COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-1062
DESIGNING AND TESTING A SUBSEA TOOL FOR PIPELINE INSPECTION: DETECTING FLOODED ANNULUS USING DIFFERENTIAL PRESSURE METHOD

Carlos Alberto Nogueira Jr.[1]
Doglas Negri[2]
Ismael José Secco[3]
João Vítor Herrmann[4]
Instituto Senai de Inovação em Sistemas de Manufatura
carlos.nogueira@sc.senai.br[1], doglas.negri@sc.senai.br[2], ismael.secco@sc.senai.br[3], joão.herrmann@sc.senai.br[4]

Andrea Piga Carboni[5]
UFSC - Universidade Federal de Santa Catarina - Centro Tecnológico de Joinville
andrea.piga@ufsc.br[5]

Eduardo César Cordeiro Vieira[6]
Sapiens Parque S.A.
eng.eduardocv@gmail.com[6]

Abstract. *Flexible pipelines play a vital role in the offshore industry, serving as essential structures for various functions, for instance, oil extraction and gas lifting. A major issue currently faced is the lifespan reduction of flexible pipelines due to annular flooding, which compromises its structures. Regular inspections of flexible pipelines are crucial for ensuring their integrity and preventing operational issues. Therefore, the discussion about inspection techniques highlights the advantages of the depressurization technique for diagnosing annulus conditions. This paper presents an excerpt of a research, focusing on describing the design and simulation of the anchor mechanism for a subsea tool capable of detecting flooded annulus using depressurization technique, allowing for the inspection of the entire pipeline section at once. The authors describe the design process from the mechanism synthesis to the 3D concept. Additionally, kinematics and rigid body dynamics simulation were conducted. The developed tool demonstrated its effectiveness in quickly self-centering anchoring to pipeline end-fittings, providing a robust alternative for operations in the challenging subsea environment. Overall, this research presents a valuable contribution to the field of flexible pipeline inspections, addressing the need for remote and efficient techniques to ensure the integrity of offshore oil and gas infrastructure.*

Keywords: *Non-destructive testing, subsea inspection, offshore oil and gas, flexible pipeline, rigid body dynamics.*

1. INTRODUCTION

The offshore oil and gas (O&G) industry provides numerous socioeconomic benefits to society. Since offshore oil and gas reserves represent a crucial component of global energy security, they play a pivotal role in meeting global energy demands. Besides, the offshore oil and gas industry has been a key driver of economic growth, energy security, and technological advancement for many countries over the past several decades.

On the other hand, operational expenditure (Opex) is a crucial aspect of sustaining day-to-day activities in industries such as oil and gas. It encompasses recurring costs such as maintenance, inspections, equipment operation, and data analysis, as well as safety and environmental compliance. Opex directly affects profitability and operational efficiency. To enhance Capex efficiency and reduce Opex, closely monitoring assets is essential. This strategic approach prevents issues including environmental disasters and reputational damage, ensuring a competitive edge for petroleum companies.

Following the discoveries of new offshore O&G reservoirs, the amount of floating production storage and offloading (FPSO) units has considerably increased. In this scenario, flexible pipes, also known as unbonded flexible pipes, have assumed a primary role in the transportation of O&G from these reserves to the production unit. Unlike traditional rigid pipelines, flexible pipelines are constructed using a combination of layers that provide structural integrity while enabling flexibility to effectively absorb platform movement as well as smoothly adapt to the seabed conditions. Furthermore, the flexibility of these pipelines enables them to accommodate lateral, axial, and angular movements, making them suitable for challenging offshore environments and dynamic seabed conditions. Its typical structure, from inside to outside, consists of the following main layers:

- Interlocked carcass layer, designed as helical stainless-steel wire, usually to resist uniform external pressure from seawater and avoid the erosion of the inner sheath from the medium;
- Internal pressure sheath, a cylindrical polymer layer, typically made of materials such as high-density polyethylene (HDPE), designed to provide a sealing barrier for the internal medium while transmitting of internal pressure;
- Interlocked pressure armor layer, steel wire helically wound around the inner sheath, mainly used to resist the internal pressure from the inner sheath;
- Anti-wear layer composed of a polymer with an extremely low friction coefficient, mainly used to reduce the possible friction and wear between the metal layers;
- Inner and outer tensile armor layer, steel wire helically counter-wound around the interior structure, mainly used to resist the axial loads and ensure the torsional balance of the pipeline itself;
- Aramid reinforcement tape, is a fiber reinforced tape material. Its function is to avoid buckling and provide tensile strength and creep resistance. This avoids as well the birdcaging situation. (Offshore mag, 2017)
- Outer sheath, made of a polymeric material such as polyurethane or HDPE, is extruded over the pressure armor layer, providing mechanical protection, and acting as a barrier against seawater and environmental elements.

The entire region contained between the outer sheath and internal pressure sheath is called annulus. The Figure 1 shows the typical flexible pipes structure.

Figure 1 – Typical flexible pipe structure (Provasi et al., 2022).

Despite flexible risers being engineered with strong anti-collapse capacities, they do occasionally fail due to various factors, including excessive increase in external pressure, carcass corrosion, installation damage or even fabrication anomalies. (Cosham and Hopkins, 2002) (Li et al., 2021).

A highly concerning failure mode of flexible risers is known as Stress Corrosion Cracking in the presence of CO2 (SCC CO2), considering that all the metallic material in the annulus region is subjected to this phenomenon. This type of failure occurs in the presence of CO2 and high stresses. Moreover, the SCC CO2 phenomenon is enhanced in a condition known as flooded anulus (presence of water in the annulus region). This is because CO2 converts to carbonic acid when it comes into contact with water, creating a risk scenario for some extraction conditions (Brandao et al., 2021).

