Flexible Riser Installation Optimisation Based on Virtual Prototyping

Pierre Major, Shuai Yuan, Houxiang Zhang
Dept. of Ocean Operations and Civil Engineering (IHB)
NTNU
Aalesund, Norway
{pierre.major, shuai.yuan, hozh}@ntnu.no

Inge Blaalid, Mathieu Edet, Martin Ferstad
Offshore Simulator Centre
Aalesund, Norway
{inge, mathieu, martin}@osc.no

***Abstract*—Flexible riser installations or replacements are operations which need to be accurately planned and trained for. Virtual prototyping (VP) allows engineers to interact with simulation tools in real time (RT) during the planning phase, thereby finding optimal solutions and enhancing operational procedures in terms of safety and speed. Literature research has found scarce publication of simulation of flexible riser installation operations. This study compares the outcomes of a RT VP with a benchmark based on the finite element method. The approach presented throughout this paper can provide some suggestions with respect to the installation of a flexible pipe in practical engineering.**

Keywords—virtual prototyping, flexible riser, installation operation, mechanical analysis, finite element method

I. Introduction

Flexible production risers (FPR) are used to inject water into reservoirs, extract oil and gas during production. According to the Norwegian Petroleum Safety Authority (PSA/PTIL), 326 flexible risers were in use on the Norwegian Continental Shelf in 2013, with a major incident rate of 1.5%, further estimating that 25% of the FPR of had been replaced [1]. Research on FPR is not scarce: publications on corrosion, fatigue and mechanical damage are plenty [2], but to our knowledge, a handful of publications has been published on simulation of flexible riser installation operations, which is a critical part of the life cycle during which handling errors can damage the pipes [3].

Flexible riser replacement and installation operations need to be carefully planned. Riser replacements are critical operations during which specialized vessels operate in close range to platforms. The risers are hanging on the platform in near vicinity to each other with a high risk of entanglement called spaghetti effect. In addition, replacement operations are preferably performed without shutting down field production which increases probability of oil spills occurrence. Thanks to major developments of game engines and performance improvements in both accelerated hardware and real-time (RT) compliant mathematical models, virtual prototyping (VP) technology can reach wider markets to promote safer operating procedures through iterative engineering design and crew training. The VP framework is applied to optimize the operation, so to find maximum wave height to perform the operation, the weather window (minimal amount of time required to safely perform offshore operation, including safety margin), inconsistencies and inefficiencies in procedures. The framework can also be used to identify bottlenecks and possible human communication challenges between the various teams during the simultaneous operations (SIMOPS) such as offshore operation manager, crane operator, remotely operated vehicle (ROV) pilot, offshore vessel captain. Using advanced VP tools, including ghosting based on real environmental models for wind, waves and, current allows the visualisation of the predicted course of operations during contingency scenarios such as vessel drift-off, crane black-out, riser joint failure etc. The VP framework allows for concept verification, simulation and training in a flexible, and efficient way. Its purpose is not to train skilled and unskilled personnel, but rather to provide a holistic perspective of the operation to planning engineers.

As an initial work for VP, the VP model is necessary to be verified by the benchmark physical model for the conceptual design. The purpose of this paper is to validate the VP framework against the simulation by ABAQUS, a general finite element analysis software, in a case study. Within this paper, a flexible riser retrieval operation is performed correspondingly and a FEM-based model for topside pull in operation has been built to simulate the consistent procedure. The pay out and haul in for winch wire and flexible riser are controlled by the simple drums. The bend stiffener (BS) connected with riser end is also taken into consideration. The tension and the curvature along the flexible riser can be calculated. Attention is paid to the influence on the maximum effective tension and maximum bending curvature of the flexible riser during the operation.

The paper is organized as follows. Section II introduces recent related work on flexible risers and VP of offshore operations. Section III introduces the simulated riser pull-in operation, while Sections IV and V respectively present the VP and FEM models. Section VI compares the simulated results. Section VII concludes the paper and opens direction for future work and other applications.

II. RELATED WORK

Flexible pipes are vital to subsea developments worldwide and for Norwegian oil and gas production facilities since 1986 [4]. The installation phase for a flexible pipe includes complicated steps, which needs detailed analysis to understand installation limitations [5]. Advances have been achieved in the research related to flexible riser installation. Control problem of a marine flexible riser installation system was investigated in [6] with numerical simulations. A dynamic analysis model where installation vessel was coupled with the riser system was developed and used to assess risk and weather limitations for riser replacements [7].

