

Overview of presentation topics

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- Introduction: Motivation for project
- Role of OpenFOAM
- Physics/Governing equations
- Problem set-up
- Verification: planned benchmark cases
- Challenges and future exploration
- Conclusions



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Introduction: Motivation for project

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Major challenges currently facing offshore wind farms:

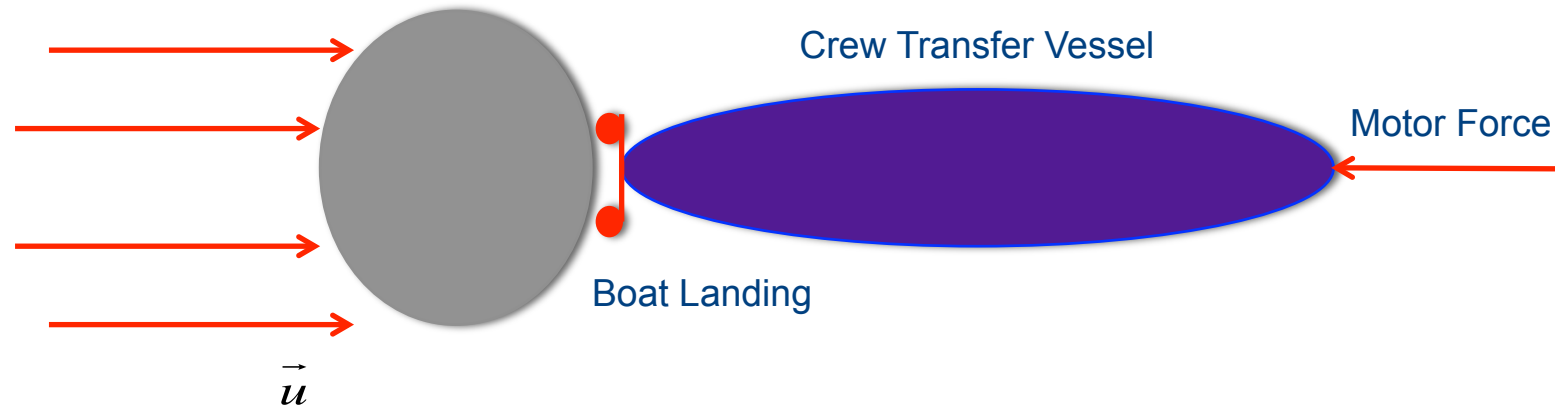
- Operations and maintenance (O&M) strategically difficult due to locations of turbines
- Prohibitively high cost of O&M
 - ~ 50% of total cost of energy production
- Limited turbine access
 - Parameter used to determine accessibility of turbine is sig. wave height, H_s (not very reliable; no information wave conditions directly at the turbine)

Most importantly:

- **Safety of repair workers:**
 - No available statistics on frequency of dangerous circumstances – more later
- **Economic loss:**
 - Length of time turbines go without repair due to unfavourable repair conditions leads to large monetary losses (approximated loss per year ~ €9.4 Million for a typical !!)
 - Approximation includes lost production time, repair workers pay without repair, average downtime per fault
 - Note: approximation provided by Resilience Energy Ltd. consultation

Introduction: Motivation for project

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- Monopile blocks the vessel from incident waves during landing operation – *implies that vessel lies within the wake of the turbine*
- Vessel held in place through controlled thrust from motor and frictional forces between vessel and the boat landing – *no mooring lines*
- Vessel must remain in place for the time it takes a worker to move from the vessel onto the turbine or from the turbine to vessel – *Implies the vessel must remain steady for a certain length of time, regardless of changes in the kinematics within the wake*



Video courtesy of Alexis Billet, Resilience Energy

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What is the role of Open▽FOAM in this project?

