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# Fluid–structure interaction study for the DIFIS system's composite riser tube

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## ABSTRACT

Double Inverted Funnel for the Intervention on Ship wrecks (DIFIS) was developed for oil recovery from shipwrecks and for the elimination of the pollution threat during EU FP-6 framework. The installation time's reduction in cases of environmental pollution is a crucial factor for DIFIS system design. In the current work, the polyethylene riser tube parts (15 meter) of DIFIS System was replaced by a composite riser tube parts (30 meter) succeeding lower installation time for the DIFIS's riser. The analysis and development of composite riser was based on the verified two–way fluid structure interaction (FSI) results from polyethylene riser. A methodology based on polyethylene riser's normal modes (target values) was proposed and the composite riser's structural integrity was investigated in order to reach these target values. The normal modes analysis and the two–way fluid structure interaction simulation were performed in ABAQUS software. The riser tube lay outs was also validated using experimental tests in MARIN's hydro-channel. The composite riser's dynamic response under sea current is significant better than polyethylene riser (lower displacements in axes, parallel and vertical to flow) regarding both numerical analyses and testing results. In overall, the time reduction of the DIFIS' riser installation by 40% was achieved, using longer riser parts.

**Keywords:** 2 – way FSI; Composite riser tube; CFRP; DIFIS System; Abaqus

## INTRODUCTION

In marine environment there are different types of loads that lead to the dynamic response and the fatigue damage of a marine structure[1]. A 2 –way FSI analysis is used, in order to study the dynamic response of a structure. Vortex Induced Vibrations (VIV) is a common environmental phenomenon in marine environment which can be investigated through a FSI analysis [2].DIFIS system is an innovative and quick deployed structure, which can be used, in maritime disaster in order to eliminate the oil pollution threat. Specifically, DIFIS System limits the oil leakage from the shipwreck to marine environment[3]. An extensive study for design, analysis and optimization of DIFIS system was performed [4]. In this study, a 1 – way FSI analysis was presented for a part of the polyethylene riser tube. The results show that the response of the polyethylene part of the riser tube is quasi-static. Furthermore, the results of this study has been validated and compared with experimental measurements from MARIN's hydrochannel [5].Moreover, an additional 2 – way FSI analysis for a polyethylene part of the DIFIS riser tube (RTD) was performed[6], based on low computational time. The results showed the excellent performance of Abacus co – simulation module. The response of the RTD can be characterized as static in low Reynolds numbers and quasi- static in high Reynolds numbers.

The use of composite materials in marine structures and offshore industry has been increased the last decades, due to the development of high qualified composite materials [7, 8]. Significant studies have been performed in design of riser tubes from composite materials and in analysis of composite riser tubes perform in comparison with metallic riser tubes. Specifically,[9] presents a review of studies that have performed in design, manufacture and mechanics of composite risers. Thermoplastic composite (TPCR) and Fiber Reinforced Polymer risers have high specific strength and stiffness, good durability, low thermal conductivity and moderate corrosion resistance in comparison with metallic risers. Moreover, in many studies[9] the riser tests were performed under different load cases, such as VIV and tensile force. The VIV effects in composite riser are more significant than steel risers due to their higher fatigue damage tolerance[9]. Improvements such as the change of fiber's angle and the increase of the normal modes range are also introduced. A typical composite riser wall thickness is proposed by [10], which was analyzed in blast, buckling, bending and axial stress numerically and it was observed that the fatigue life of the composite riser can exceed the design life.

The DIFIS system is a rapid installed underwater structure used for oil recovery from shipwrecks [4], so the reduction of the RT installation time is a main factor. The main scope of this paper is the reduction of risers' installation time for the DIFIS system, by using longer section of riser parts. The use of composite materials (CFRP) instead of polyethylene for the riser parts is mandatory for this application.

The DIFIS system consists of seven parts and is anchored on the sea bed for oil recovery from shipwrecks[4]. A schematic representation of the system is given inFigure 1. These parts are: 1) the buffer bell (BB): An underwater tank for the temporary storing of recovered oil. It also keeps the system fully pre-tensioned, producing buoyancy forces, 2)The dome (DM): A conical shaped structure made of a fabric material which covers the shipwreck and drives the collected oil through the riser tube, 3) The riser tube (RT): An almost vertical pipe made of HDPE for the connection of the buffer bell to the dome that covers the shipwreck, 4) The dome interface unit (DIU): A conical steel substructure serving as a connection interphase between the riser tube and the dome structure, 5) The mooring lines (ML): Vectran cables which support the riser tube and the dome, and are anchored to the seabed, 6) The stiffening rings (SR): Aluminum disks that connect each part of the riser tube with the mooring lines, 7) The anchoring system (AS): Deadweight cement anchors, holding the overall structure to the seabed[4].

In contrast to common offshore structures, this new design for oil recovery is not affected by weather conditions at the sea surface such as waves, storm conditions etc., because it is fully submerged. As a result the structure needs to withstand only the hydrodynamic loads from sea currents and the high hydrostatic pressure due to the operational depth. This is an advantage as the system may need to remain submerged for long periods of time until oil recovery is completed[4].

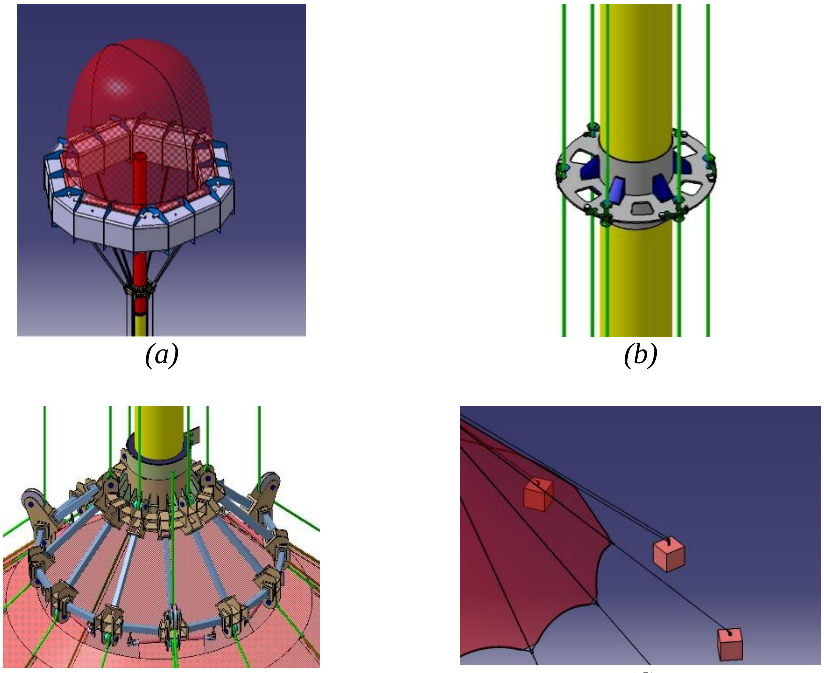
*(a)* *(b)* *(c)* *(d)*

Figure 1. The Underwater Structure (DIFIS System), a) Buffer Bell, b) Riser Tube, Stiffening Rings, and Mooring lines c) Dome Interface Unit, d) Dome and Anchoring System