Finite element method (FEM) is adopted as an effective method in dealing with nonlinearity and boundary conditions [8][9][10] in the global analysis of flexible riser and has been used to verify the model based on rod theory [11][12]. However, the efforts that have been made rarely focus on the mechanical analyses for a whole planned procedure but single step, which means the impact from the previous step on the next one is ignored.

Ref. [13] extensively details the requirements of physics engines for simulation of shipyard and offshore operations, especially for coupled systems, but the essential RT requirement is not mentioned. While advanced mooring system response solvers [14][15][16] or control design VP framework [17][18][19] already exist, they often lack the integration possibility to interact with humans in the loop (HITL) a virtual environment in RT. VP is often associated with the conjunction of Virtual Reality (VR) and mathematical models for the purpose of training unskilled workers [20][21].

The original contribution of the study is first to integrate VR, RT, and HITL into a VP framework, and second to validate against a benchmark.

III. RISER INSTALLATION OPERATION

Replacement operations involve the removal of an end of life riser and installation of a new one. The operations are more complex and perilous when the production platform is connected to multiple risers. For the sake of simplicity, in this study, the operation consists in the installation of a riser in shallow waters (75 m). More specifically the retrieval of a new riser delivered by a specialized vessel.

The initial conditions of the operation, depicted in Fig. 1 are as follows:

- Offshore vessel (OV) equipped with Vertical Laying System (TLS) mounted over a moonpool stays in close range to the platform, using Dynamic Positioning (DP) to keep position and heading.

- OV pays out riser through the moonpool. Riser tension is measured at the lower end of the upper tensioner.

- A platform winch (PW) is connected to the riser via a wire with a special riser connector.

The goal of the operation is to retrieve the riser from boat. The platform winch pays in the cable to receive the riser while the TLS continues paying out and the vessel drifts away from the platform during the whole operation.

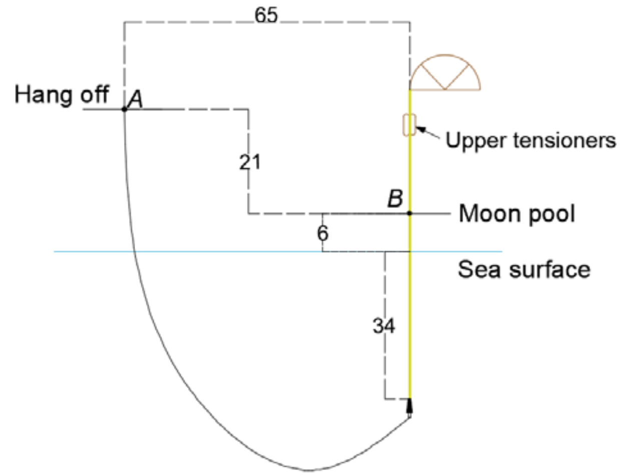


Fig. 1 Initial configuration of pull-in operation (Unit:m)

This phase stops when the BS's hook reaches the platform and can be disconnected from the cable in order to be connected to the locking mechanism on the platform.

During this phase, the vessel is connected to the platform via the riser, this is a potential hazard if the vessel drifts off to the platform due to the risk of collision and from the riser due to the risk of pulling the winch and additional equipment on the platform or simply excessive stretch due do the tension. Other potential damages are collision of the riser with the moonpool's wall or on the jackets' legs or seabed, and in case of high seas successive compression and tension due to the vessel's heave.

IV. OSC SANDBOX VIRTUAL PROTOTYPING

A. *Software Architecture*

The software architecture of the system is sketched in Fig. 2. The Sandbox is the instructor module which starts and controls the simulation scenario. The Core is the central module which dispatches the commands and feedback to the various modules and acts as an interface between them. The Physics is a general-purpose physics solver with able to properly solve collision of rigid body, behavior of ropes, hydrodynamics of

TABLE 1 SANDBOX MODEL PROPERTIES

Property	Value
Ancillaries dry weight	4382kg
FPR (water filled) density	2235kg/m^3
FPR diameter	0.2359m
FPR mass per meter	102.1 kg/m
FPR Bend Modulus	9.904E7
FPR Strech Modulus	3.25E10
Wire density	7800kg/m^3
Wire diameter	0.030m
Wire mass per meter	5.50 kg/m
Wire Bend Modulus	1E9
Wire Strech Modulus	1.5E11
Bend-stiffner bend modulus	Rigid body
Bend stiffener volume	2.1m^3
Water density	1080 kg/m^3