The current article outlines the development and testing of an inspection tool designed to detect flooded annulus in flexible lines, capable of operating at depths up to 3000m. This tool introduces an alternative approach utilizing a method called differential pressure, which is unaffected by critical locations such as beneath bending stiffeners, sag-bend areas, and end-fittings. The present invention aims to provide agility in the inspection process, since the differential pressure method inspects one entire pipeline section at once.

2.PROJECT REQUIREMENTS

Flexible pipelines are expected to have an operational lifespan of 20 years in seawater. Ensuring their integrity throughout their lifetime is crucial, necessitating regular inspections to assess the condition of the annulus space. This becomes particularly challenging in offshore environments where depths can reach up to 3000 meters, making it impractical for divers to perform inspections. Therefore, it is essential to develop a specialized tool capable of operating at such depths, enabling remote inspections without the need for human divers.

In the offshore environment, inspections are typically performed using work class Remoted Operated Vehicles (ROVs), hence, it is important to develop a tool that can be installed on this type of equipment.

There are some annulus inspection techniques available, and one important technique involves the use of a vent valve embedded in the end-fitting, known as the differential pressure method. This technique requires access to the vent valve, which requires the creation of an isolated region and enables pressure control using specific equipment. Once the connection is established, it's necessary to communicate with the annulus region and induce a pressure drop until the valve opens. Once the vent valve is open, it becomes possible to measure the pressure in the annulus region. Based in this pressure measurement, it is possible to determine the presence or absence of water. If the annular pressure returns to equilibrium with the surrounding environment, it indicates the presence of water. Figure 2 presents the overall function of an inspection system, along with its elementary functions.

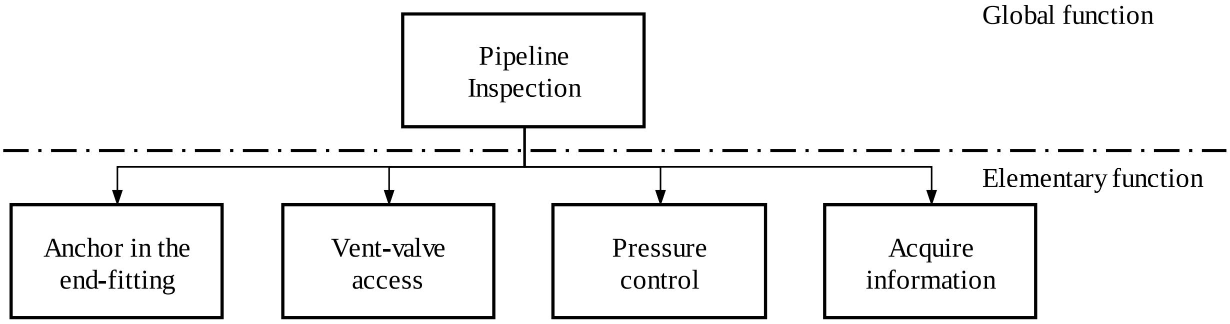


Figure 2 – Function tree with the global and elementary level for a pressure inspection system.

Flexible pipes are available in various sizes, with 6-inch (152,4mm) and 8-inch (203,2mm) being the most used sizes. The vent valve in their end-fitting can be positioned radially or axially, depending on the design provided by the supplier. In the Brazilian scenario, there are three major suppliers of flexible pipes. The proposed tool, referred to as the inspection tool, is specifically designed for inspecting two of these suppliers, namely Baker Hughes (BH) and National Oilwell Varco (NOV). This article focuses on the development of the inspection tool, which is one of the three equipment components comprising the inspection system, as illustrated in Figure 3. The tool highlighted by the dotdash line, consists of 3 interchangeable modules that allow specific assembly arrangements, which can be either axial or radial.

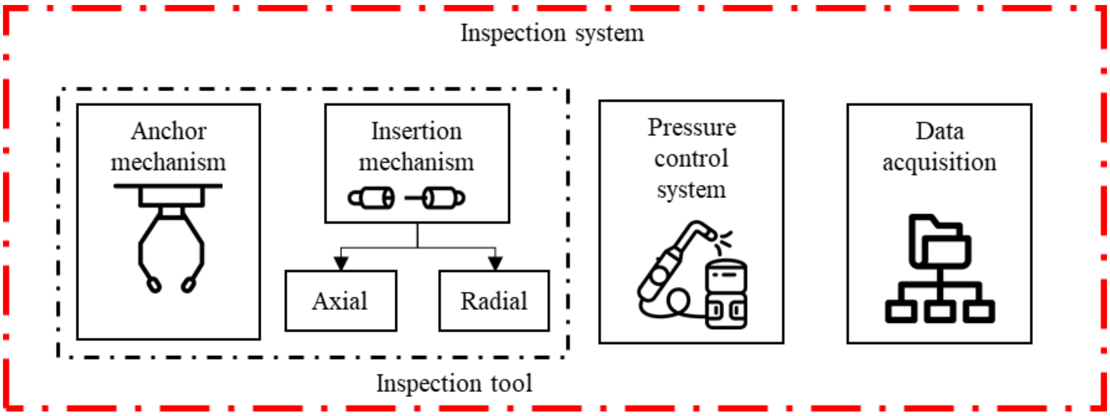


Figure 3 – Diagram of required equipment for inspection system.