To sum up, the novelty of the present study is the application of an optimized riser tube, made of composite materials, with reduced length relative to existent PE tubes, in order to reduce the installation time for the DIFIS system. This objective achieved through a new design methodology that allows the use of longer composite riser parts, instead of the initial polyethylene riser parts. This study concludes with the investigation of composite riser tube dynamic response following the operational requirements (sea current velocity profile) using FSI numerical models and experimental data.

## FUNCTIONAL SPECIFICATIONS

The polyethylene Riser Tube (RTD) was the primary selection for the DIFIS System during the early design stages and the detail design. Due to its high applicability in offshore and onshore structures and its manufacturability based on thermoplastic processes, its selection was mandatory for the feasibility study of DIFIS System. The composite Riser Tube (RTComp) (Figure 2) is proposed as an evolution of DIFIS RTD regarding the reduced deployment time. Due to the DIFIS System's specifications, the design method of RTComp was based on the design method of RTD requirements [4]. InTable 1, the operational requirements and structural demands of RTComp's design are presented. The Riser Tube set up on DIFIS System remained the same (External Diameter, Mooring Lines etc.) as the initial design [4].

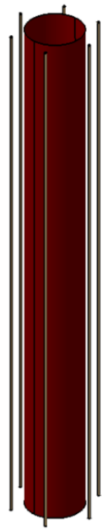

Figure 2. RTComp and mooring lines

Table 1. Structural requirements for design of RTComp

| RTComp Design Requirements | |
|---|---|
| Material Properties | CFRP |
| Wall Thickness (mm) | >2.5 |
| Maximum Length (m) | 15 - 50 (deployment time reduction) |
| Bouyancy | Positive or Neutral |
| Chemical Corrosion Resistance | Withstand the seawater (>35 ppt) and oil corrosion |
| Fatigue Resistance | Avoid excitation from VIV phenomenon |
| Structural Loads | Each part has to withstand hydrodynamic forces from sea currents and local buckling |
| 1$^{st}$ Eigen frequency | • >1.2 Hz in water, at least<br>• >= 2.13 Hz is recommended, from RTD polyethylene design analysis |
| Maximum mass per part | 25 tons (in air) |

## FLUID STRUCTURE INTERACTION

### Two–way fluid structure interaction

A 2 – way fluid structure interaction analysis is used when the interaction between the fluid and the structure is significant and the structure displacements are large [11]. With a 2 – way fluid structure interaction analysis is possible to capture the structure motion in dynamic phenomena such as VIV. Figure 3represents a partitioned approach of a 2 – way coupling algorithm between CFD and FEA solvers. During the first time step the CFD solvers converges and provides the hydrodynamic forces for the FEA solver. The hydrodynamic forces are obtained in the coupling surface as boundary conditions from FEA solver. As consequence the mesh is deformed. These structure displacements are interpolated in the coupling surface of the CFD solver, causing a deformation in the fluid domain. The process is repeated until the completion of the computational time. Time step has to be selected carefully in order to prevent the increase of residuals, which can lead to solver interruption. Figure 4 shows the transferred data between the two solvers and the results that can be extracted from each solver.

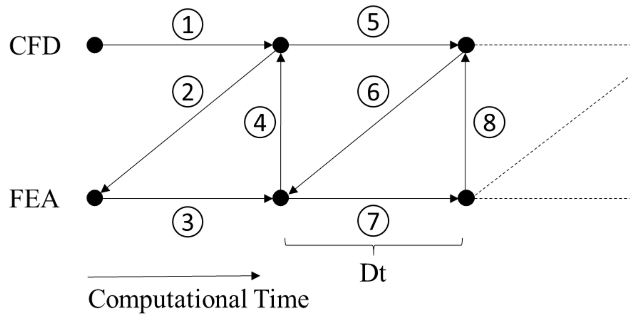


Figure 3. Partitioned Coupling Scheme

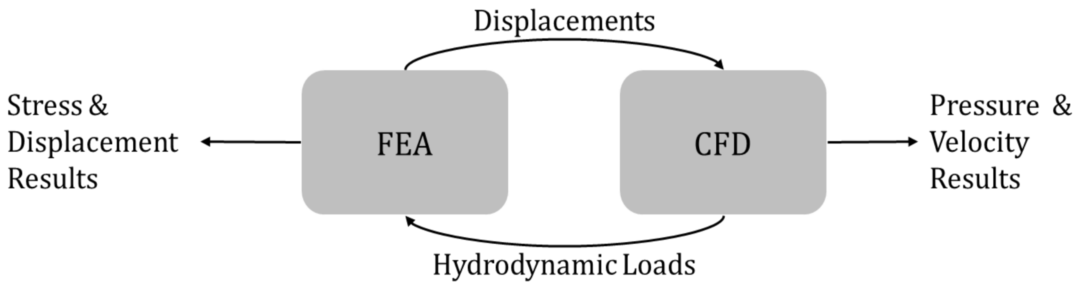


Figure 4. 2 – way FSI analysis procedure for each time step

**Flow Model**

The governing equations for the fluid are the unsteady Reynolds Averaged Navier Stokes equations (RANS). For an incompressible Newtonian fluid, the equations are expressed as below (Equations (1) and (2)):

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\rho \frac{\partial U_i}{\partial t} + \rho U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(2\mu S_{ji} - \rho \overline{u_j' u_i'}\right) \tag{2}$$

Where $U$ is the averaged velocity, $u'$ is the fluctuating velocity, $P$ denotes pressure, ρ represents density, $S_{ji}$ is the rate of strain tensor and μ represents molecular viscosity. Additional equations needed due to number of unknown variables [12]. In this study, the RNG k – epsilon viscous model was used.

**Structural Model**

The motion of a riser tube exposed in sea currents can be described by the Equation (3).