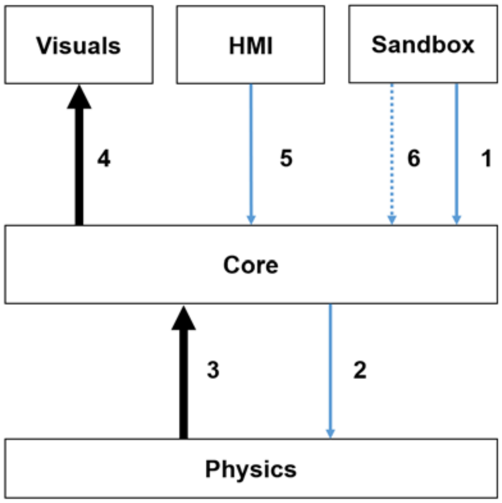


Fig. 2 Sandbox framework architecture

rigid bodies and ropes. The Visuals, implemented a game engine platform with broad developer base called Unity [22], provide life-like immersive environment in which the participants forget they are in a simulation. Finally, the Human Machine Interface (HMI) module sends the winch/crane/vessel lever commands from the human experts performing the simulation.

B. Flow of Information between the modules

Following the numbering of Fig. 1. The user chooses a scenario and starts the Core simulation on the Sandbox and sets the environmental parameters such as wind, wave and current settings (1). The Core starts the simulation and forwards the commands from both the Sandbox and the HMI (2). The Physics module, implemented by Agx, a general-purpose physics solver [23], runs at 60Hz and calculates the forces, accelerations, velocities, positions, orientations of all objects in the scene, then forwards them to the Core (3). The Core forwards the positions and orientations to the Visuals (4). The HMI module transfers the commands from the winch operators to the Core (5). Finally, the Sandbox subscribes to elements in the scene such as winch tension, riser length or curvature, and logs their behavior for the purpose of the analysis.

C. Sandbox Physical Model

A scene is a description of how the models are interconnected and how they behave. All scene items are placed and connected in the Sandbox 3D scene composing tool. Composing advanced scenes in a 3D environment, saves the user time-consuming and error prone XML tree structure editing of scene configuration.

The physical properties of the elements are enlisted in TABLE 1. The FPR and the steel wire are modeled as ropes, with no torsional properties. The tensioner is modeled as a winch connected at the lower end of the top tensioner in the 3D model of the ship. The platform winch is placed at the relevant deck position. The winch drums are not modelled, which gives a significant performance boost, without sacrificing precision.

The vessel is modelled with a Dynamic Positioning (DP) system which controls the ship's heading and position during offshore operation. To simplify comparison between the results, the sea state is no wave and no wind. To circumvent a limitation of Agx not handling properly the buoyancy of the riser, the water density is chosen to be at 1080 kg/m^3.

D. Logged information

The retrieval operation is defined beforehand with a detailed plan for paying in the platform winch and paying out the riser on the tensioner side and moving the ship. The logging, or data acquisition, is not performed continuously but only at predefined operational steps. The logged data comprises time, procedural step, riser tensioner tension, platform winch tension, radius of curvature at BS. For initial and end conditions, the whole riser points positions are stored and for the critical phase where the BS is horizontal, the curvatures along the riser, following Equation (1) from [24], where r is the position on the riser, $\dot{r}$ is the change of direction between 2 consecutive points, $\ddot{r}$ the difference of 2 consecutive changes of direction, and κ the curvature at that position.

$$\kappa = \frac{|\dot{r} \times \ddot{r}|}{|\dot{r}|^3} \qquad (1)$$

Tensioner tension (TT), Platform Winch tension (PW), are also logged, together with the riser point position at step 0 and step 14. The winches are commanded by operators with the help of joystick. As preventing excessive riser bend is key to operation, the position with minimal radius of curvature is added to the logs.

E. Sandbox Results

The operation was run on a standard gaming machine with an i7 6700K @4Ghz CPU and could be performed at real time factor of 2 and lasted one hour. This means that the simulation time went twice as fast as the wall clock time. The simulation starts as pictured in Fig. 3, with the riser hanging vertically and stop as pictured in Fig. 4. The riser is highlighted in pink and the water is not rendered for the sake of visibility.

