CFD Simulation of Propeller Performance using Compressible and Incompressible Flow Solvers

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Introduction

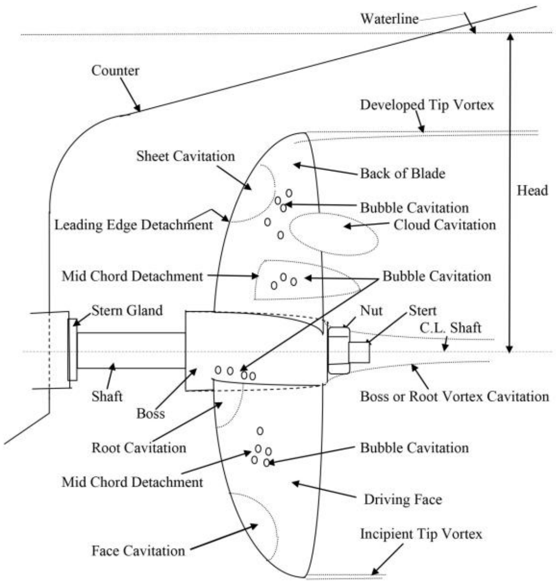
Background – Cavitation

- Cavitation inception occurs when liquid transitions into vapour due to the local reduction in pressure.
- For cavitation inception, the inception pressure is assumed to be equal to the vapour pressure.
- Incompressible solvers are widely used, however, compressible solvers that incorporate energy equation and temperature during computations provide credible results.
- Compressibility effects have advantages in describing the cavity dynamics.

Introduction

Background – Propeller Cavitation

- Study of cavitation is important in marine propellers since it has effects such as reduced propeller thrust, propeller erosion, vibration and propagated noise.



Types of propeller Cavitations

Erosion Damage (Pfitsch W. et al., 2009

Introduction

Objectives

1. 2D Cavitation Validation(modified NACA66 hydrofoil)
2. 3D Cavitation Using Incompressible and Compressible Flow Solvers
3. Comparison of Compressible and Incompressible Flow Solvers

Computational Method

Governing Equations

- $\nabla \cdot U = 0$

Continuity equation corrected with source term, $\dot{m}$ is interphase mass transfer

- $\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p + \nabla \cdot \tau + S$

Momentum Equation

- $\frac{\partial(\rho e)}{\partial t} + \nabla \cdot (\rho U e) + \frac{\partial(\rho K)}{\partial t} + \nabla \cdot (\rho U K) = \nabla \cdot \mathrm{q} - \nabla \cdot (p U)$ *Energy Equation*

- $\frac{\partial \alpha}{\partial t} + \nabla \cdot (U \alpha) = \frac{\dot{m}}{\rho_l}$

Transport equation for fraction of the liquid phase corrected based on ***Schnerr Sauer cavitation model***

- Modelling of the interphase mass transfer rate($\dot{m}$) is done by cavitation models.

Cavitation Model

- Schnner Sauer Cavitation Model is used to model the $\dot{m}$ which is the interphase mass transfer

$$\dot{m} = \begin{cases} C_C \frac{\rho_v \rho_l}{\rho} \alpha(1 - \alpha) \frac{3}{R_B} \sqrt{\frac{2}{3} \frac{p - p_{sat}}{\rho_l}}, & p > p_{sat} \\ - C_V \frac{\rho_v \rho_l}{\rho} \alpha(1 - \alpha) \frac{3}{R_B} \sqrt{\frac{2}{3} \frac{p - p_{sat}}{\rho_l}}, & p < p_{sat} \end{cases}$$

Where

$$R_B = \sqrt[3]{\frac{3(1 + \alpha_{Nuc} - \alpha)}{4\pi n_0 \alpha}}$$

$$\alpha_{Nuc} = \frac{V_{Nuc}}{1 + V_{Nuc}} \text{ and } V_{Nuc} = \frac{\pi n_0 d_{Nuc}^3}{6}$$