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \tag{3}$$

Where [M] denotes the mass matrix of the structure, [C] represents the damping matrix, [K] is the stiffness matrix of the structure and $x, \dot{x}, \ddot{x}$ are displacement, velocity and acceleration respectively. The vector of the external loads {F(t)} can be written as a summation of the parallel to the flow acting forces (drag) and the vertical to the flow acting forces (lift). Drag force may induce in – line vibration and lift force may induce cross – flow vibrations. Vortex induced vibrations are caused from the lift force, which can be analysed as described in Equation (4) [13].

$$F_L(t) = \frac{1}{2}\rho U^2 D C_L \sin(\omega_v t) \tag{4}$$

## VALIDATION OF COMPUTATIONAL MODELS

The validation of the computational models (CFD, CSD) is based on the results presented on the works of S. D. Fanourgakis et al [6]. In this study, mesh convergence analysis for the CFD and CSD models was carried out. Furthermore, the study presents an assessment on viscous models in relation with the sea current velocity. Finally, the two-way fluid structure interaction analysis was compared with one-way fluid structure interaction analysis [4] and experimental results.

### Fluid Model Mesh Convergence

The mesh convergence analyses for the CFD model focus on the examination of mesh topology in the riser's boundary layer. The Reynolds number was $1.4 * 10^6$ and the RNG k – epsilon viscous model was used. The theoretical boundary layer thickness can be calculated from Equation (5) [14].

$$\delta \approx \frac{0.37 * x}{Re_x^{1/5}} \tag{5}$$

With the above parameters, the thickness of boundary layer is 40.5 mm. The initial 4 cases are described inTable *2*. For all the cases the number of periphery elements is equal to 40. This sensitivity study is important as the riser is a cylindrical structure. Figure 5presents the drag coefficient relative to time for the above cases.

Table 2. Initial cases for the boundary layer thickness sensitivity analysis

| Case | Boundary Layer Thickness | Number of Elements |
|---|---|---|
| 1 b.l. | δ = 1∗T.B.L. (Theoretical Boundary Layer) | 5 |
| 2 b.l. | δ = 2∗T.B.L. (Theoretical Boundary Layer) | 10 |
| 3 b.l. | δ = 3∗T.B.L. (Theoretical Boundary Layer) | 15 |
| 5 b.l. | δ = 5∗T.B.L. (Theoretical Boundary Layer) | 25 |

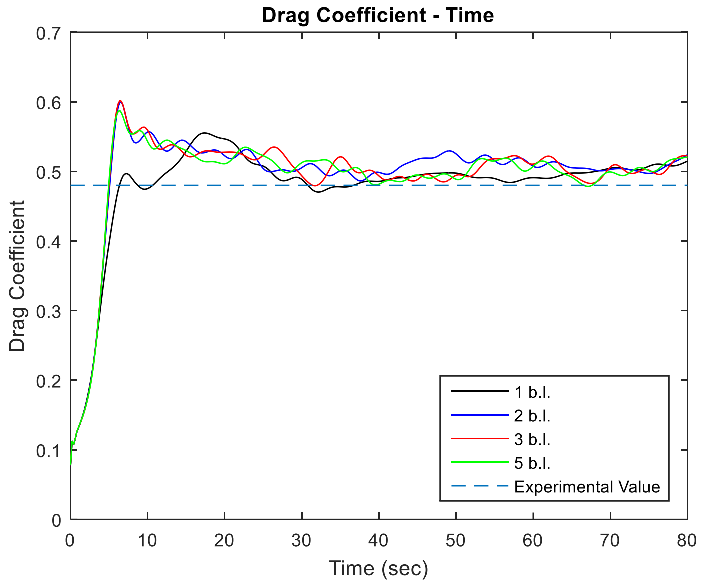


Figure 5. Boundary layer thickness results

According to the above results the cases of 3 b.l. and 5 b.l. have minor differences. The case 3 b.l. was selected as the most appropriate mesh regarding to the low solution time. For the mesh generation the command "Bias" was also used. The cases studies are presented in Table *3*. The number of elements at the thickness of the boundary layer ranges from 5 to 15.

Table 3. Case studies of boundary layer elements' simulation

| Case | Number of Elements | Bias |
|---|---|---|
| 3 b.l.-5 elem. | 5 | 3 |
| 3 b.l.-10 elem. | 10 | 3 |
| 3 b.l.-15 elem. | 15 | 3 |

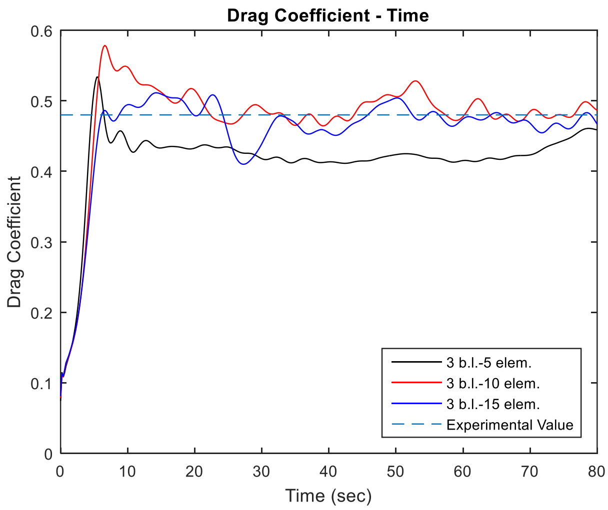


Figure 6. Elements for boundary layer simulation

Following the comparisons (Figure 6), the 3 b.l. – 10 elem. case was selected as the most appropriate mesh regarding the low solution time for the model.

**Structural Model Mesh Convergence**

For the mesh validation of CSD model, 3 cases were examined in which the number of peripheral elements is increased. The parameters of mesh generation in CSD model are presented in

Table 4. The vertical displacement relative to number of horizontal elements is presented in

Figure 7.