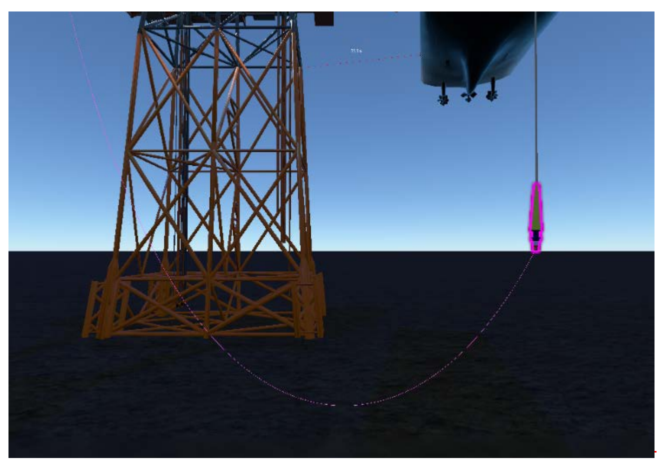


Fig. 3 Initial condition, South view

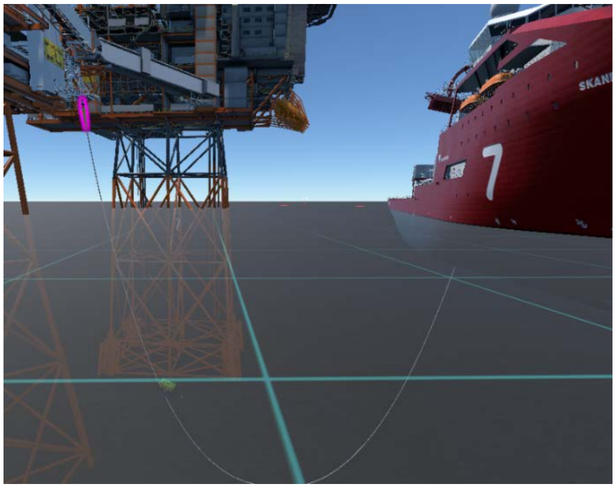


Fig. 4 End condition, South view

V. FEM-BASED SIMULATION

A. Basic introduction of FEM model

This section presents a FEM-based simulation model of a flexible riser topside transferred from installation vessel to the platform. Based on the operation procedure described in Section III, 4 basic parts are introduced in the FEM model by ABAQUS software. The parameters are shown in TABLE 2. The initial lengths are defined without gravity and buoyancy.

1) Flexible riser

Hybrid beam element B31H with 2-node linear beam in 3D space[25] is introduced to model the flexible riser part from moonpool level to BS tip in the FEM. The part above the moonpool is ignored for no need to consider the contact with edge of moonpool during the process. According to the nominal bending stiffness and axial stiffness, the equivalent geometry and material for the cross section can be obtained. The mesh is confirmed by a sensitive study and the other components as well.

2). Ancillaries

This includes BS, pup piece, end fitting and pull head. These parts are extended from the riser and modeled as beam element B31H with larger bending stiffness compared with riser cross-section to simulate the rigid body based on the VP model. Similarly, the equivalent principle is adopted based on the volume and weight.

TABLE 2 PARAMETERS FOR RISER, BS, AND WIRE

Property	Value
Total riser length	214.6 m
Distributed water filled weight	102.1 kg/m
Outer diameter	0.2359m
Nominal bending stiffness	15.059 kNm^2
Nominal axial stiffness	160102 kN
BS length	4.977 m
BS weight	2219kg
Wire Length	140m
Outer diameter	0.03 m

3). Winch wire.

B31H element is adopted for the same reason. The connection between riser and wire is modeled as a joint without rotation restriction.

4). Reeling systems.

Two reeling systems are both simplified as drum shapes and simulated as rigid bodies in the model. The radius of two drums are set as 6m. The reeling analysis incorporates nonlinear geometry and the contact/separation between drums and line structures.

5) Environment.

According to the benign environment of the project, only the buoyancy is considered in the Abaqus for this simulation.

B. Finite-element analysis (FEA) modeling of operation

The procedure simulation consists of several steps. The steps simulated include the reeling procedure, position initialization, riser pay out, wire pay in and vessel translation. These steps are all set as static analysis in the Abaqus. Firstly, a static analysis is performed whereby the boundary constraints and gravity load are applied.