Constants used were

$$n_0 = 1.6 \times 10^{14}$$

$$d_{Nuc} = 2.0 \times 10^{-8}$$

Model Description

Test Conditions for 2D Hydrofoil Cavitation

w/ Cavitation

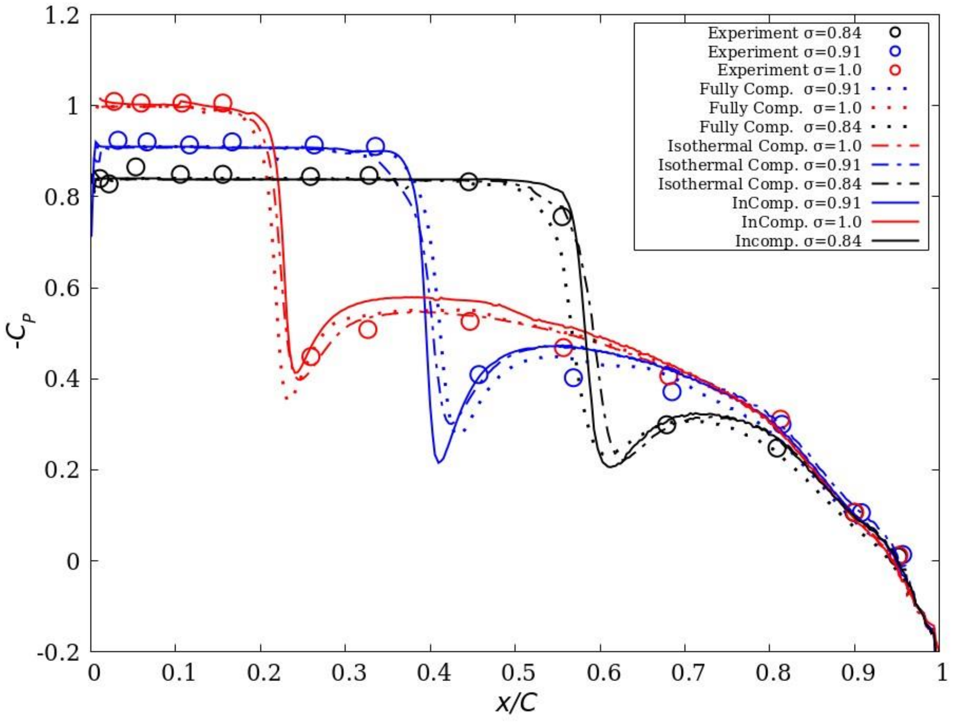
- Fully - Compressible flow solver
- Isothermal Compressible Solver
- Incompressible flow solver

Parameter	Value
Cavitation Number (σ)	1.0/ 0.91/0.84
Vapour Pressure (P_v)	2420
Reynold Number	2 x 10^6

No. of Cells	167,271
Solvers	Incompressible flow solver (interPhaseChangeFoam)/ Fully-Compressible flow solver (compressibleInterFoam) Isothermal-Compressible flow solver (compressibleInterFoam)
Time Scheme	CrankNicolson 0.5/Euler
Gradient Scheme	Gauss Linear
Divergence Scheme	Gauss vanLeer
Turbulence Model	kOmegaSST