Table 4. Parameters in CSD mesh generation

| | |
|---|---|
| **Boundary Conditions** | $x = 0$, $u_x = u_y = u_z = \theta_x = \theta_y = \theta_z = 0$ |
| **Loads** | Gravity force (-y axis) |
| **Case studies** | 40, 48 and 60 periphery elements |
| **Lengthwise Elements** | 5-350 |

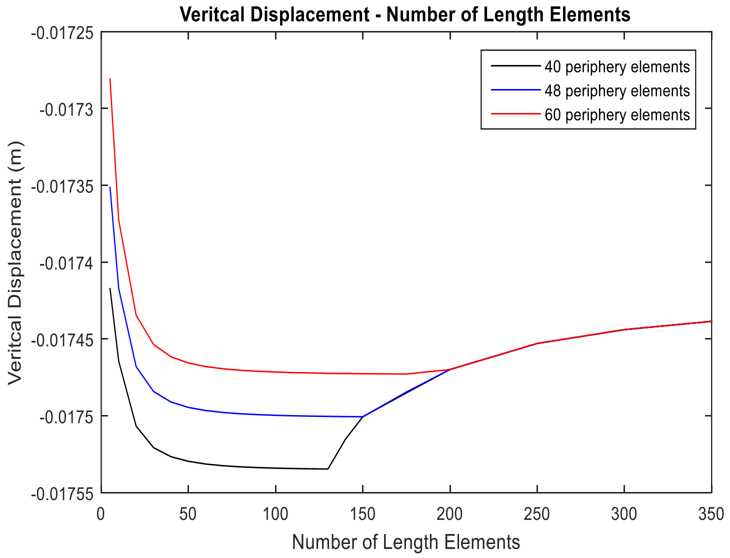


Figure 7. Structural mesh convergence analysis

The differences, for all the cases are negligible. The vertical displacement converges for values greater than 200 elements lengthwise. The selection of the elements on the RT's periphery and length is based on two factors: the results' accuracy and the simulation time. Following this, the most convenient case was the 2nd (48 elements in periphery) and 80 along the RT.

**Viscous models validation**

Two viscous models were set for analysis: 1) *k*–omega SST and 2) RNG *k*–epsilon, in Reynolds number$1.4 * 10^6$. In

Figure 8 the drag coefficient in relation with time is presented for these 2 viscous models. From the literature, the drag's coefficient curve in relation with Re, the theoretical value of drag coefficient is 0.48 for $Re = 1.4 * 10^6$ [14]. The RNG *k*–epsilon model shows better results than the *k*–omega SST model in the specific Reynolds number. For $Re = 1.4 * 10^6$, the laminar boundary layer has undergone turbulent transition and the wake is narrower. The RNG k–epsilon turbulent model leads to better results regarding to randomness in the flow [14, 15].

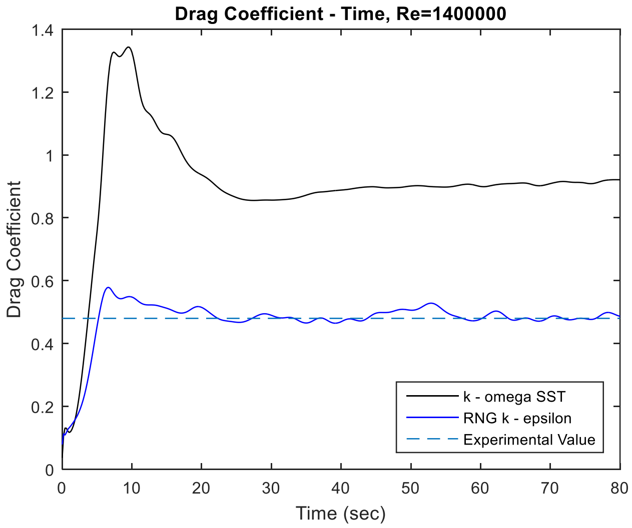


*Figure 8. Viscous models comparison in* $\boldsymbol{Re = 1.4 * 10^6}$

## DESIGN METHODOLOGY

### From polyethylene RTD to composite RTD (RTComp)

The results from RTD 2 – way FSI analysis[6]show that the most critical response is at velocity 0.6 m/s. For this velocity the drag and lift coefficients oscillates leading to undamped motion but the $A_y/D$ is small ($4.1*10^{-5}$). If the RTD's length was greater or the stiffness was lower, the lock – in phenomenon would be presented. The satisfactory performance of the RTD, set the basis for the RTComp development for the reduction of the installation time. It was estimated that the RT column deployment time could be reduced 40% if risers with greater length could be installed. For this reason, a design of an innovative riser with greater length from RTD's has set a primary scope of work. Composite materials were an appropriate candidate for this application due to their large stiffness to mass ratio. A multidisciplinary method was set in MATLAB program, controlling the riser's buoyancy and mass in relation with the normal modes. Figure 9 presents the design process of RTComp and ABAQUS software is used for the 2 – wayFSI analysis.

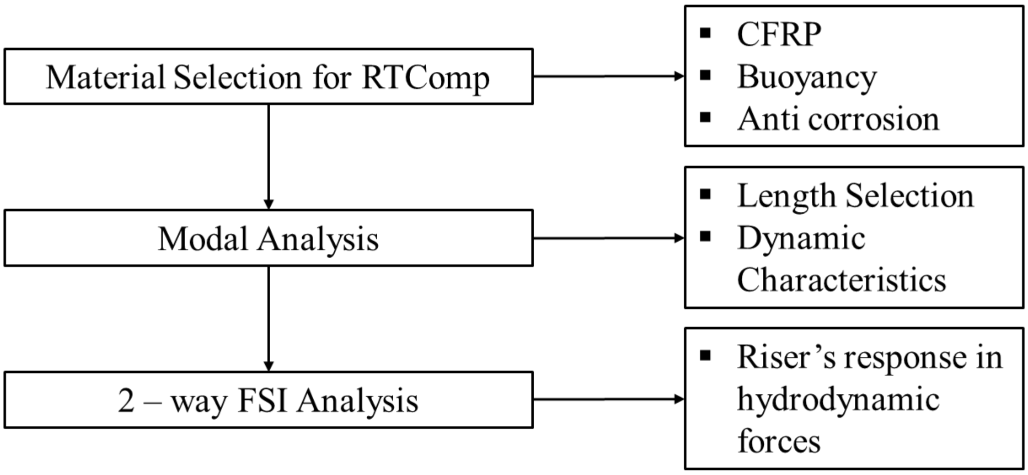


Figure 9. Flow chart of RTComp analysis

For the multidisciplinary design MATLAB code[7], the mass=25 tons, RTD 1st Eigen frequency=2.13Hz and the buoyancy=25.01 tons from the functional specifications were set as target values. The physical and material properties were defined by the literature [16] and the riser's wall thickness and length were set as parameters. The modal analysis is performed using ABAQUS software. All the values combination (riser's length, CFRP wall thickness, foam thickness) that accomplish the target values criteria, are valid. The FSI analysis was performed in later stage for the comparison between polyethylene RTD and RTComp dynamic response.

Many studies[2, 16-18] were carried out for the design and structural analysis of composite risers in offshore industry. However, the Riser Tube of DIFIS System differs from the conventional risers in geometry dimensions and operation. Based on the study [9] the material that was selected for the RT was the CFRP. In [16] a fluid structure interaction analysis was performed, in order to evaluate the performance of a deep water composite riser. The riser's mechanical properties were used to model the RTComp's CFRP layer. The mechanical properties of CFRP are presented inTable 5.

