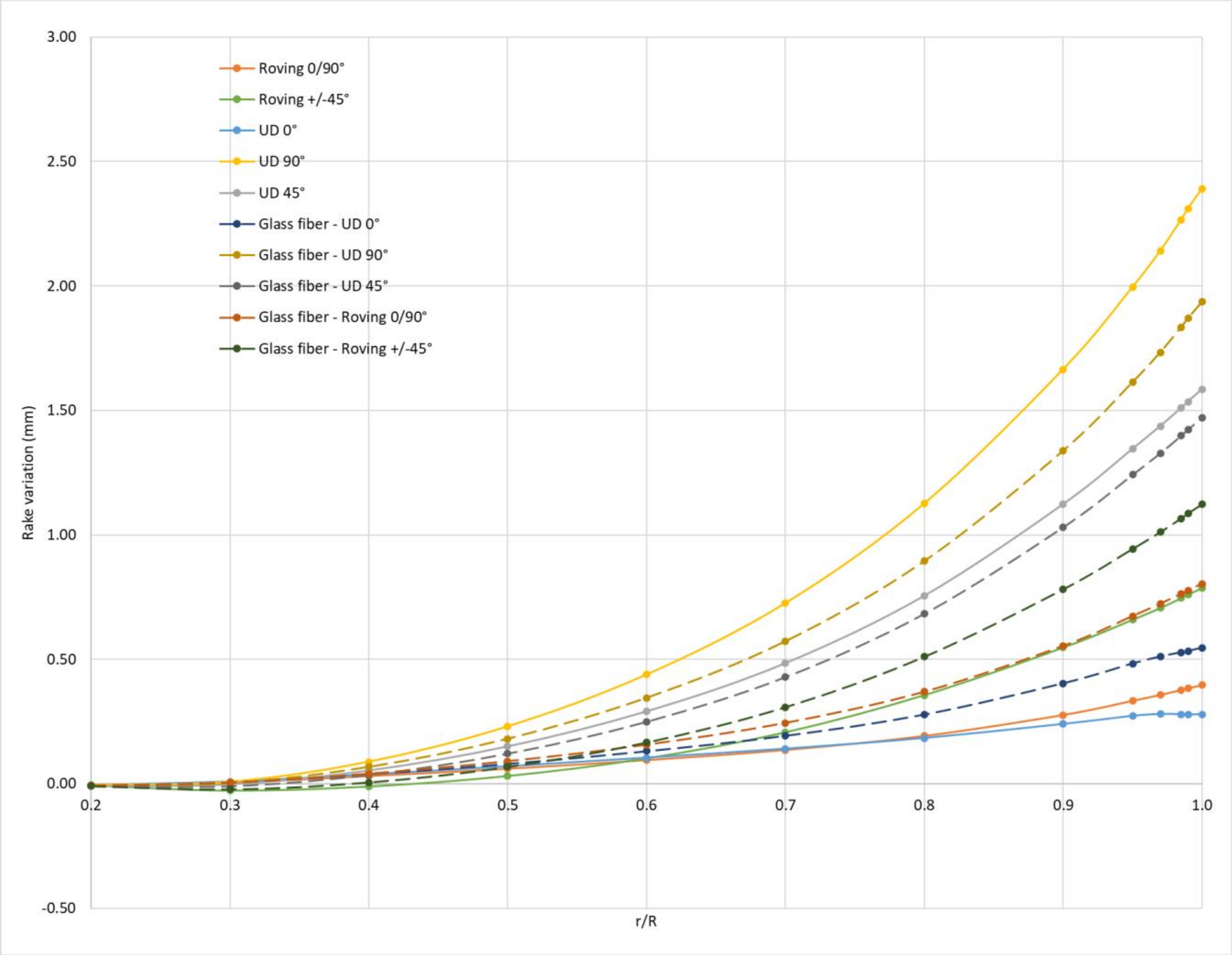
Comparison of deformed shape obtained with carbon and glass fibers





ComPropApp – Hydro-Structure coupling

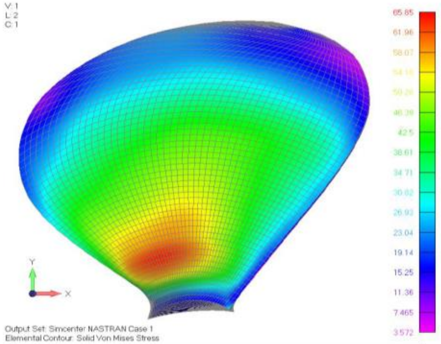
Analysis of results

Isotropic materials

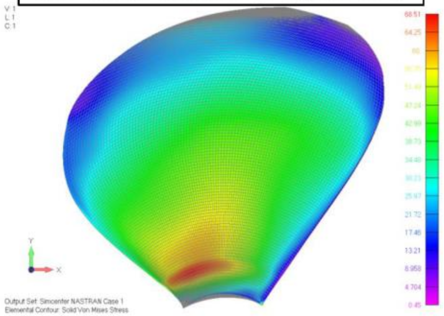
ISOTROPIC STEEL BLADE CASE

1. BEM-FEM one-way coupled FSI Analysis (PROCAL &FEMAP)
2. RANSE-FEM one-way coupled FSI Analysis (STAR-CCM+&FEMAP)
3. BEM-FEM explicit two-way coupled FSI Analysis (ComPropApp)
4. RANSE-FEM strong two-way coupled FSI Analysis (STAR-CCM+)

	CASE 1	CASE 2	CASE 3	CASE 4	Relative Difference: CASE 1 & CASE 2	Relative Difference: CASE 3 & CASE 4
Thrust (N)	50,720	49,195	50,160	49,420	3.10%	1.5%
Torque (N.m)	10,673	10,220	10,372	10,280	4.43%	0.90%
Max. displacement (mm)	1.789	1.798	1.7	1.875	-0.5%	-9.33%
Max. Von Mises stress (MPa)	65.85	68.51	65.7	66.5	-3.88%	-1.2%



CASE 1: Max. Von Mises stress (65.85 MPa)



CASE : Max. Von Mises stress (68.51 MPa)

Rehman W. et al, *A comparison of different fluid-structure interaction analysis techniques for the marine propeller*, Proceedings of the ASME 2021 Power Conference, Online, July 2021.

ComPropApp – Hydro-Structure coupling

Analysis of results

	Pre-processing	Computation	Post-processing	Total Time	Processor	Number of cores	RAM
1 **BEM-FEM** One-way • ComPropApp	4 hours	30 mins	10 mins	≈5 hours	Intel i7	4 cores	16 GB
4 **RANS-FEM** Two-way • StarCCM+ • FEMAP & Nastran	5 days	6 hours	10 hours	≈7 days	Linux cluster	112 cores	60 GB