Results and Discussion

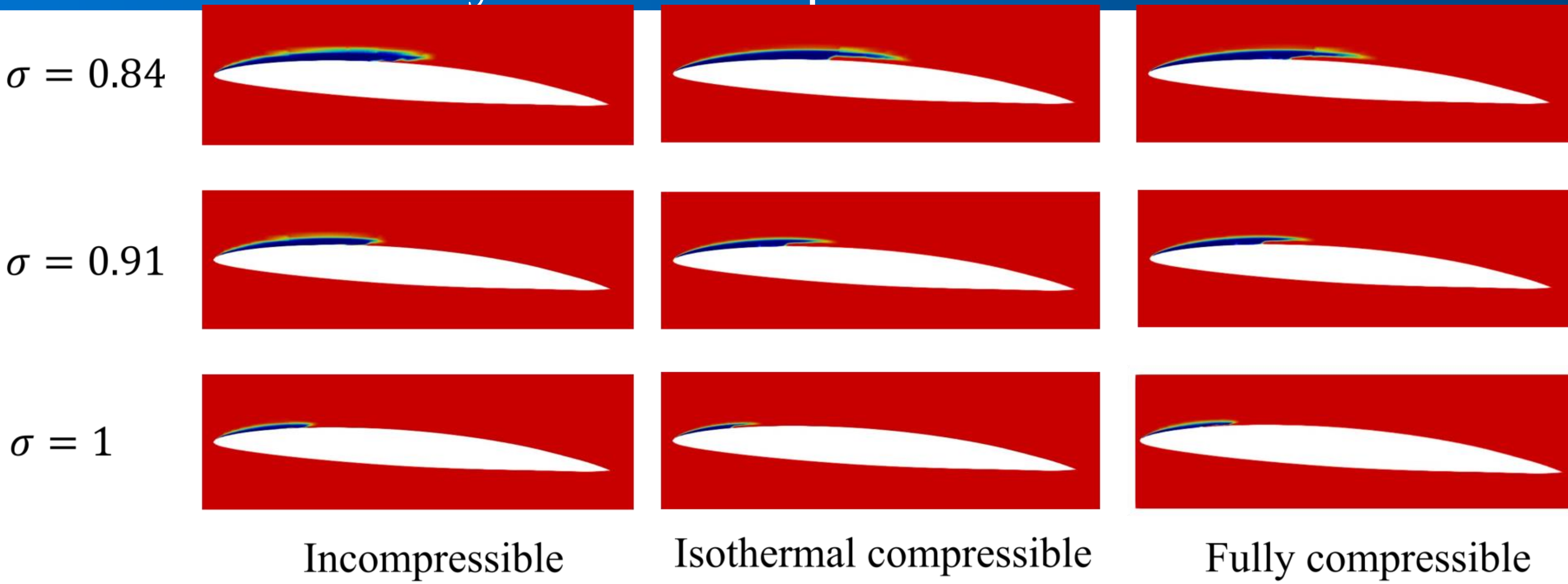
Cavitation on a Hydrofoil(2D Cavitation)



- Compared with the experimental data the present result captured the cavity inception, closure and pressure distribution well.
- The difference in behavior between short and long cavities can be related to difference in adverse pressure gradient in closure region.

Results and Discussion

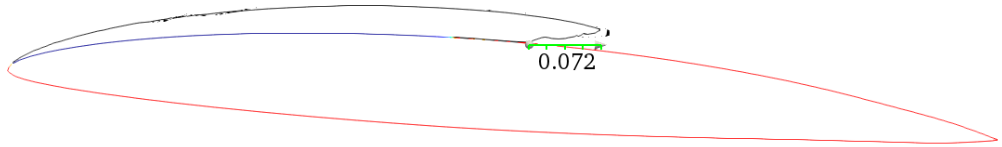
Cavitation on a Hydrofoil – Vapour Fraction



- Only steady cavity is observed among incompressible, isothermal-compressible and fully-compressible flow solvers
- Cavity inception is only on the leading edge and closure at the mid-chord
- As the cavitation number increased the cavity closure moved towards the leading edge of the hydrofoil