Based on the similarities of the pipelines, an analysis was conducted to determine the adjustments required for the proper positioning of the tool in the vent valve region. It was observed that the end-fittings have diameters of 495mm and 625mm. Additionally, adjustments in three axes were identified as necessary, which apply to both suppliers. These adjustments involve rotation and translation along the pipe axis, as well as translation along the radial direction of the pipe. To accommodate the different inspection positions (axial or radial), a change in the setup is required as the insertion mechanism alters the translational motion. However, once the appropriate setup is in place, the tool can effectively cater to the inspection needs of both manufacturers of end-fittings.

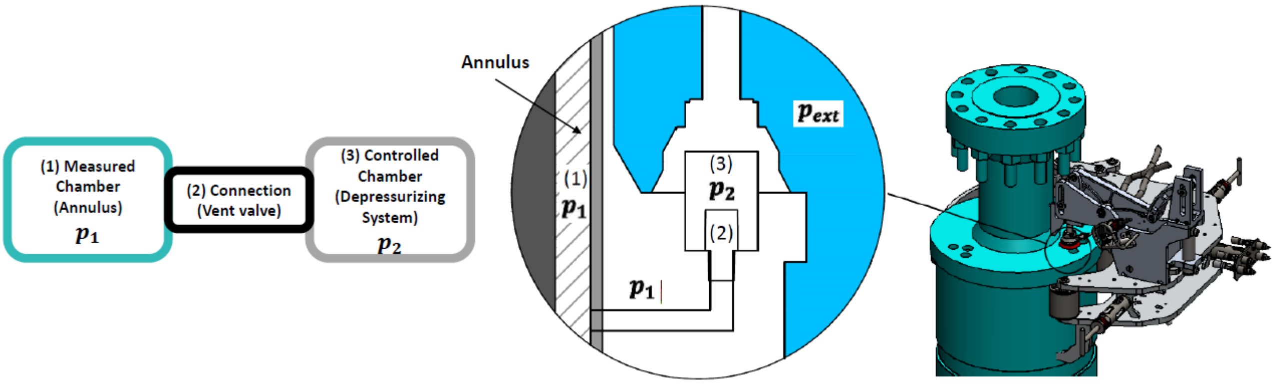
3. INSPECTIONS TECHNIQUES

To ensure the integrity, reliability, and prevent collapse of the flexible pipelines, effective in-service inspections aimed at detecting annulus condition must be managed using non-destructive testing (NDT) techniques. An effective inspection must establish the present condition and predict the possible degradation of the pipeline thus preventing loss of containment. Although flexible pipes represent an attractive alternative to rigid pipes, its complex multi-layered structure is not favorable for inspection using most conventional NDT techniques. Furthermore, the ability to inspect critical locations such as beneath bending stiffeners, in sag-bend areas and end-fittings is a major challenge (Dahl et al., 2011a).

Studying the integrity monitoring of flexible risers is not a novel endeavor. In 1996, (Dahl et al., 2011b) has published the implementation of instrumented flexible risers with the aim of monitoring loads and strain. The author used various sensors to collect data, including strain gauges, accelerometers, and gravity sensing inclinometers. The study demonstrated the strong correlation between the bending moment of the riser and the connection heave of the riser, which supports the case that the primary source of riser excitation is vessel motion.

3.1. DEPRESSURIZATION TECHNIQUE

The depressurization technique involves creating a chamber around the vent-valve. The pressure in this chamber is monitored and can be altered by the depressurization system, enabling access to the annulus region for the vent-valve and facilitating the checking of the annular pressure. Figure 4 provides a visual representation of how this technique works, allowing for the observation of the inspection tool assembled at a pipeline's end-fitting. In the figure, it is possible to see how the chamber is created around the vent-valve.



a) b)

Figure 4 – Visual representation of depressurization technique a) simplification of the measuring process; b) real parts performing the measuring process, for the end-fitting configuration. The p_{ext} stands for external pressure.

This inspection technique is straightforward, but some main advantages are that with the results measured it’s possible to determine a range of situations that occurs inside the riser’s shield. The measured chamber in this method is the annulus (Marinho et al., 2022), (Kuhn et al., 2020a). Some situations that can be inferred from this measurement are: a) annulus flooding, b) breach of outer sheath, c) venting valve proper functioning and d) end-fitting proper sealing. When compared to other non-invasive technologies for offshore inspection (Dahl et al., 2011c), this method demonstrates more range of applications and diagnosis for the riser duct, when comparing to other existing methods.

It is possible that long term monitoring with this technique may correlate to other diagnosis and symptoms as well. Further studies are necessary to ensure that this is possible. One potential example is the seabed level and depth variation, that may cause changes in the annulus internal pressure, that shall be measured by the inspection tool.

3.2. FURTHER TECHNIQUES

Considering the situations that can be diagnosticated by the Depressurizing system, some other technologies apply, such as the ones displayed in Table 1. It is important to emphasize that the method the Depressurizing system uses is the only capable of diagnosing problems within the end-fitting Sealing. It should be noted that there may be other detection methods that the authors didn’t know of that are not cited in Table 1.

Table 1 – Detection methods and possible diagnosis for each method.

Detection Techniques	**Diagnosis possibility**			
	Annulus flooding	Breach of outer Sheath	Venting Valve Function	End-Fitting Sealing
Depressurizing system - Annulus Vacuum and Volume Testing	**X**	**X**	**X**	**X**

Survey of armour wires and water in annulus	X			
Venting Volume Monitoring		X	X	

Few techniques can diagnosis the annulus flooding and guarantee a proper end-fitting sealing. The depressurizing method can do that while checking for the venting valve function. It is important to refrain that the venting valve function is crucial to long term life for flexible pipes.