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- CFD is *not* the first choice of small consultant firms working in this field, but OpenFOAM is good choice for CFD if necessary:
 - Readily parallelised
 - User control
 - Open-source and portable (small consultant companies do not have access to commercial software)
- Role of OpenFOAM in this project is to provide approximate validation for analytical solutions to the following problems:

1. Free surface effects within the near-wake (surface elevation that differs from significant wave height, H_s)
2. Turbine effect on the flow around it and effects on a vessel located directly in the very near wake
3. Verify analytical solution found using Control Volume Method

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Physics and governing equations

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- Incident waves (i.e. linear):

$$\left. \begin{aligned} U_{\infty,x} &= \frac{\partial \varphi}{\partial x} \\ U_{\infty,z} &= \frac{\partial \varphi}{\partial z} \end{aligned} \right\} \text{where } \varphi(x,z,t) = \frac{\omega}{k} a \frac{\cosh[k(h+z)]}{\cosh(kh)} \sin(kx - \omega t + \varphi)$$

- Requires solution to unsteady NS equations for rotational and viscous flow
- Non-dimensional analysis provides important information about type of flow; i.e. :
 - whether flow is laminar or turbulent
 - Approximate important of viscosity

e)		Wake completely turbulent. A: Laminar boundary layer separation	$300 < Re < 3 \times 10^5$ Subcritical
f)		A: Laminar boundary layer separation B: Turbulent boundary layer separation; but boundary layer laminar	$3 \times 10^5 < Re < 3.5 \times 10^6$ Critical [Lower transition]
g)		B: Turbulent boundary layer separation; the boundary layer partly laminar partly turbulent	$3.5 \times 10^5 < Re < 1.5 \times 10^6$ Supercritical
h)		C: Boundary layer completely turbulent at one side	$1.5 \times 10^6 < Re < 4 \times 10^6$ Upper transition
i)		C: Boundary layer completely turbulent at two sides	$4 \times 10^6 < Re$ Transcritical

Note: practical engineering applications are nearly always in subcritical regime and above

Governing Equations: Non-dimensional analysis of flow features

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Dimensionless quantities	Reynolds Number	Keulegan-Carpenter Number	Strouhal Number	Pressure Coefficient
<i>Definition</i>	<ul style="list-style-type: none"> Describes flow regime (laminar or turbulent) 	<ul style="list-style-type: none"> Describes relative importance of viscous to inertial forces 	<ul style="list-style-type: none"> Describes the frequency of oscillating flow and determines presence of vortex shedding 	<ul style="list-style-type: none"> Used to compute relative pressures between a point of interest (i.e. pressure on the cylinder) and ambient pressure in the field
<i>Formula</i>	$Re = \frac{U_{\infty} D}{\nu}$	$KC = \frac{TU_{\infty}}{D}$	$St = \frac{f_s D}{U_{\infty}}$	$C_P = \frac{(P_s - P_{\infty})}{\frac{1}{2} \rho_{\infty} U_{\infty}^2}$
<i>Uses</i>	<ul style="list-style-type: none"> The Reynolds number is useful for anticipating features in the flow 	<ul style="list-style-type: none"> Useful parameter for predicting the presence of vortex shedding 	<ul style="list-style-type: none"> Shedding frequency (f_s) found from FFT of fluctuating velocities within the wake 	<ul style="list-style-type: none"> Used to find other parameters (i.e. drag/lift force) by integrating around the surface

Governing Equations: Non-dimensional analysis of flow features

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Plugging in some numbers, what do the non-dimensional terms tell us about the flow conditions?