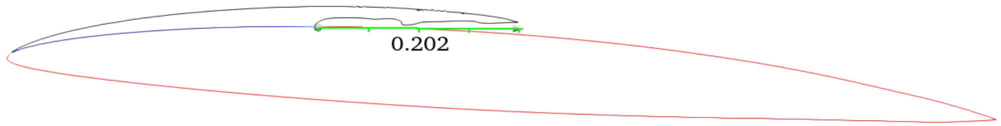
Results and Discussion

Cavity Length - $\sigma = 0.84$ comparison



incompressible

Isothermal compressible

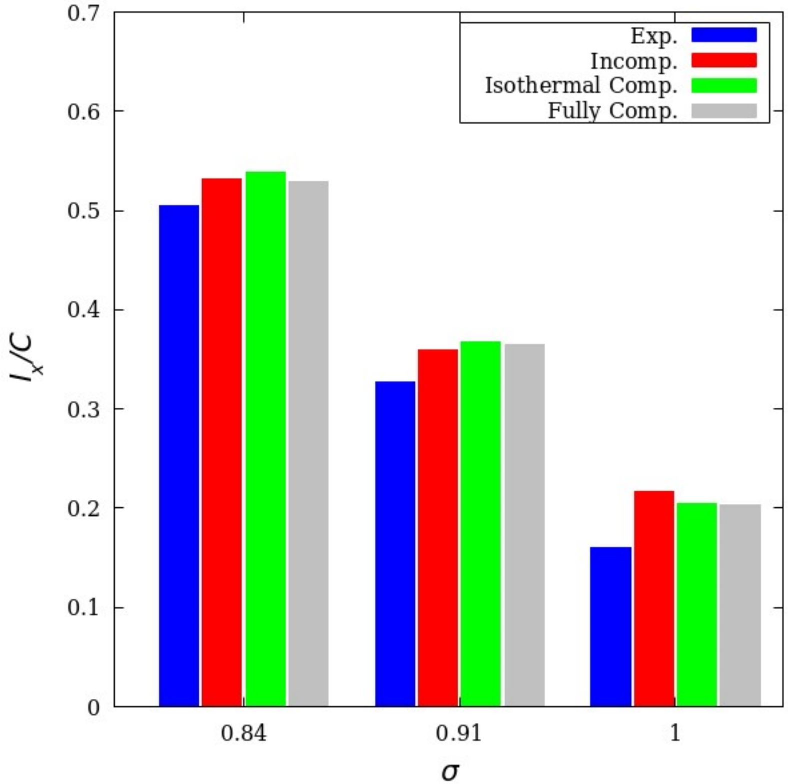


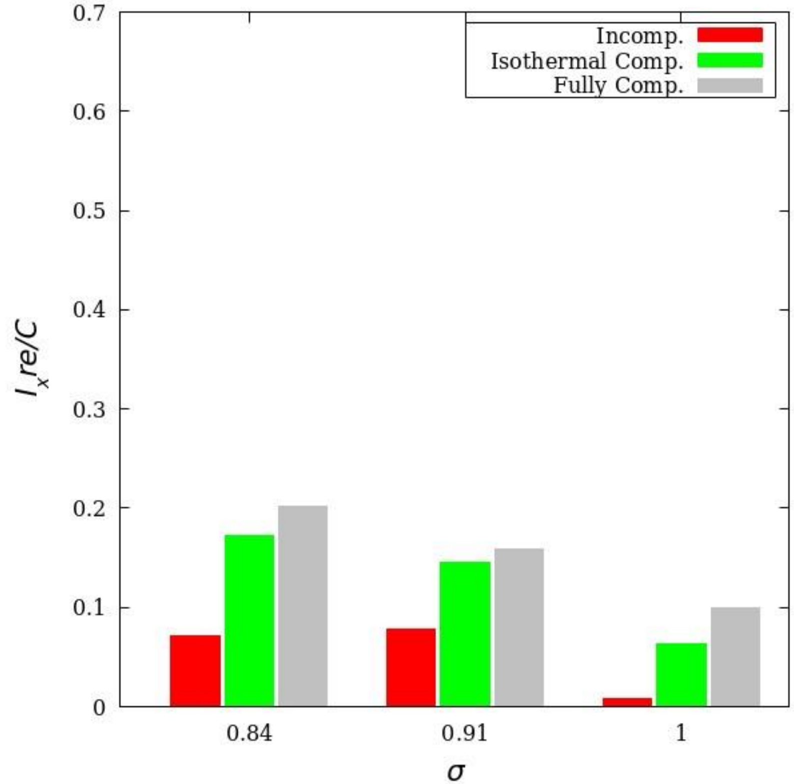
Fully compressible

- Re-entrant jet length predicted by compressible flows approach is longer than by the incompressible flow approach (0.174C & 0.202C against 0.072C)
- Generally the compressible flow solvers predict re-entrant jet dynamics better than the incompressible flow solver.