Table 5. Global RTComp specifications [16]

| **Property** | Density | $E_z$ | $E_r$ | $E_\theta$ | $G_{zr}$ | $G_{r\theta}$ | $G_{z\theta}$ | $v_{zr}$ | $v_{r\theta}$ | $v_{z\theta}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **Unit** | kg/m$^3$ | GPa | GPa | GPa | GPa | GPa | GPa | - | - | - |
| **Value** | 2293 | 54.73 | 71.68 | 11.99 | 22.89 | 3.43 | 3.25 | 0.27 | 0.3 | 0.36 |

The total thickness of RTComp's is 53.34 mm. The number of the CFRP layers and lay – up are based on[16]. In order to maintain the buoyancy of riser, foam was applied at the RTComp's external surface. AIREX C70.40 was the most appropriate foam for this application due to the zero water absorption and it's widely use in marine structures [19]. The thickness of foam is 65 mm in order to maintain the neutral buoyancy. The mechanical properties of the AIREX C70.40 are presented in
Table 6. For the foam protection from accidental loads and corrosion, a thin layer of elastomer material (Rubber) is applied. The thickness of rubber is 0.5 mm and its mechanical properties are presented in
Table 6[20].

Table 6. Physical and mechanical properties of AIREX C70.40 and Rubber[19, 20]

| Mechanical Property | Unit | AIREX C70.40 | Rubber |
|---|---|---|---|
| Density | $kg/m^3$ | 40 | 1100 |
| Young's Modulus | MPa | 28 | 2.01 |
| Poisson's Ratio | - | 0.07692 | 0.45 |

Consequently, the overall thickness of RTComp is 118.84 mm and the internal diameter of RTComp tube is 1762.32 mm.

**Modal Analysis**

The modal analysis was mandatory in order to define the dynamic characteristics for the RTComp. The modal analysis is part of multidisciplinary process. The CFRP and foam wall thicknesses based on buoyancy and mass criteria[7]. Moreover, the selection of the appropriate length was set under consideration relative to the material properties. A parametric analysis was launched estimating the normal modes for five different RTComp length between 30 – 50 meters (Table 7).

Table 7. Modal analysis results of RTComp

| | Length 50 m | | Length 45 m | | Length 40 m | | Length 35 m | | Length 30 m | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mode** | **Frequency (Hz)** | **Type** | **Frequency (Hz)** | **Type** | **Frequency (Hz)** | **Type** | **Frequency (Hz)** | **Type** | **Frequency (Hz)** | **Type** |
| 1 | 1.0212 | Bending | 1.2337 | Bending | 1.5428 | Bending | 1.9818 | Bending | 2.6345 | Bending |
| 2 | 1.0212 | Bending | 1.2337 | Bending | 1.5428 | Bending | 1.9818 | Bending | 2.6345 | Bending |
| 3 | 2.7111 | Bending | 3.2569 | Bending | 4.0342 | Bending | 5.1157 | Bending | 6.6808 | Bending |
| 4 | 2.7111 | Bending | 3.2569 | Bending | 4.0342 | Bending | 5.1157 | Bending | 6.6808 | Bending |
| 5 | 5.0782 | Bending | 6.0632 | Bending | 6.9145 | Torsional | 7.901 | Torsional | 9.2169 | Torsional |
| 6 | 5.0782 | Bending | 6.0632 | Bending | 7.4354 | Bending | 9.3088 | Bending | 11.96 | Bending |
| 7 | 5.5358 | Torsional | 6.1466 | Torsional | 7.4354 | Bending | 9.3088 | Bending | 11.96 | Bending |
| 8 | 7.9718 | Bending | 9.4593 | Bending | 11.488 | Bending | 14.213 | Bending | 17.862 | Axial |
| 9 | 7.9718 | Bending | 9.4593 | Bending | 11.488 | Bending | 14.213 | Bending | 18.003 | Bending |
| 10 | 10.891 | Axial | 11.973 | Axial | 13.451 | Axial | 15.345 | Axial | 18.003 | Bending |

The selection of RTComp was based on the criterion:

$$f_{n\ RTComp} \geq f_{n\ RTD} \tag{6}$$

Where $f_n$ is the first bending Eigen frequency of the riser. The response of the RTComp will be similar to the RTD's response. The final selection is a 30 meters RTComp. Its Eigen frequency is equal to 2.6345 Hz which is greater from the frequency of RTD's first mode ($f_n$=2.1294 Hz)[6].

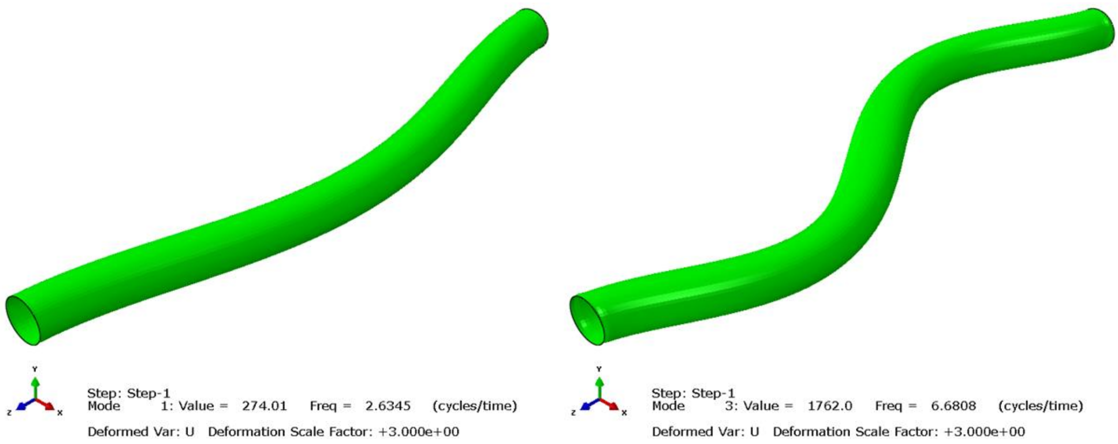


Figure 10. 1st and 3rd modes from modal analysis of RTComp (30 meters)

## TWO–WAY FLUID STRUCTURE INTERACTION ANALYSIS AND RESULTS

According to mesh convergence the number of elements on the two models is presented inTable 8. Moreover, the boundary conditions, the dimensions of the fluid domain and the modeling assumptions and specifications that are presented in study [6] are used in the present 2 – way FSI analysis.