- Example: from linear waves with maximum access conditions:
 - $H = 1.5$ m, $h = 25$ m, $D = 6$ m, $T = 8$ sec, $L = 93.27$ m
 - Origin of the monopile at $x = 0$, z measured positively upward: Maximum horizontal incident velocity, $U_{\infty, x} \approx 1.22$ m/s gives
 - $Re = 3.79e6$
 - implies turbulent boundary layer, decreased viscosity)
 - $KC = 0.8417$
 - indicates that flow never detaches from cylinder; inertial component dominant
 - Vortex shedding does not occur for $KC < 3$
 - $\beta = Re/KC = 4.5e6$
- At the flow conditions detailed above: component of force on the cylinder increases for decreased KC in super-critical Re regimes: difficult regime to analyse due to formation of vortices **without separation**

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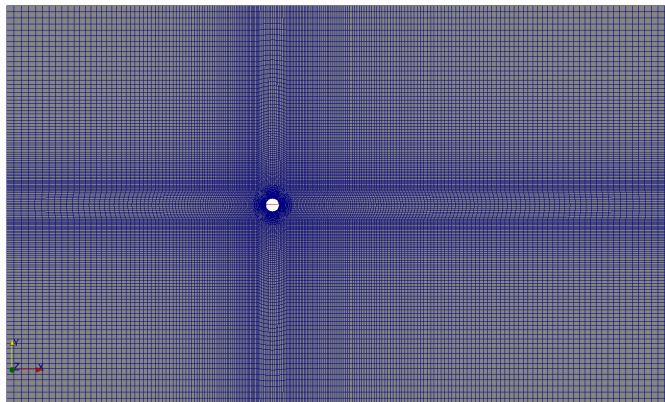
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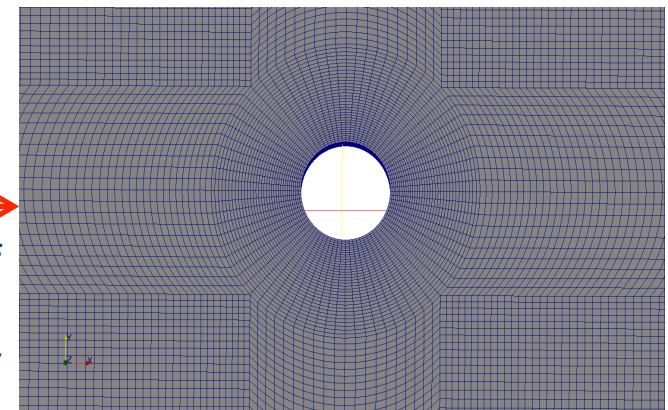
Problem set-up: Computational Domain

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Length of element (m)					
<i>Mesh</i>	<i>Upstream</i>	<i>Downstream</i>	<i>Cylinder</i>	<i>Other region of interest</i>	<i>No. of elements</i>
1	D/4	D/4	$\pi D/76$	3.5D/16	895,200
2	3.5D/16	3D/16	$\pi D/96$	3D/16	1,387,440
3	3D/16	3D/16	$\pi D/106$	3D/16	1,870,560



Surface view of mesh



Close-up of cylinder grading around cylinder



Problem set-up: Boundary Conditions

// *****

Mesh part	U	p_rgh	alpha.water	k	omega	nut
<i>inlet</i>	waveVelocity	zeroGradient	waveAlpha	fixedValue	fixedValue	calculated
<i>outlet</i>	fixedValue	zeroGradient	zeroGradient	zeroGradient	zeroGradient	calculated
<i>Top/ bottom</i>	slip	slip	slip	fixedValue	fixedValue	calculated
<i>cylinder</i>	zeroGradient	zeroGradient	zeroGradient	kqRWallFunction	omegaWallFunction	nutkWallFunction
<i>atmosphere</i>	pressureInletOutletVelocity	totalPressure	inletOutlet	inletOutlet	inletOutlet	calculated
<i>seaFloor</i>	slip	slip	slip	fixedValue	zeroGradient	calculated

Note: these boundary conditions are for a case that uses a non-slip boundary condition on the cylinder and a k-omega SST turbulence model.

- Arguments exist for using a slip condition on the cylinder due to the low KC number.