Results and Discussion

Cavity Length - $\sigma = 0.84$ comparison

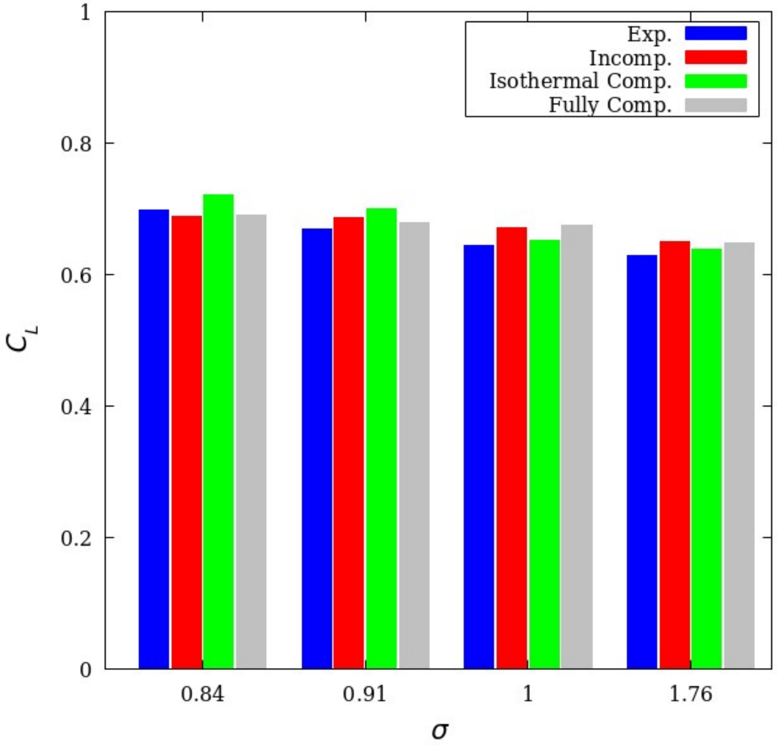


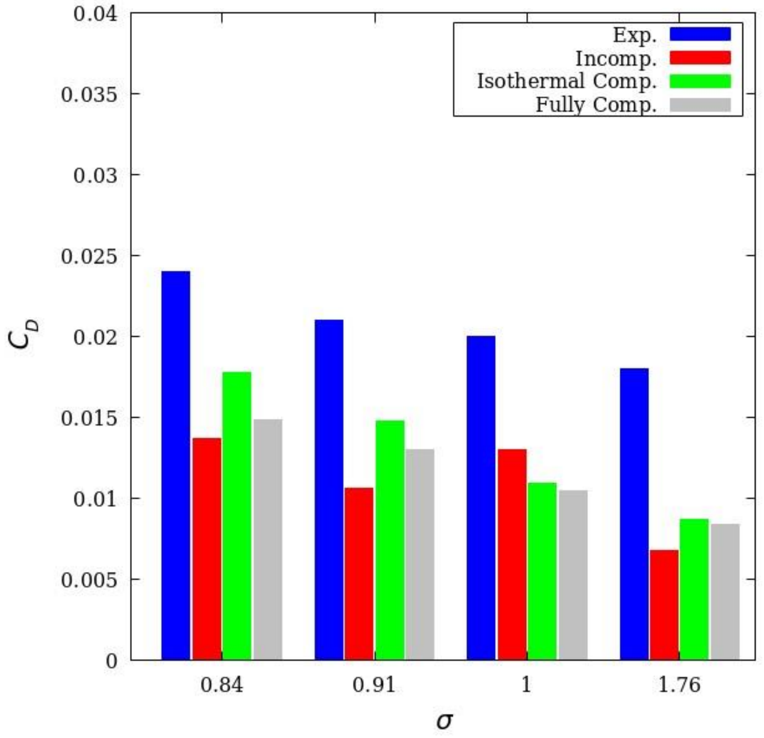


- All numerical methods over-predicted the cavity length but were relatively close
- Fully compressible solver had longer re-entrant jets than the other solvers for the three cavitation cases.