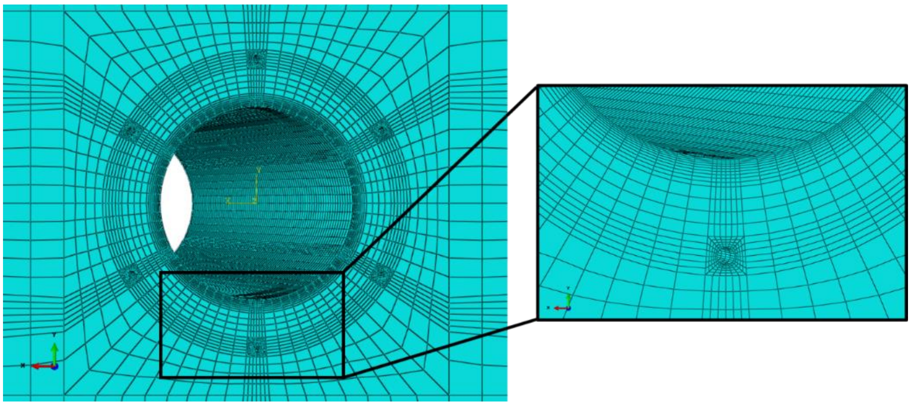

Figure 11. Mesh details for the CFD analysis for both RTD and RTCcomp

Table 8. Mesh parameters

| Model | Elements | Amount |
|---|---|---|
| CSD | S4R (Riser Tube), C3D8R (Mooring Lines) | 7680 |
| CFD | FC3D8 (Fluid Domain) | 693760 |

Table 9 present the data of the 2 – way FSI analysis of RTComp riser and the Figure *13* present the results of the analysis.

Table 9. RTComp 2 – way FSI analysis data

| | |
|---|---|
| **Reynolds Number** | $1.2*10^6$ |
| **Turbulence Model** | RNGk – epsilon |
| **Turbulent Intensity** | I = 5% |
| **Strouhal Number** | 0.45 |
| **Theoretical Vortex Shedding Frequency** | 0.12 Hz |

Table 10. RTComp 2 – way FSI analysis data

| **Modeling Specifications/ Assumptions** | |
|---|---|
| **Riser Tube** | Flexible cylinder including seawater |
| **Sea Water** | Nonstructural mass on the internal surface of riser tube |
| **Riser's Boundary Conditions** | $z = 0, u_x = u_y = u_z = 0$<br>$z = L, u_x = u_y = u_z = 0$ |
| **Interaction Boundary** | External surface of RT (Type: Fluid – Structure Co – simulation boundary |
| **Damping factor** | Structural Damping (ζ = 2 %) |
| **Hydrostatic pressure** | Same for the internal/external surface |
| **Inlet Velocity** | Use of amplitude to prevent intense flow phenomena |
| **Mooring Lines** | Rigid Body due to high pretention load |