Problem set-up: Wave generation with waves2Foam

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- Mesh created using blockMesh utility, renumberMesh
- Initial conditions defined by wave choice:
 - waveVelocity boundary condition specified in waveProperties.input file where wave type is specified and necessary parameters – dependent on wave type
- Relaxation zones and volume of fluid techniques are used to capture the interface
 - Relaxation zones set in waveProperties.input
 - Used for absorption of reflected waves at input and output

```

seaLevel          0;

relaxationNames   ( inlet outlet );

initializationName  outlet;

inletCoeffs
{
    waveType          stokesFirst;
    depth              25;
    period             8;
    direction          ( 1 0 0 );
    phi                0;
    height             1.5;
    waveNumber         (0.0673664 0 0);
    omega              0.785398;

    relaxationZone
    {
        relaxationScheme  Spatial;
        relaxationShape   Rectangular;
        beachType         Empty;
        relaxType         INLET;
        startX            ( -120 -90 0 );
        endX              ( -70 90 0 );
        orientation       ( 1 0 0 );
    }
}

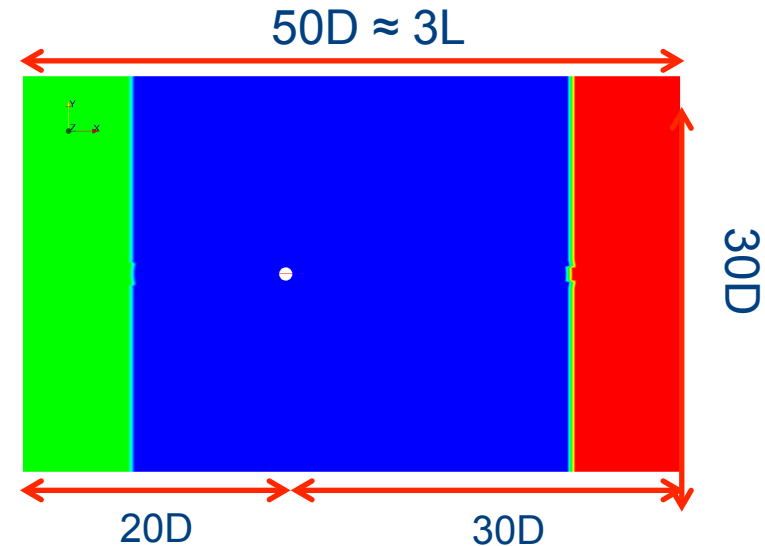
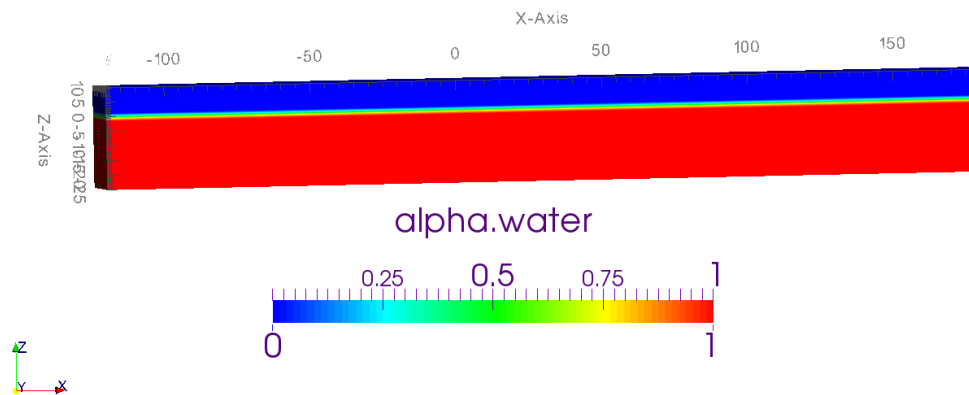
outletCoeffs
{
    waveType          potentialCurrent;
    U                 ( 0 0 0 );
    Tsoft             0;

    relaxationZone
    {
        relaxationScheme  Spatial;
        relaxationShape   Rectangular;
        beachType         Empty;
        relaxType         OUTLET;
        startX            ( 130 -90 0 );
        endX              ( 180 90 0 );
        orientation       ( 1 0 0 );
    }
}