Results and Discussions

Hydrodynamic Forces on Hydrofoil



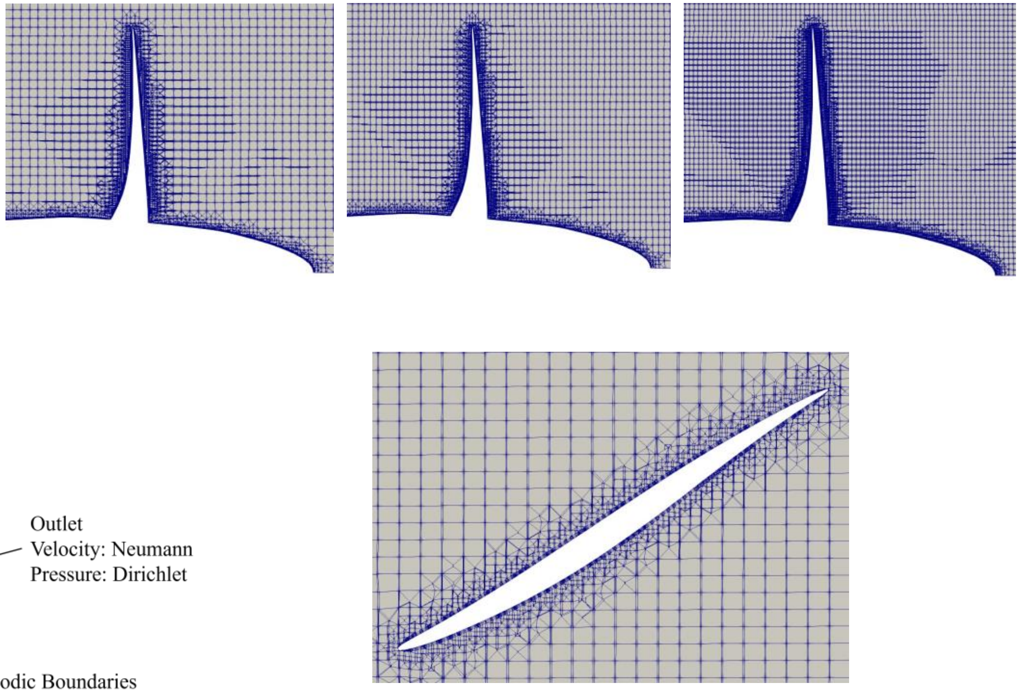


- Compared to experimental data both incompressible and compressible flow solvers predicted the lift correctly, however the drag value was underestimated in this case

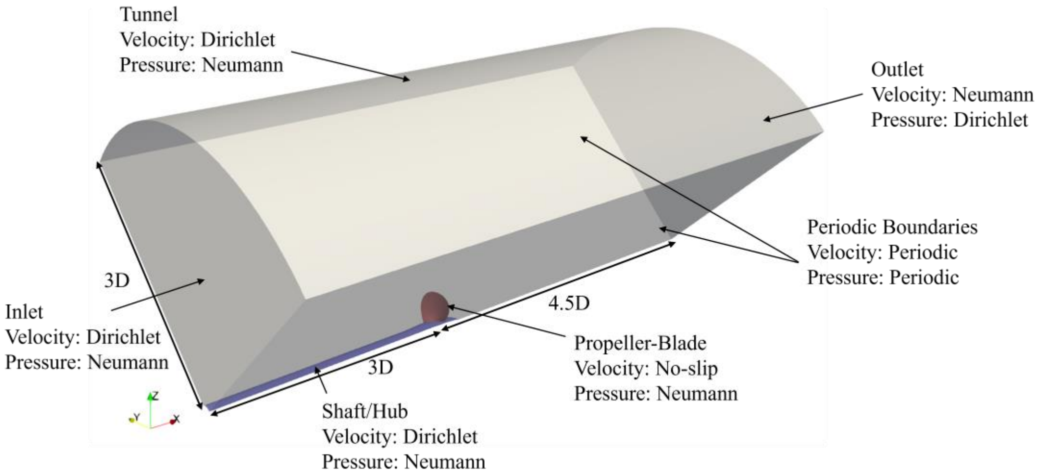
Mesh and Boundary Conditions

INSEAN 779A Propeller Particulars

No. of Blades	4
Diameter (M)	0.227
Pitch ratio (P/D) at *r/R=0.7*	1.1
Pitch (P)	0.152
Expanded Area Ratio (Ae/Ao)	0.69