C. Initialization of the Operation in FEM

A schematic of the initial configuration of pull-in in the engineering can be seen in Fig. 1, which shows the spatial position relations of components in the system. In this model, firstly, the top points of riser/wire are coupled with the reference points of drums by all the degrees of freedom. Three steps below are adopted to obtain the initial configuration in the FEM model.

Step 1: Both the riser and wire keep straight. The spatial relation is kept based on the horizontal distance 65m. The joint is set in this step.

Step 2: The gravity is applied on the wire and riser. The riser is reeled on the drum based on the length paid out in the process while the joint is restricted along the Y axis to avoid riser contacted with each other.

Step 3: The winch drum is lowered down to the actual position, pictured in Fig. 5. Blue line represents wire; Yellow line represents riser.

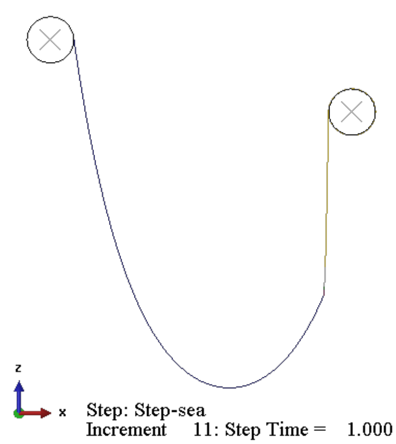


Fig. 5 Step 3 of initialization

1) *Pull in operation*

The pull in is finished basically by flexible riser paid out, winch wire paid in and vessel motion. The procedure is designed to meet the requirements of the facilities capacity. The first procedure is simultaneously paying out the products and hauling in on the platform winch. Then, the pay out and haul in are operated alternately according to the schedule. The FEM simulation is exactly the same as this procedure and has run on a i7-4770U@ 3.4GHz CPU.

VI. VERIFICATION OF TWO MODELS

In order to verify the accuracy of the methods presented and the efficient of virtual prototyping, comparisons are made between the results obtained from the VP simulation and the FEM method.

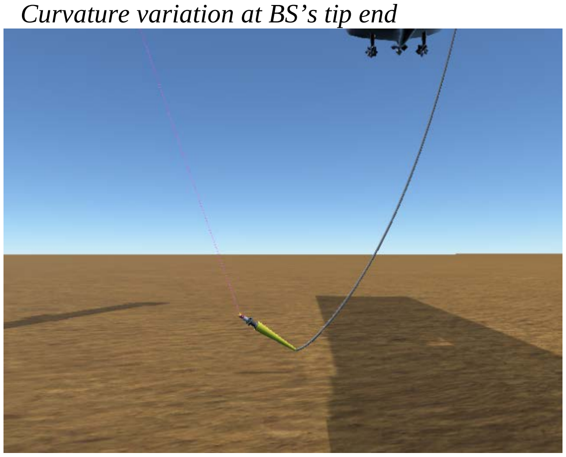
2) *Tension at the measure points.*

The maximum allowable tension is considered as an important design criterion for the tensioner capacity for the installation process. Through the procedure, the maximum effective tension of the riser occurs at the topside above the sea. It can be seen clearly in TABLE 3 that the differences at all the steps are within 10% which means the results from VP are basically correct but further improvement is still necessary.

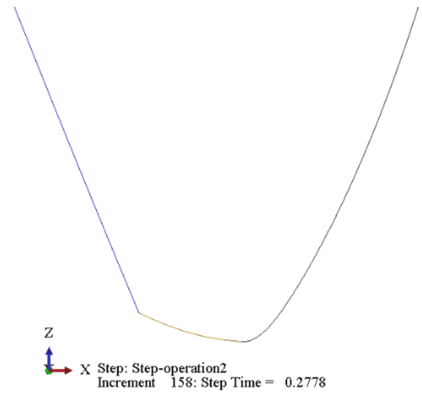
TABLE3. TENSION AT THE MEASURE POINTS

	TT [T]		
Step	VP	FEM	Error
0	8.38	7.86	6.62%
1	9.34	8.83	5.82%
2	7.27	7.60	-4.35%
3	6.44	6.89	-6.47%
4	6.98	7.44	-6.22%
5	6.63	7.09	-6.53%
6	7.47	7.63	-2.07%
7	7.16	7.65	-6.47%
8	7.76	8.19	-5.23%
9	7.66	8.22	-6.77%
10	7.64	8.23	-7.22%
11	7.77	8.37	-7.12%
12	7.75	8.39	-7.58%
13	7.91	8.52	-7.12%
14	8	8.49	-5.77%