For the breach of outer sheath diagnosis, some methods were not shown in Table 1: ultrasound; visual/video inspection by diver/ROV; laser leak detection survey; I-tube camera survey; RFID (Kuhn et al., 2020b); acoustic emission (Clarke et al., 2011) and electromagnetic testing (ASNT, 2007). There are restrictions that can be cited for some methods. Regarding the RFID method, this method requires intervention in the flexible pipe prior to the field installation. Also, for the acoustic emission method, it should be noted that there should be some permanent physically installed equipment in the region of interest. For the ultrasound method, the entire length of the flexible must be inspected, for example. When comparing the depressurizing system with other methods, it should be noted that this method applies well for existing and new flexible pipes and lacks the need of intrusions in the flexible pipe armor outer sheath.

There is a range of NDT technologies in existence or being developed, including radiography, fiber optic stress monitoring, gamma ray, and more (Carneval, 2006) (Kaur et al., 2021) developed a robotic system for deployment of radiography-based NDT system for subsea environment. Although the radiography method yields good results, the developed system is only capable of operating up to depths of 100m. Jacques *et al* compared optical fiber Bragg grating and acoustic emission technique to monitor the rupture of flexible pipe armor into a controlled environment. Despite showing promising results in accurately determining wire failure, the authors acknowledged the complexities associated with applying this technique in real offshore environment due to its invasive nature.

Marinho et al developed a non-invasive system capable of detecting the presence of water in the annulus (flood condition) of a flexible pipe using the gamma rays transmission technique. The authors build an experimental setup and collect a great amount of data in laboratory environmental dry conditions. However, in underwater environments, the scattering and absorption of gamma rays by water can further reduce their penetration capabilities. This can result in limited visibility and reduced image quality, making it challenging to detect flooded annulus accurately.

4. TOOLING DESIGN

The development of a tool based on a linkage mechanism involves several important steps, including project and structural requirements, number and type synthesis, dimensional synthesis, geometric modeling, simulation, force analysis, and manufacturing. The synthesis and modeling steps play a pivotal role in reaching a functional and efficient design, while simulation, analysis and manufacturing are crucial to ensure reliability.

The gathering of project and structural requirements is a crucial step in initiating the development process. In this context, the proposed mechanism is required to have 1 degree of mobility, consisting of 6 links and 7 joints. These specifications serve as fundamental guidelines for designing and creating the mechanism. The number and type synthesis helps assess the feasibility of the solution, while the dimensional synthesis determines the sizes of the individual components or bodies involved (Martins and Murai, 2019)**.** Furthermore, it is imperative to consider the mechanism's high-alignment capability with the end-fitting to ensure optimal functionality and performance.

The first step to start a mechanism design is to define its path. In Figure 5 a) the points R3 and R’3, which represent the minor contact position and major contact position, respectively, are crucial in defining a significant portion of the mechanism’s path. With the trajectory defined, the distribution of the other joints of the mechanism was initiated. These points R3 and R’3 serves as key reference, allowing for the proper arrangement and alignment of the remaining components, ensuring the mechanism functions as intended.

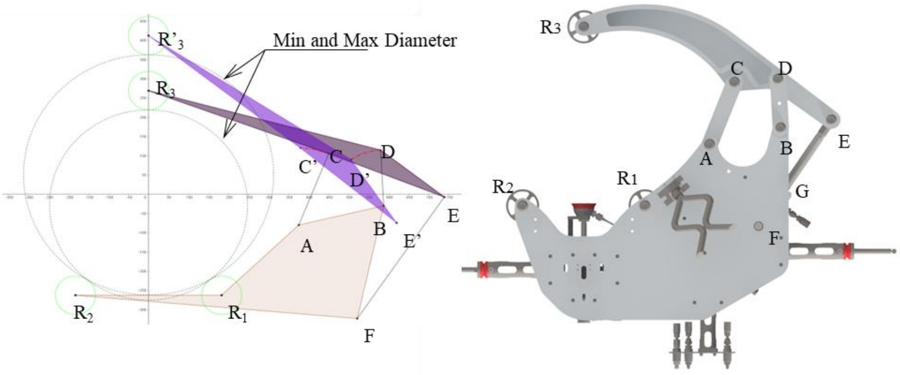


Figure 5 - Mechanism synthesis transformed into 3D model.

An accurate geometrical modeling of mechanisms is fundamental for engineering design, analysis, and manufacturing. For creating a realistic geometry representation of the proposed mechanism, the SolidWorks® software by Dassault Systèmes was employed. This software provides parametric modeling capabilities to accurately represent its geometry and physical properties maintaining the mechanism concept design constraints. The 3D representation of the mechanism is shown in Figure 6 and Figure 8. Basically, the joints position of the mechanism was maintained, and the links were carefully modeled to prevent any collisions with the pipe.

For the Figure 6, the following parts are: 1 – Roller 2, 2 – Finger, 3 – Link 1, 4 – Link 2B, 5 – Link 2A, 6 – Cylinder rod, 7 – Base, 8 – Roller 1, 9 – Roller 3 and 10 – Cylinder cover.