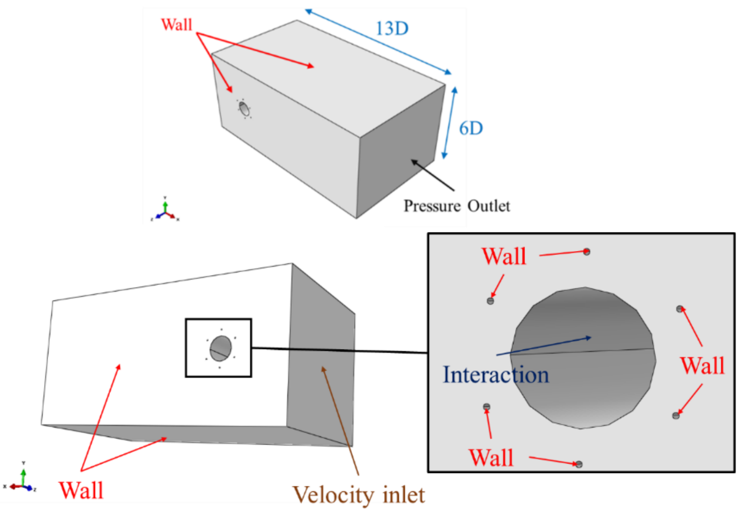


Figure 12. Boundary conditions for the CFD

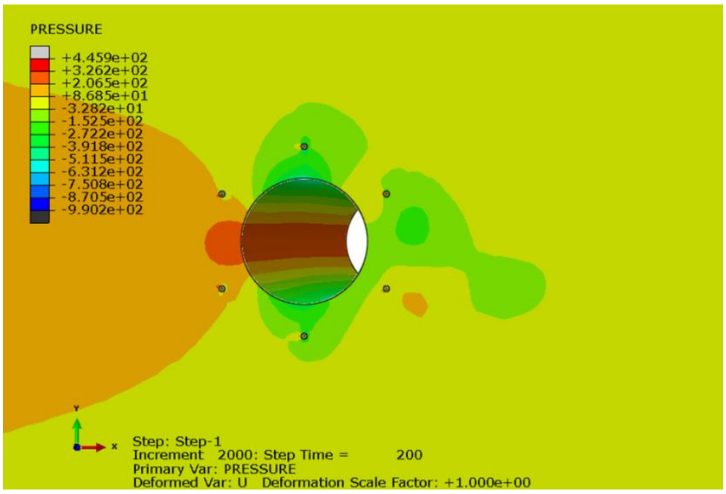


Figure 13. Pressure contour in 200 seconds of analysis time

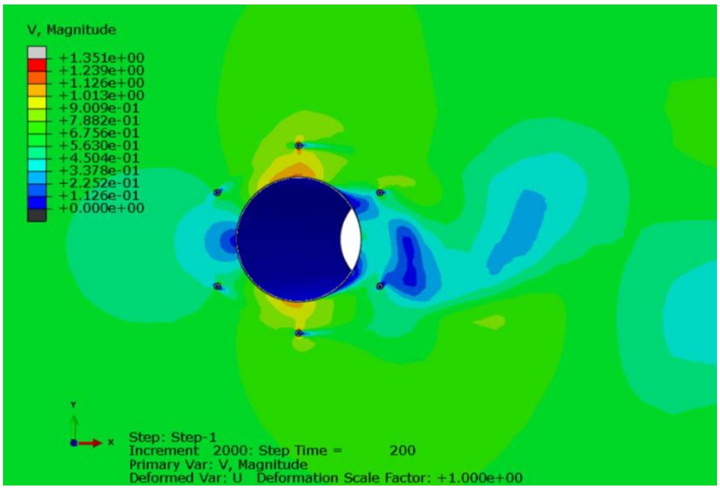


Figure 14. Velocity contour in 200 seconds of analysis time

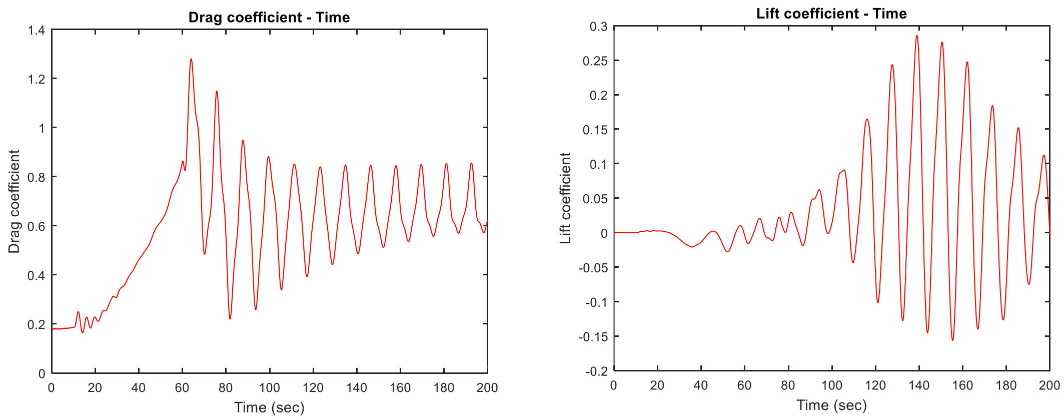


Figure 15. Hydrodynamic coefficients of RTComp

The hydrodynamic coefficients (drag and lift) are presented in Figure 15. The coefficients show an oscillatory response. The mean values for the periodic motion of the forces can be adopted, after 100 seconds ($C_D = 0.66$ and $C_L = 0.05$).

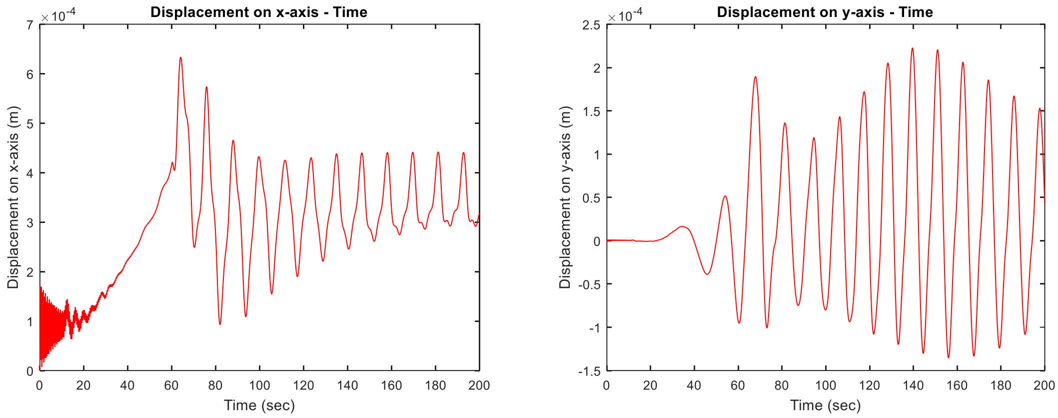


Figure 16. RTComp's center displacements

The RTComp's response is clearly oscillatory and the mean value of the displacements can be easily estimated. The static equilibrium of the riser is reached after 150 seconds. The riser's horizontal (x – axis) displacement is between 0.29 mm and 0.42 mm. In the vertical axis (y – axis) the riser performs oscillation with steady amplitude. If the analysis time was greater the riser's behavior in vertical axis will follow the pattern in**Figure** 16, after 60 seconds (oscillation without damping). The riser's maximum vertical displacement is 0.218 mm. Summarizing, the displacement of the RTComp in both axes do not exceed the critical value of 1 mm from the specifications. Following the F.F.T. analysis (Figure 17), the peak magnitude is 0.09 Hz and is very close to the theoretical value (0.12 Hz) which estimated by Strouhal number [13, 21]. The difference between the two values is based on the presence of the mooring cables in the periphery of the riser and on the deformation of the riser due to flow forces. Figure 17 shows the comparison between FFT analysis of RTComp and RTD.

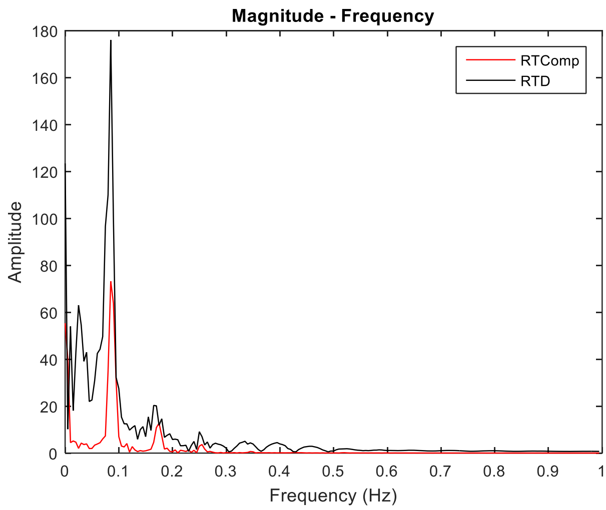


Figure 17. Results of F.F.T. analysis in the lift force for RTComp in comparison with RTD

Comparing the present results with the study of [6] resulting that the RTComp's dynamic response is better than the RTD's response under the same sea current's velocity (0.6 m/s).

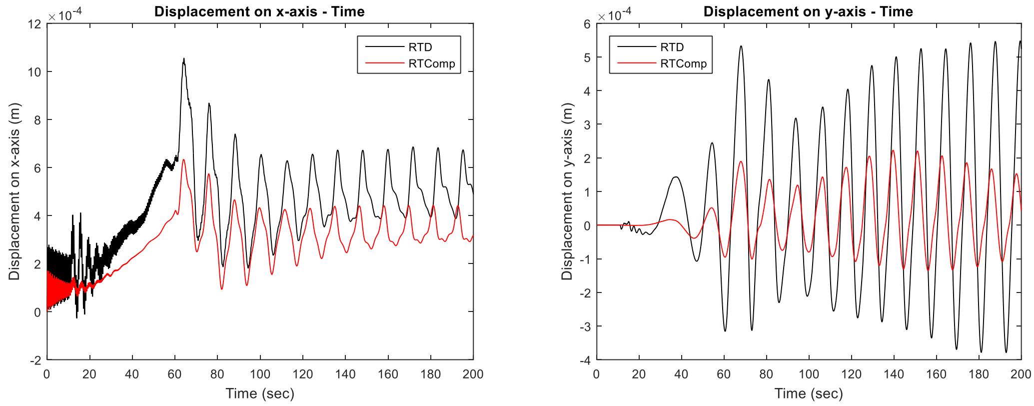


Figure 18. Displacements comparison, for RTD and RTComp

Regarding Figure 18, the displacement of RTComp, in both axes, is lower than the corresponding RTD's displacements. In both axes, the 2 risers follow an oscillatory response. The RTComp amplitude ($A_y$/D) is lower than RTD's amplitude while the RTComp's length is twice the RTD's length (Figure 19).