```

Problem set-up: VOF and relaxation zones

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- Relaxation zones easily parallelised; independent of each other
- Length of relaxation zones $\sim 0.5L-1.5L$
 - Length kept to minimum to avoid expanding computational domain too much
 - Future step would be to minimise the domain to increase focus on area around the cylinder, rather than so much in front and back

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Benchmark Cases

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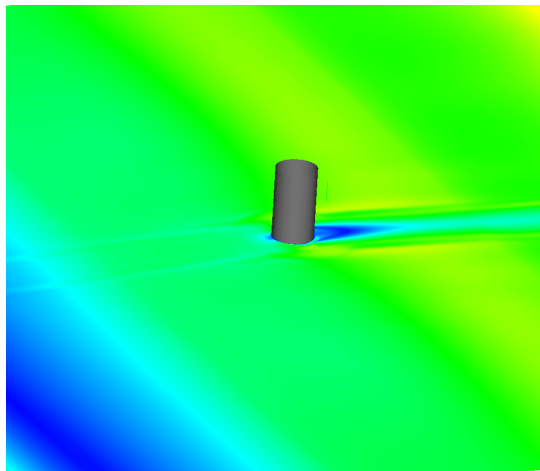
- These are planned cases to test the model

Test Case number	Benchmark Study
<i>testCase1</i>	Re = 40 (potential current)
<i>testCase2</i>	Re = 40 (linear waves)
<i>testCase3</i>	Re = 250 (potential current)
<i>testCase4</i>	Re = 250 (linear waves)
<i>testCase5</i>	Re = 3900 (potential current)
<i>testCase6</i>	Re = 3900 (linear waves)
<i>testCase7</i>	MacCamy & Fuchs Diffraction solution
<i>testCase8</i>	oscillating water column

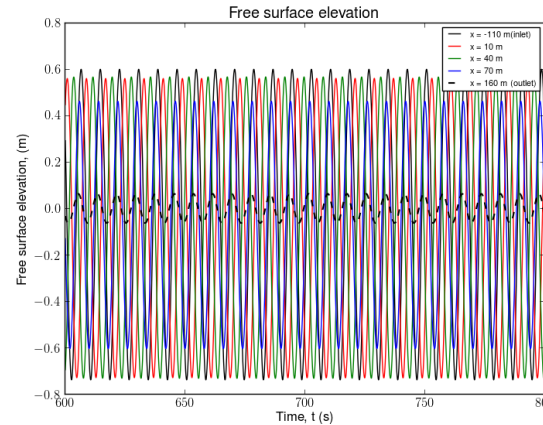
Benchmark Case: Verification in Progress

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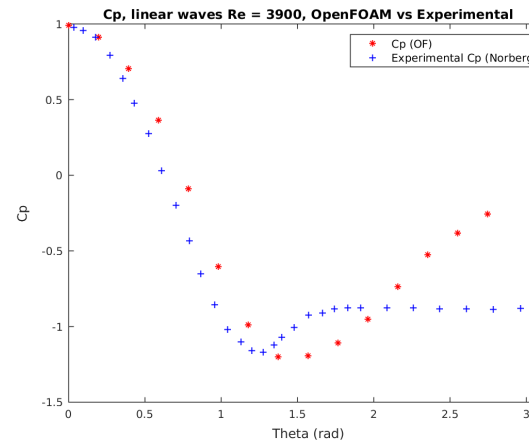
Re = 3900, KC = 0.8417



- No of cells: 387,700
- No turbulence model used
- Linear waves



- Free surface elevation: accurately representing directly behind cylinder may prove useful for further understanding



- Plot for C_p does not behave exactly as expected: shows later effect of adverse pressure gradient than experimental data

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Challenges and future exploration

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- **Challenges**

- Issues with verifying benchmark cases against experimental data
- Results for other parameters (i.e. Strouhal number) are not as expected
 - Different method of obtaining? Currently attempting to use fluctuating velocity and average velocity
- Unexpected asymmetry in results: improved by widening domain, but again this extends the computational demand
- Obtaining drag using a consistent formula
 - How important is the drag coefficient? Not very! Better to be confident with pressure calculations
- Improving the mesh to focus more specifically on the near-wake area: issues using waveFoam to do this due to relaxationZones
- Very open to advice!