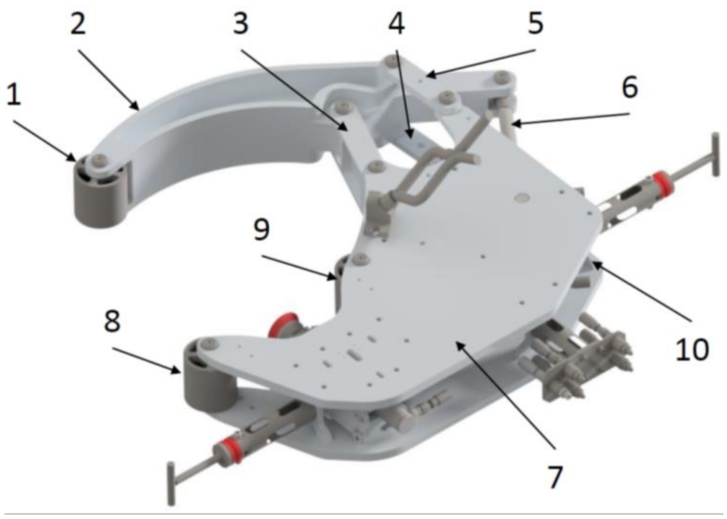


Figure 6 - 3D tool concept perspective view and its respective main bodies.

Using the geometric model of the tool, a dynamic simulation using the MSC Adams was conducted to employ the resulting force from the inspection process in the mechanism, referred to as the operational force (F_O). This force is derived from a project requirement. This simulation determined that the force necessary to apply to the hydraulic cylinder. The tool design followed the force given by standard hydraulic cylinder with 50mm of piston diameter, being F_O = 40.6 kN.

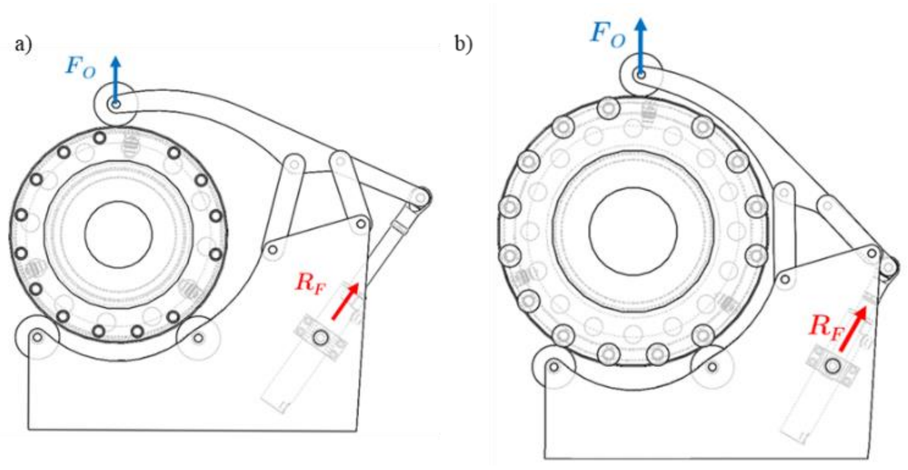


Figure 7 – Projection of the tool anchored to the end-fitting. a) End-fitting with 495mm of diameter; b) End-fitting with 625mm of diameter.

5. MECHANISM SIMULATION

The kinematical and dynamic analysis play a crucial role in understanding the behavior and performance of mechanisms. They involve the study of motion and the interrelation between various components of a mechanical system. The main goal of this simulation was to test whether the mechanism is capable of effectively anchor and centralizing around end-fitting with diameter of 625mm. The analysis was conducted using MSC Adams View® software by Hexagon AB, a widely used tool for rigid body simulation and analysis of mechanical systems.

The centralizing mechanism aims to provide greater agility and speed in positioning the inspection tool, ensuring self-alignment of the mechanism in the duct. This self-alignment being due to the use of three contact points, which naturally center themselves in cylindrical structures when anchoring in them. In the start of the self-centering mechanism, only one roller is in contact with the flexible pipe, then it pulls the mechanism into the pipe, allowing another roller to clamp together. The final roller then comes by and completes the three contact points, thus providing the centering position of the mechanism into the flexible pipe. Those steps can be visualized in Figure 8.

To implement the proposed analysis, the following main tasks have been executed: importing the 3D model to Adams View® environment, creating appropriate joints connecting the rigid bodies, applying actuating external forces, adding solid to solid contact forces and analyzing the mechanism temporal behavior.

By utilizing the import functionality in Adams View®, it is possible to incorporate a 3D model created in third-party CAD software such as Solidworks, Autodesk Inventor or even a CAD data exchanging formats including STEP or Parasolid. However, when a 3D model is imported, the solids are disconnected, meaning that there are no recognized joints between the bodies, requiring the creation of appropriate joints. To reproduce the desired motion of the proposed anchor mechanism, four different types of joints were utilized: spherical “S” (locks 3 translational Degree of Freedom - DOF), revolute “R” (locks 3 translational and 2 rotation DOF), cylindrical “C” (locks 2 translational and 2 rotational DOF) and inline “I” (locks 2 translational DOF). In a simulator, it is essential to eliminate hyper-redundancy because an over-constrained mechanism makes it impossible to solve the kinematics accurately. To address this issue, the inclusion of spherical joints can help alleviate the problem. Spherical joints offer a greater degree of freedom and flexibility, allowing for smoother and more realistic motion within the simulator.

When considering the physical construction of the mechanism, polymer bushings are particularly suitable in this context. Polymer bushings possess low lateral stiffness, which means they allow for greater flexibility and adaptability.

The insertion points of the joints are depicted in Figure 8, and their respective descriptions are provided in Table 2.