Mesh around Propeller



One blade propeller simulation set up

Model Description

Test Conditions

w/o Cavitation

- Open water conditions

w/ Cavitation

- Fully - Compressible flow solver
- Isothermal Compressible Solver
- Incompressible flow solver

Parameter	Value
Advanced Ratio (J)	0.71 / 0.83
Cavitation Number based on n (σ_n)	1.763/ 1.029
Rotation speed (1/s)	36
Vapour Pressure (P_v)	2337
Reynold Number	5 x 10^5

Where,

$$V_{in} = J \cdot n \cdot D$$

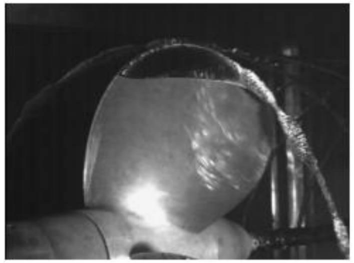
$$P_{out} = P_V + \sigma_n \cdot 0.5 \cdot \rho_l \cdot (n \cdot D)^2$$

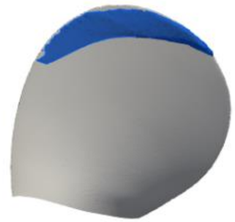
No. of Cells	544,612
Solvers	Incompressible flow solver (interPhaseChangeFoam)/ Fully-Compressible flow solver (compressibleInterFoam) Isothermal-Compressible flow solver (compressibleInterFoam)
Time Scheme	CrankNicolson 0.5/Euler
Gradient Scheme	Gauss Linear
Divergence Scheme	Gauss vanLeer
Turbulence Model	kOmegaSST

Results and Discussions

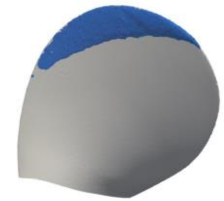
Propeller Cavitation – Comparison Among Solvers

Case 1 (J=0.71)

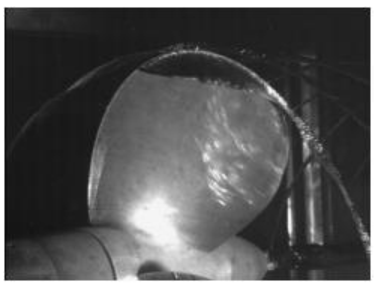

(a)

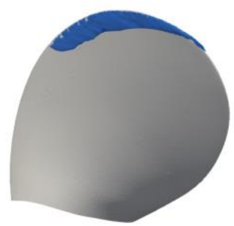

(b)

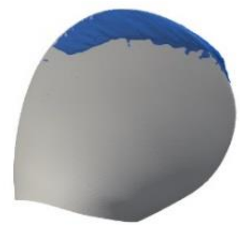

(c)

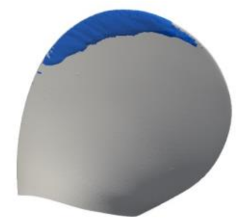

(d)

Case 2(J=0.83)


(a)


(b)


(c)

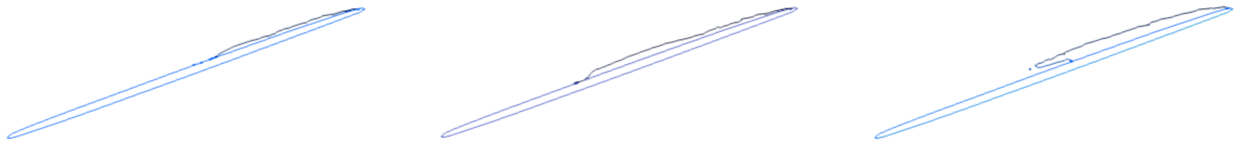

(d)

(a) Experiment (a) Incompressible (c) Isothermal Compressible (d) Fully Compressible

- Propeller cavitation behaviors was similar in all approaches

Results and Discussions

Propeller Cavitation – Comparison Among Solvers



(a) (b) (c)