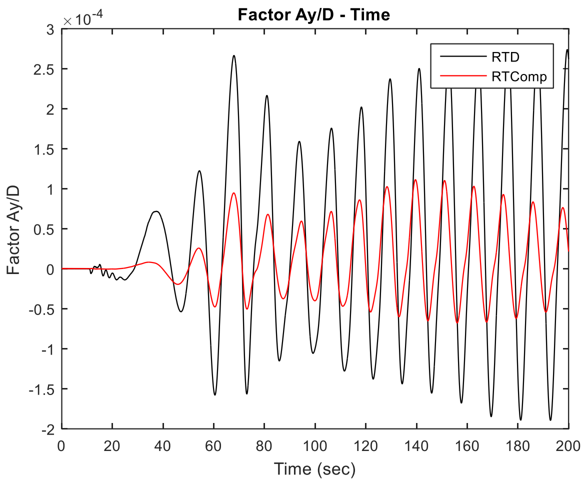


Figure 19. Comparison of factor $A_y$/D, for RTD and RTComp

The use of composite materials for the Riser tube leads to a better structural behavior of the riser tube. The lift amplitude is lower for the RTComp, thus the displacements are expected to be lower due to the greater stiffness.

## RISER TUBE VALIDATION USING HYDRODYNAMIC TESTS

The riser's tube structural integrity was investigated using hydrochannel testing. The experiments carried out in MARIN's facilities using a 1:60 scaled model (Figure 20).

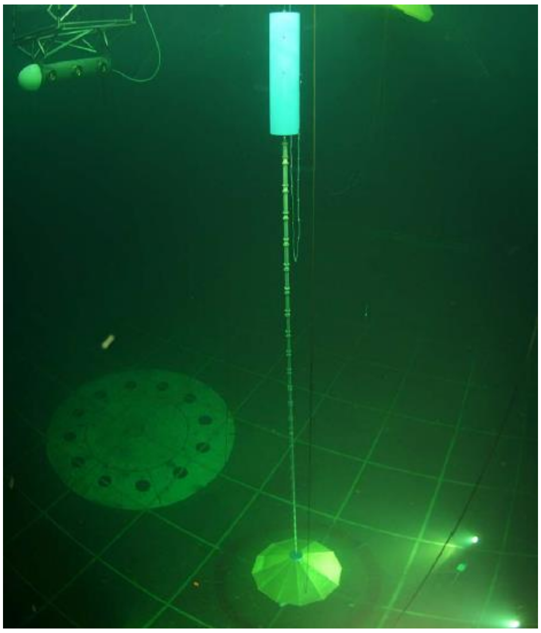

Figure 20. DIFIS scaled model in MARIN's basin during operational tests

The PE riser tubes were also scaled as part of the DIFIS whole structure. PVC pipes stiffened with steel wires assembled the whole riser tube column. The steel wires were used to increase the bending stiffness of the pipes and to investigate the hydrodynamic flow field around the riser. Different diameters for steel wires were also used to reach the inertia and the stiffness of the polyethylene and composite riser. Strain gauges were attached on riser's center of mass and on the mooring lines in order to monitor the forces at the riser and at the anchoring system, respectively.

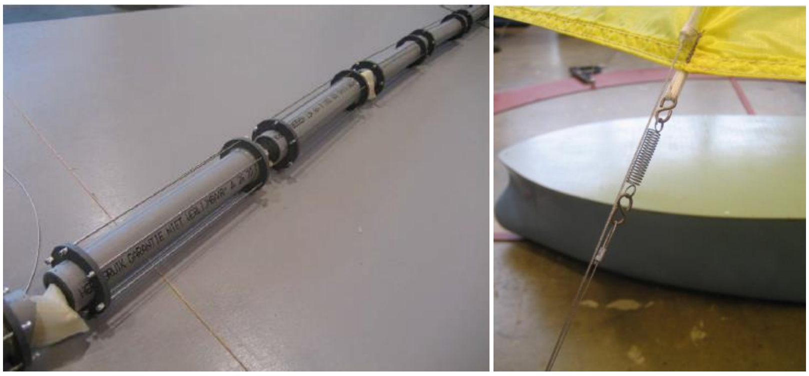

Figure 21. (Left) Risers' assembly for testing and (Right) Strain gauge location on the mooring line.

The Hydro-channel testing campaign included operational, survival and extreme loads on the DIFIS scaled model. The installation procedure and the dome unfolding operation was also tested in the subsea environment at the basin. For the operational scenario: Sea currents 0.6 m/s, the results for the composite numerical (present study) in comparison with the PE numerical study and the experiments are presented in Table 11. The displacement values were further extrapolated and corrected using the scale factor.

Table 11. Comparison of DIFIS's RT displacements for flow velocity 0.6 m/s

| Study/Displacements | X – axis Displacement | Y – axis Displacement |
|---|---|---|
| **2 – way FSI analysis/ Composite Riser (present study)** | 0.355 mm (average value) | 0.025 mm (average value) |
| **2– way FSI analysis /PE Riser[6]** | 0.512 mm (average value) | 0.082 mm (average value) |
| **Experimental study[5]** | 0.7±0.1 mm | n/a |

The comparisons show that the composite riser tube has a better response relative to the PE tube and the initial scaled model at the hydro channel.

## CONCLUSIONS

In this study, the design method for the composite RT (RTComp) for the DIFIS System was summarized. The RTComp's length increase leads to a 40% time reduction of the deployment process of Riser Tube column. The necessity of the composite materials for the DIFIS System risers was proven. The combined features of the better deployment time and the greater Eigen frequency for the RTComp improve the DIFIS System as a rapid deployed structure against oil sea pollution. The numerical results for the riser tube were further validated using hydrodynamic tests in MARIN's basin. For future work, a further investigation to the composite materials as riser's core structure is necessary. The CFRP application could be evaluated taking into account the development cost options, which are critical for the production. E-Glass, triaxial/quad axial fabrics, hybrid (glass/carbon, carbon/Kevlar) composites could also be investigated for the further increase of the stiffness/weight ratio.

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