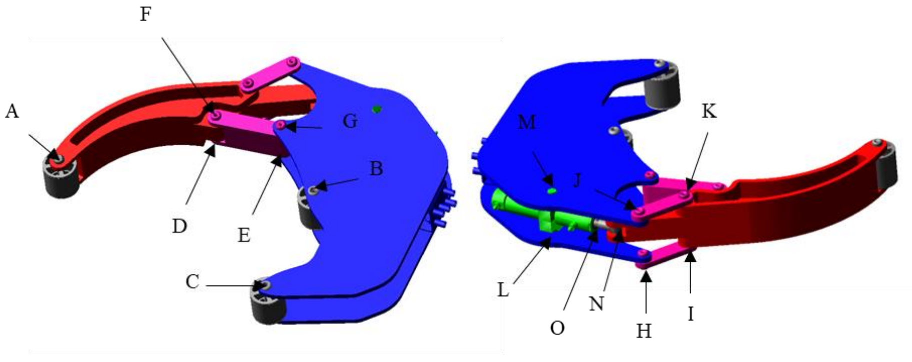


Figure 8 - Joint locations.

Table 2 - Defined joints configuration.

Representation	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
First Body	1	9	8	3	3	3	3	4	4	5	5	10	10	6	6
Second Body	2	7	7	2	7	2	7	7	2	7	2	7	7	2	10
Joint type	R	R	R	S	I	I	R	I	R	R	I	S	I	I	C

Furthermore, a force of 40.6 kN was employed to simulate the cylinder actuator, which is responsible for closing the anchor mechanism. The force was set up on the cylindrical joint, and the net force in each joint are given in the Table 3.

Table 3 – Net forces in each joint of the clamp mechanism, the force are in kN.

Joint	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Ø 495 mm	26.5	2.7	2.5	62.8	62.7	62.8	62.7	2.6	2.5	2.6	2.5	41.1	41.1	41.1	40.6
Ø 625 mm	37.3	13.3	14.8	102.3	51.1	102.3	51.1	14.7	14.7	14.7	14.7	21.9	21.9	43.5	40.6

In addition, contact forces were created to simulate the interaction between the anchor mechanism and the end-fitting. These forces were established between the rollers and the end-fitting body. In this study, the end-fitting was attached to the ground, while the anchor mechanism was free to move in space. The first simulation, focused on the utilization of the 625mm diameter end-fitting. Figure 9 shows four significant stages depicting the temporal motion of the anchor mechanism. In the first stage, the mechanism is in an open position, prepared for attachment to the end-fitting. As the actuator moves forward, it reaches the second stage where roller 2 contacts the end-fitting. The third stage occurs when both roller 2 and roller 1 touch the end-fitting. Finally, the last stage is attained when all three rollers make contact with the end-fitting, effectively centralizing the mechanism to the end-fitting.

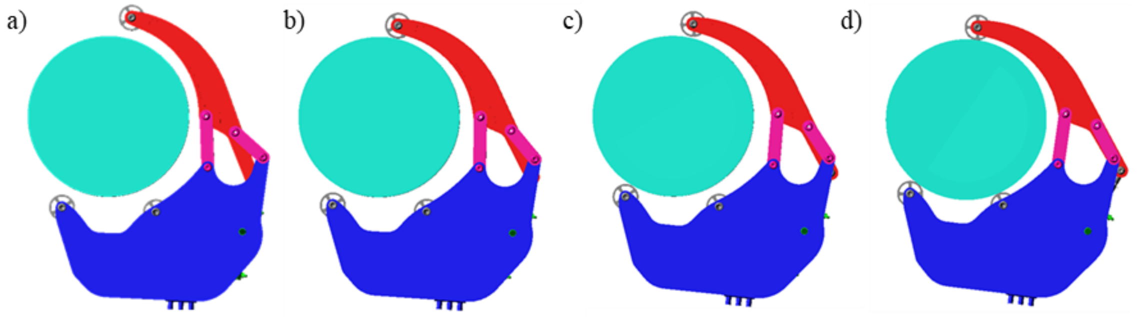


Figure 9 – The temporal kinematics of the anchor mechanism. a) Initial stage; b) second stage; c) third stage d) last stage.

It is well known that applying a constant force to displace a certain mass leads to an acceleration that is directly proportional to the applied force. Considering the influence of the damping force on the dynamics of the mechanism ensures a smooth motion that closely resembles real-world behavior, as illustrated in the Figure 10-a. In this illustration, the closing velocity is established at a constant value of 25mm/s until it reaches the final position, reaching zero velocity. The damping force should act in the opposite direction to the acting force and can be mathematically described as follows:

$$Fd(t) = \boldsymbol{C} * \dot{\boldsymbol{x}}(t), \quad (1)$$

where $\dot{\boldsymbol{x}}(t)$ is the real-time velocity of the cylinder and $\boldsymbol{C}$ is the damping coefficient. Considering that the damping force must be proportional to the real-time velocity, and once the cylinder's constant velocity is chosen, the damping force can be rewritten as:

$$Fd(t) = \frac{\mathrm{Fc}}{x_0} * \dot{\boldsymbol{x}}(t), \quad (2)$$

where Fc is the cylinder acting force, in this case 40.6kN, and x_0 is the desired constant velocity, set at 25mm/s. In the Figure 10-b shows the different between the velocity of cylinder and finger. On the other hand, the Figure 11-a illustrates the net force of the cylinder and its components, including acting force and damping force, one can observe that the damping force maintains its magnitude equal to the acting however pointing in the opposite direction, resulting in a net force equals to zero and maintaining a constant velocity. As the rollers contact with the end-fitting, the damping force diminishes due to the decreasing velocity, when the net force and the acting force become equal. The contact forces that act between the three rollers and the end-fitting can be seen in the Figure 11-b.