Challenges and future exploration

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Future exploration:

- Extend simulations to include:
 - Non-linear waves
 - Directional spectra (JONSWAP spectra included in waves2Foam package)
- How do these results compare to other results from open sea (i.e. MacCamy and Fuchs-type solutions)
 - Can this help to determine the effects of diffraction?
 - If results compare to MacCamy and Fuchs-type results, diffraction could play a more significant role (see: benchmark cases)
- Non-linear forces: FFT of time-dependent forces could reveal unanticipated non-negligible higher order forces
- Vorticity without vortex shedding could imply an increase in forces due to vorticity without dissipation

Most important question to answer:
Which of the calculated parameters will prove to cause the largest vessel motions not predicted by the wave height alone?

Additional Exploration with OpenFOAM

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- Fixed Oscillating Water Column (OWC): Can OpenFOAM more correctly predict forces and internal pressures with the inclusion of viscosity and non-linear components relating to the velocity?
 - Current predictions with boundary element method code, WAMIT, and SPH methods overestimates frequency as they assume inviscid flow
 - OpenFOAM may be more successful at handling viscosity and correctly determining the pressure response

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comparison to benchmark cases
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Conclusions

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- OpenFOAM could prove to be an invaluable tool for determining flow characteristics and structures within the wake
 - Applications extend to industrial needs
 - Further tests against benchmark cases (OWC) could verify extended uses for OpenFOAM
- Goal to use OpenFOAM solutions in conjunction with a boundary element method (i.e. NEMOH) for determining vessel motion



Acknowledgements

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Thank you for your attention!

Also thank you to my supervisors in industry and academia: Dr. Denis Kelliher, Professor Alistair Borthwick, Dr. Gareth Thomas and Alexis Billet

Thank you to my funding bodies: Science Foundation Ireland (SFI) and The Centre for Marine and Renewable Energy (MaREI)

To the organisers of this workshop and to everyone who is taking part and

Selected Bibliography

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Full scale example case

- **Case 1**

- linear wave:

- $H = 1.5$ m, $h = 25$ m, $T = 8$ s, $D = 6$ m,

- $k = 0.06374$

- 895,200 cells

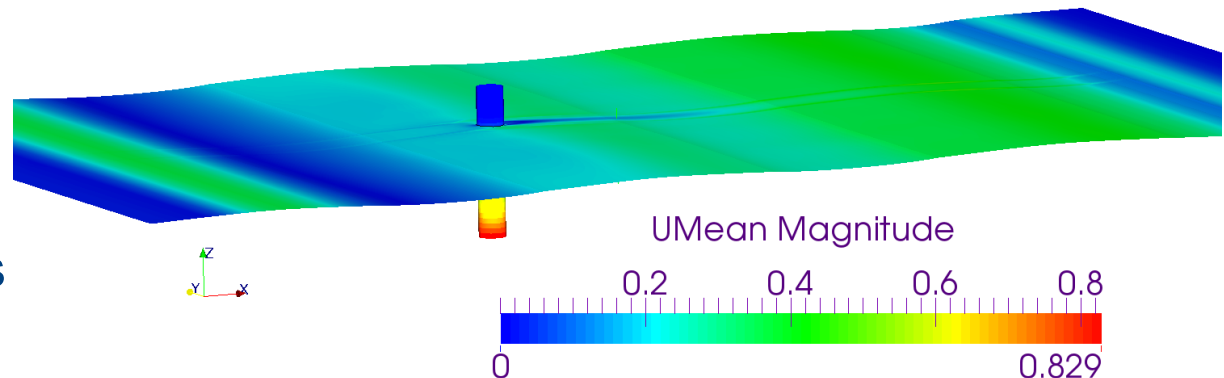
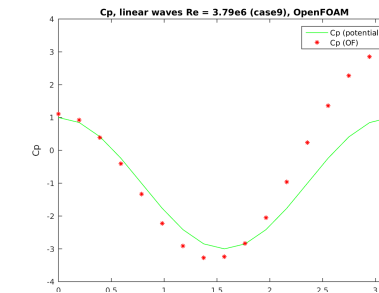
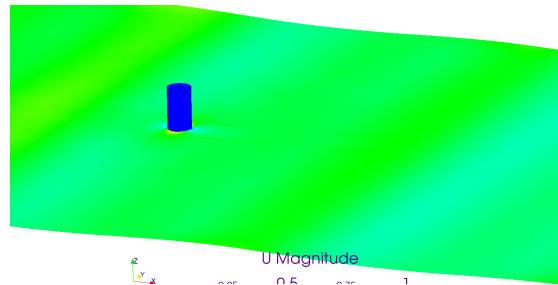
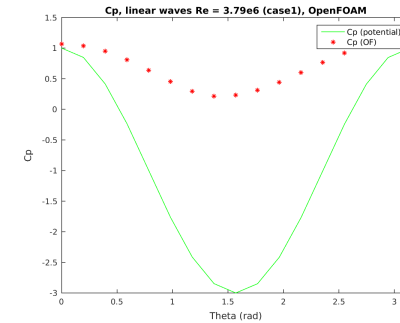
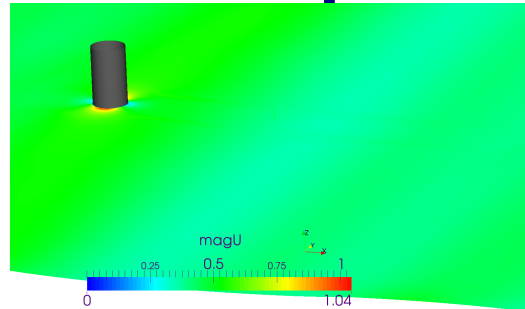
- **Case 9**

- Same flow conditions as case 1

- 1,342,800 cells

- **Case 19**

- non-linear Stokes 2nd order wave



	Crew Transfer Vessel	Service Operations Vessel	Helicopter
ACCESSIBILITY	<ul style="list-style-type: none"> ▪ Up to 1.5m Hs (significant wave height) ▪ Uses boat landing ▪ Daylight hours preference 	<ul style="list-style-type: none"> ▪ Up to 2.5m Hs, increasing accessibility by 23.5% in winter months and 8.2% in summer months ▪ Motion compensated gangway ▪ 24 hr access 	<ul style="list-style-type: none"> ▪ Wave height independent ▪ Winch ▪ Daylight hours restriction
OPERATIONAL TIME* (HRS/YEAR)	5,500	7,195	4,105
NUMBER OF TECHNICIANS	12	45	6
MATERIAL TRANSFER	400kg, 15m crane	3t, 20m crane	Small transport capacities
COST IMPACT	Approx. EUR 500 per operational hour	~2 x CTV cost	~5 x CTV cost
STRENGTHS & WEAKNESSES	<ul style="list-style-type: none"> ✓ Favourable charter rates ✓ Access to small ports * Non-productive travel time * daylight hours preference * Possible seasickness 	<ul style="list-style-type: none"> ✓ Good Accessibility ✓ 24/7 operations ✓ Less downtime of the turbine ✓ Spare parts on board * Possible sea sickness 	<ul style="list-style-type: none"> ✓ Good Accessibility ✓ Fast Transfer ✓ No Sea Sickness * Limited to daylight hours * High costs

Figure 6 – Comparison of Maintenance Strategies (Adapted from [REF])