3) *Curvature variation at BS's tip end*



(a) VP result



(b) FEM result

Fig. 6. Bending condition of BS's tip end at critical moment

Fig. 6 shows the configurations when the maximum curvature happens. (Fig. 6(a) for VP result/Fig. 6(b) for FEM result). Since the BS is modeled as rigid body in VP and with larger stiffness in FEM, there is a sharp change at the connection between BS and riser. It is obviously verified by Fig. 6. Thus, the real tapered bending stiffness of BS should be taken into account in both simulation and real practice to avoid local buckling at the connection. The result in Fig. 6(b) is from the critical moment during the whole procedure.

For the further study about the curvature variation, Fig. 7 presents the curvature variation along the riser length at the critical moment based on Equation (1). It is noted that the maximum curvature happened at different moment (different pay out) but the same position (BS's tip end) in the simulations of FEM and VP. The results of VP are similar to those achieved from the FEM simulation.

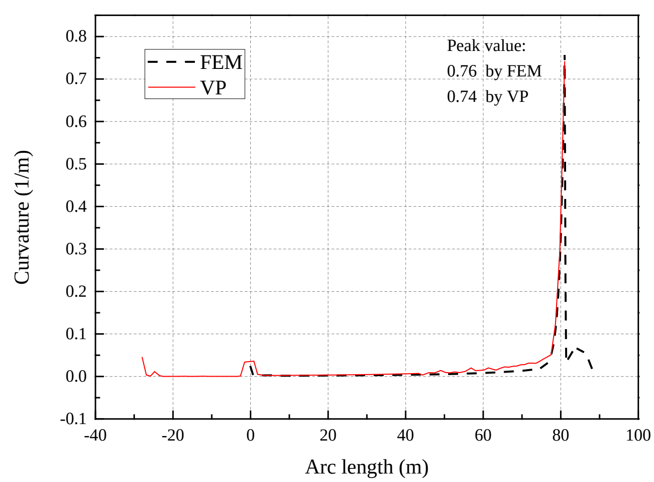


Fig. 7. Curvature variation along the riser length

VII. CONCLUSION

Within this paper, the installation of a flexible pipe transferred from an installation vessel to a jacket platform is studied in a 3D space, and the results obtained from the VP framework are compared with the ones achieved from the FEM simulation. With the whole procedure modeling, the changes of tension and curvature of the riser section are studied in detail.

The two sets of results are basically in good agreement, and it can be concluded that:

- The VP model is physically suitable for the prediction of the riser behavior.
- The proposed FEM simulation can be applied to verify the installation. Consistent procedure can predict the mechanical variation at any time in the process of operation.
- Simulating winches without reels in the VP Framework did not affect the accuracy of the tension at both ends. The VP framework simulated the operation twice as fast as the FEM. The performance hit in ABAQUS is partially linked to the more advanced winch model.
- Modelling the BS as a rigid object coating the riser, is a conservative approach, since it tends to overestimate the curvature of the riser at its open end.

However, the operation simulated in this simulation is simple. Future work should be extended to more severe environmental loads and boundary conditions applied. This implies improving the vessel model with Response Amplitude Operator (RAO) from a hydrodynamics analysis tool such as Wamit [26] or ShipX [27], necessitating a more advanced control system to hold dynamically the ship heading and position. The comparison with ABAQUS will then be based on statistical estimates of multiple runs.

Once dynamical analysis validated, it will be possible to conduct virtual prototyping of riser installation operation with crews of experts improve procedures, avoiding collision and unnecessary bending.

ACKNOWLEDGMENT

We thank Offshore Simulator Centre, Aker Solutions Visioneering and Subsea7 for the inputs. The Norwegian Research Council financing the MAROFF research project called "Riser Operation Replacement Optimization" Grant 282398. Special thanks to the reviewers.