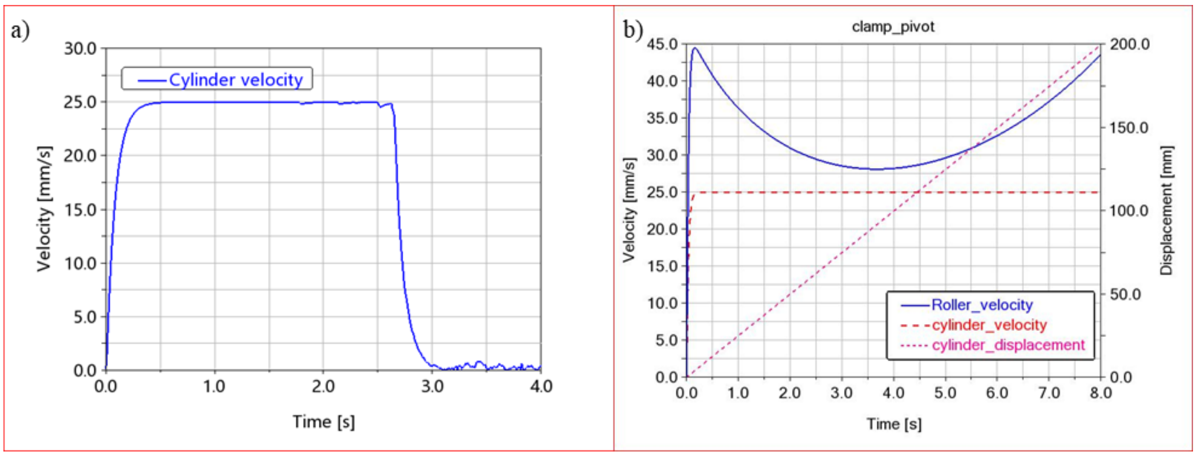


Figure 10 - Cylinder velocity. a) considering a anchoring at end-fitting; b) correlation between the cylinder and finger.

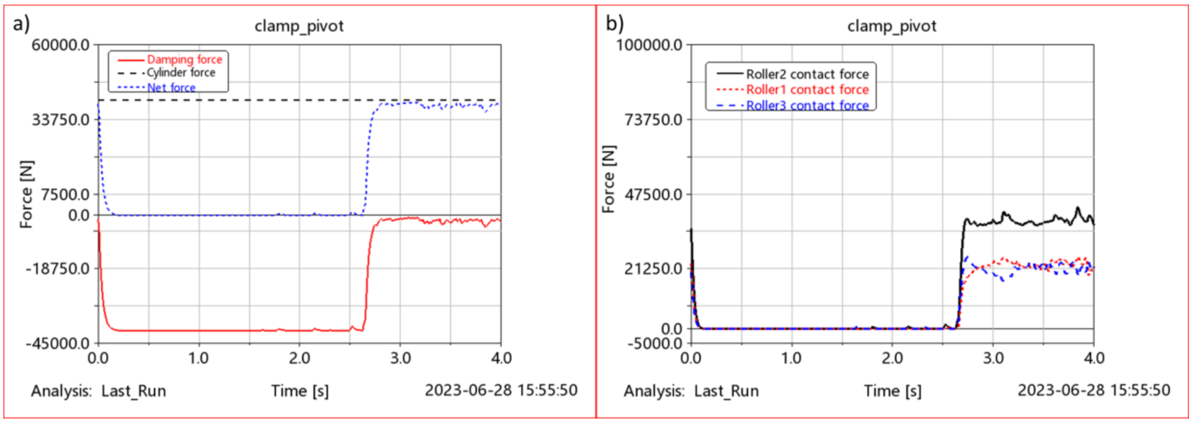


Figure 11 - External acting forces. a) forces acting on the cylinder; b) contact forces between rollers and end-fitting.

6. MECHANISM MANUFACTURING

The manufacturing of the designed tool involved using a 5-axis CNC milling machine, lathe, and 3-axis CNC milling machine. The components were manufactured using aluminum 6351-T6 and underwent hard anodization as a surface treatment. Additionally, the joints utilized special bushings designed for underwater applications. The Figure 12 shows the manufacture and assembly of the tool, and it is now ready for inspection.

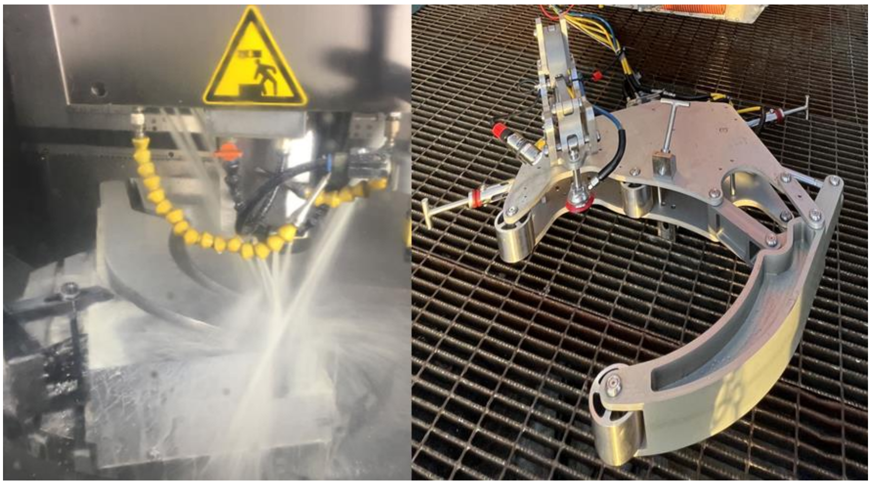


Figure 12 - Manufacturing and inspection tool assembled.