(a) Incompressible

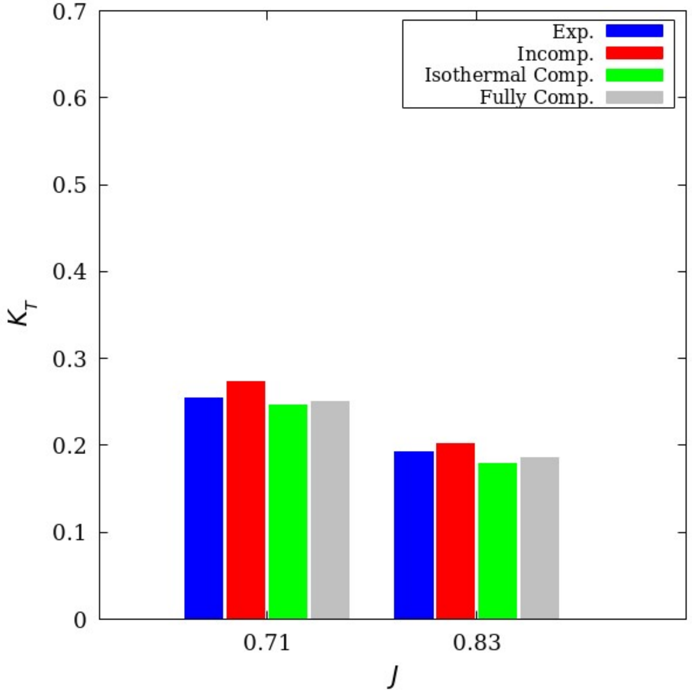
(b) Isothermal Compressible

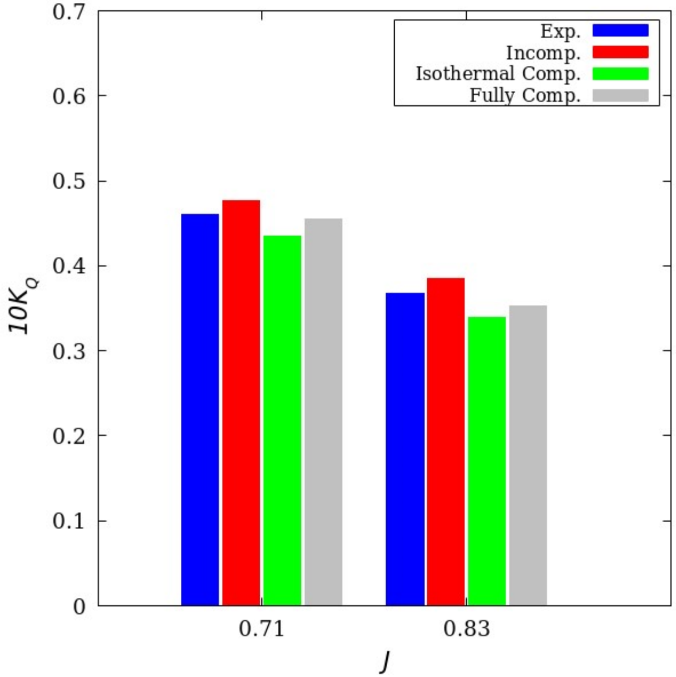
(c) Fully Compressible

- Propeller Re-entrant jets Case 2 at r/R=0.95. It was noted that all other diameter points had no reentrant jet observed.

Results and Discussions

Propeller Cavitation – Hydrodynamic Performance





- The propeller hydrodynamic performance had small discrepancies compared to experiment data, however
- Both compressible solvers(fully & isothermal) the pattern showed underestimation.
- Fully compressible solver had better results than both isothermal compressible and incompressible flow solver.

Conclusions

- The cavitation in 2D was conducted and verified using incompressible and extended to compressible flow solvers.
- The fully compressible and isothermal compressible solvers were able to predict cavitation similar to incompressible flow solver for both 2D (hydrofoil) and 3D (propeller) cavitation.
- Compressible flow solvers showed capability to capture re-entrant jet better than the incompressible flow solver.
- There was no major differences observed in the predicted lift generated from hydrofoil cavitation however the drag was underpredicted with a huge margin.
- Fully compressible flow solvers predicted propeller hydrodynamic performance in cavitation better than both isothermal compressible and incompressible flow solver even though showed little discrepancy compared to experiment results.

QUESTIONS & COMMENTS

THANK YOU