REFERENCES

[1] https://www.ptil.no/contentassets/c2a5bd00e8214411ad5c4966009d6ade/un-bonded-flexible-risers--recent-field-experience-and-actions--for-increased-robustness.pdf

[2] Pipelines, risers and umbilicals failures: A literature review, Geovana P.DrumondIlson P.PasqualinoBianca C.PinheiroSegen F.Estefen, Ocean Engineering, Volume 148, 15 January 2018, Pages 412-425

[3] https://www.ptil.no/contentassets/0e4d166cf8524bf8ae81ceb9d34d8a39/psa-norway-state-of-the-art-bonded-flexible-pipes-2018.pdf

[4] Leira, B., Berge, S., Løtveit, S.A., Fergestad, D., Langhelle, N., 2015, May. Lifetime extension of flexible risers: a generic case study. In: Offshore Technology Conference. Offshore Technology Conference.

[5] Fergestad, D., Løtveit, S.A., Handbook on Design and Operation of Flexible Pipes, NTNU, 4Subsea and MARINTEK, 2014.

[6] He W, Zhang S, Ge S S. Boundary control of a flexible riser with the application to marine installation[J]. IEEE Transactions on Industrial Electronics, 2013, 60(12): 5802-5810

[7] Chrolenko M, Gundersen G, Eikanger T E, et al. Fully Coupled Time Domain Simulation Model Used for Planning and Offshore Decision Support During Riser Replacement Operations[C]//ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, 2018: V001T01A070-V001T01A070.

[8] Owen, D.G., Qin, K., 1986. Model Tests and Analysis of Flexible Riser Systems In:Proceedings of the 5th International Conference on Offshore Mechanics and Arctic Engineering, Tokyo 1986.

[9] Fylling, I., Larsen, C.M., Sødahl, N., Passano, E., Bech, A., Engseth, A.G., Lie, E., Ormberg, H., 1998. Riflex user's manual. Marintek Report, Trondheim, Norway.

[10] Chai, Y.T., Varyani, K.S., 2006. An absolute coordinate formulation for three dimensional flexible pipe analysis. Ocean Eng. 33 (1), 23–58.

[11] Chen, H., Xu, S., Guo, H., 2011. Nonlinear analysis of flexible and steel catenary risers with internal flow and seabed interaction effects. J. Mar. Sci. Appl. 10 (2), 156–162.

[12] Ruan W, Bai Y, Yuan S. , 2017. Dynamic analysis of unbonded flexible pipe with bend stiffener constraint and bending hysteretic behavior[J]. Ocean Engineering, 130: 583-596.

[13] Hye-WL, Myung-Il R, Review of the multibody dynamics in the applications of ships and offshore structures, Ocean Engineering, Volume 167, 2018, Pages 65-76, ISSN 0029-8018

[14] https://www.orcina.com/orcaflex/

[15] https://www.dnvgl.com/services/riser-analysis-software-for-marine-riser-systems-riflex-2312

[16] https://www.sintef.no/globalassets/upload/marintek/pdf-filer/sofware/simo.pdf

[17] Li G, Skogeng PB, Deng Y, Hatledal LI, and Zhang H. 2016. Towards a virtual prototyping framework for ship maneuvering in offshore operations. In IEEE OCEANS 2016-Shanghai, p. 1-6

[18] Chu Y, Hatledal, L.I., Zhang H, Æsøy V and Ehlers S. 2017. Virtual Prototyping for Maritime Crane Design and Operations, Journal of Marine Science and Technology.

[19] Major P, Skulstad R, Li G, Zhang H. 2019. Virtual prototyping: a case study of positioning systems for drilling operations in the Barents Sea, Ships and Offshore Structures

[20] Zhang X, Duan M, Mao D, Yu Y, Yu J & Wang Y. 2017. A mathematical model of virtual simulation for deepwater installation of subsea production facilities, Ships and Offshore Structures, 12:2, p.182-195

[21] Yu Y, Duan M, Sun C, Zhong Z, Liu H. 2017. A virtual reality simulation for coordination and interaction based on dynamics calculation, Ships and Offshore Structures, 12:6, p. 873-884

[22] https://unity.com/

[23] https://www.algoryx.se/download/installers/AGX_Dynamics_UserManual.pdf

[24] https://en.wikipedia.org/wiki/Radius_of_curvature

[25] Systemes D. ABAQUS Users' Guide 2019[J]. Dassault Systemes: Paris, France, 2019.

[26] https://www.wamit.com/

[27] https://www.sintef.no/en/software/shipx/