After conducting movement tests, the results have proven to be satisfactory. This positive outcome indicates that the tool functions as intended and meets the required performance criteria.

7. CONCLUSION

In this paper, a new inspection tool for detecting flooded annulus in flexible lines was developed and tested. The tool utilizes a differential pressure method, which remains unaffected by critical locations in the pipeline structure. The designed inspection tool can operate at depths up to 3000 meters, enabling remote inspections without the need for human divers. The project requirements emphasized the need for a specialized tool that can be installed on Remotely Operated Vehicles (ROVs) commonly used for offshore inspections.

Various inspection techniques for flexible pipelines are discussed, highlighting the challenges posed by the complex multi-layered structure of these pipes. Researchers identified the depressurization technique as a suitable method for detecting annulus conditions, including flooding, breach of outer sheath, venting valve functioning, and end fitting sealing. Compared to other non-invasive technologies, the depressurization method offers a wider range of applications and diagnoses for flexible pipes, without intrusions in the outer sheath.

The tooling design process involved several important steps, including project requirements, synthesis, dimensional synthesis, geometric modeling, simulation, force analysis, and manufacturing.

The developed inspection tool based on the differential pressure method provides an efficient and reliable solution for detecting flooded annulus in flexible lines used in offshore oil and gas operations. It addresses the challenges posed by the complex structure of flexible pipes and enables remote inspections at significant depths. By detecting annulus conditions and ensuring the integrity of end fittings, the tool contributes to the long-term life and safety of flexible pipelines, supporting the sustainability of the offshore oil and gas industry.

Future plans include: structural analysis and topological optimization, aiming to reduce the whole equipment and attachments weights. In this step it is also planned the use of strain gauges in order to validate any FEA and dynamic analysis and to validate the models that were used and ensure the tool's reliability under different operating conditions. Also, it is intended to test the equipment in a relevant environment such as a hyperbaric chamber.

8. REFERENCES

ASNT (2007). *ASNT Handbook, Volume 7: Nondestructive Testing (Third Edition).* , eds. G. L. Workman, D. Kishoni, and P. O. Moore.

Brandao, M., Pires, F., Poloponsky, I., Santos, F., and Lopes, D. (2021). Flexible Pipes Subjected to SCC CO2: Review and Means to Increase Reliability on Service Life Applied to Brazilian Pre-Salt Fields. in *Paper presented at the Offshore Technology Conference, Virtual and Houston, Texas, August* (Houston, Texas), Paper Number: OTC-31135-MS.

Carneval, R. D. E. O. (2006). Flexible Line Inspection. *Eur. Conf. Non-Destructive Test.*, 1–11.

Clarke, T., Jacques, R., Bisognin, A., Camerini, C., Damasceno, S., and Strohaecker, T. (2011). Monitoring the structural integrity of a flexible riser during a full-scale fatigue test. *Eng. Struct.* 33, 1181–1186.

Cosham, A., and Hopkins, P. (2002). The pipeline defect assessment manual. *Proc. Int. Pipeline Conf. IPC* B, 1565–1581. doi: 10.1115/IPC2002-27067.

Dahl, C. S., Andersen, B. A. M., and Gronne, M. (2011). Developments in Managing Flexible Risers and Pipelines, A Suppliers Perspective. doi: 10.4043/21844-ms.

Kaur, A. P., Sattar, T., Anvo, R., and Tokhi, M. O. (2021). Development of a Robot for In-service Radiography Inspection of Subsea Flexible Risers. *J. Artif. Intell. Technol.* 1, 180–187. doi: 10.37965/jait.2021.0015.

Kuhn, M. F., Missell, F. P., Borges, M. F., and Clarke, T. G. R. (2020). RFID wireless system for detection of water in the annulus of a flexible pipe. *Mar. Struct.* 72, 102776. doi: 10.1016/j.marstruc.2020.102776.

Li, X., Jiang, X., and Hopman, H. (2021). Development of an analytical model for predicting the wet collapse pressure of curved flexible risers. *Ocean Eng.* 232, 109132. doi: 10.1016/j.oceaneng.2021.109132.

Marinho, C. A., de Jesus, E. F. O., Silva, A. H. M. F. T., Oliveira, D. F., and Lopes, R. T. (2022). Annulus flooding detection system in flexible pipes using gamma rays transmission technique. *Appl. Radiat. Isot.* 184, 2–7. doi: 10.1016/j.apradiso.2022.110177.

Martins, D., and Murai, E. H. (2019). *Mechanisms: synthesis and analysis with applications in robotics (in portuguese)*. , ed. Edufsc Edufsc.

Pipelines, L. I. N. (2017). New anti-buckling tape developed for deepwater pipeline applications. Available at: https://www.offshore-mag.com/pipelines/article/16756129/new-antibuckling-tape-developed-for-deepwater-pipeline-applications [Accessed June 20, 2023].

Provasi, R., Toni, F. G., and de Arruda Martins, C. (2022). Friction coefficient influence in a flexible pipe: A macroelement model. *Ocean Eng.* 266, 112719. doi: 10.1016/j.oceaneng.2022.112719.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.