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# Implementation of a Real-Time Pressure and Tilt Angle Monitoring System for Mast Hoisting in NOV Rapid Rig 13 Equipment

## *Implementación de un sistema de monitoreo en tiempo real de presión e inclinación para el izaje del mástil en equipos NOV Rapid Rig 13*

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**Abstract:** this paper presents the implementation of a real-time monitoring system for mast hoisting operations in NOV Rapid Rig 13 equipment, using a distributed architecture with local data acquisition, processing, and visualization layers. The system simultaneously records hydraulic pressure and angular inclination data, enabling analysis of the dynamic behavior of hydraulic cylinders during hoisting operations. This data generated a static pressure curve to correlate pressure and inclination, representing the theoretical model of a three-stage hydraulic cylinder. This curve identified critical transitions and operational deviations, serving as the basis for defining alarm thresholds and enhancing operational oversight—empowering operators to make informed, safety-driven decisions. The results improve hoisting safety and establish a foundation for future automation and predictive maintenance strategies in hydraulic systems applied to drilling operations.

**Keywords:** mast hoisting, hydraulic cylinder, hydraulic system, real-time monitoring, hydrocarbon drilling.

**Resumen:** este artículo presenta la implementación de un sistema de monitoreo en tiempo real para el izaje del mástil en equipos NOV Rapid Rig 13 utilizando una arquitectura distribuida con niveles de adquisición, procesamiento y visualización local. El sistema registra simultáneamente datos de presión hidráulica e inclinación angular, permitiendo analizar el comportamiento dinámico de los cilindros durante la operación de izaje. A partir de estos datos se construyó una gráfica de presión estática que relaciona presión e inclinación, representando el modelo teórico de un cilindro hidráulico de tres etapas. Esta curva permitió identificar transiciones críticas y desviaciones operativas, sirviendo como base para definir umbrales de alarma y mejorar la supervisión; lo cual le permite al operador tomar decisiones informadas y seguras. Los resultados obtenidos no solo mejoran la seguridad del proceso de izaje del mástil, sino que también sientan las bases para la futura automatización y la implementación de estrategias de mantenimiento predictivo en sistemas hidráulicos aplicados a la perforación.

**Palabras clave:** izaje del mástil, cilindro hidráulico, sistema hidráulico, monitoreo en tiempo real, perforación en hidrocarburos.

## 1. INTRODUCTION

The hoisting system in drilling rigs plays a crucial role in ensuring stability and operational safety during the mast's assembly and disassembly phases. Its design must withstand demanding conditions, including dynamic loads, vibrations, repetitive mechanical stresses, and exposure to harsh environments. Specifically, the mast—a vertical component that supports and aligns the drill string—is subject to technical standards such as API 4F [1], which establishes criteria to ensure its structural integrity under such loads [2]. However, beyond design considerations, its actual behavior during hoisting operations critically depends on the hydraulic system that powers it and the control applied over it.

Mast lifting operations are not free from risks. Documented cases, such as the uncontrolled descent in 2021 with the NOV Rapid Rig 13 drilling unit [3], highlight the fragility of procedures that rely solely on operator experience and manual controls without continuous monitoring [4]. These incidents cause material losses and expose personnel to unsafe conditions that could be prevented through monitoring and supervision systems.

In response to these vulnerabilities, the industry has introduced improvements in maintenance routines, such as regular purging of hydraulic cylinders, non-destructive inspections, and stricter technical traceability protocols [5]. However, these corrective and preventive measures remain insufficient without real-time visualization of critical variables. The lack of immediate feedback on pressure and inclination angles hinders the early detection of anomalies, increasing the risk of operational failures. As noted in [6]-[8], such limitations raise the likelihood of human error and compromise not only the mast's stability but also the supporting substructure.

Various solutions have been proposed in the research field to improve the control and monitoring of hydraulic systems, especially in multi-cylinder configurations. Studies such as [9] and [10] have worked on advanced control schemes using neural networks, showing promising synchronization, stability, and disturbance resistance results. Additionally, [11] demonstrated that pressure data analysis enables the implementation of predictive maintenance strategies, while [8] proposed using robust algorithms such as Levant differentiators to enhance reliability in highly uncertain environments.

Considering these findings, the proposed system represents a step toward partial automation of mast hoisting. It enables real-time monitoring of pressure and inclination angle, identification of critical events, and automatic activation of alarms in case of anomalies during lifting. This article thus establishes a solid technical foundation to improve operational decision-making, enhance safety, and reduce downtime in high-risk activities within the drilling industry.

The content of this paper is organized into six sections: the first presents the general context of the research; the second summarizes key background and prior developments; the third describes the methodology applied; the fourth focuses on the results obtained and their analysis; the fifth presents the discussion; and the sixth outlines the conclusions drawn from the work.

## 2. STATE OF THE ART

Despite the crucial role that mast hoisting plays in drilling operations, scientific production focused on actively monitoring this process is still in its early stages, especially when it comes to critical variables such as hydraulic pressure or structural inclination during the maneuver.

Nevertheless, some prior cases stand out, such as the representative incident of the uncontrolled descent of the mast in 2021 on a drilling rig, where the accumulation of air in the ODS hydraulic cylinder triggered the event. This incident led to adjustments in maintenance practices, including improved purging protocols and enhanced technical traceability [3]. Although there were technical documents addressing the structural sizing of the mast by standards such as API 4F [12], dynamic field monitoring was not considered part of the control system.

Several authors have addressed the issue from different perspectives in the international literature. In [6], hoisting cylinder failure mechanisms were analyzed, highlighting the need for robust monitoring systems to anticipate abnormal behaviors. Similarly, [13] demonstrated how anchor failures, poor designs, or inadequate inspections can seriously compromise the structural stability of the mast. From an advanced control standpoint, [8] proposed a feedback-based model for asymmetric electrohydraulic cylinders, significantly improving disturbance rejection capabilities.

Complementing this, [14] applied complex network theory to study the root causes contributing to accidents during hoisting operations. Their analysis revealed nonlinear interactions between human errors, mechanical failures, and environmental conditions that collectively increase the level of risk in such maneuvers. Meanwhile, [7] developed a systematic review on diagnosis and prognosis in hydraulic cylinders, emphasizing the growing importance of predictive maintenance strategies based on advanced monitoring.

Recently, artificial intelligence-based solutions have been explored. In [9], a synchronous control scheme assisted by neural networks was proposed for dual-cylinder systems to reduce excessive internal forces and improve synchronization under dynamic scenarios. Likewise, [10] worked with fuzzy RBF neural networks integrated into PID controllers, achieving substantial improvements in the precision and stability of force/position control systems—even under nonlinear conditions and external disturbances. Finally, [11] showed that hydraulic pressure analysis can be used for predictive purposes, identifying failure trends before they manifest, thereby optimizing maintenance and reducing operational risks.

Despite the value of these investigations, most have been developed in simulated environments or industrial applications other than land drilling. So far, no approach has been documented that combines, in a single solution, real-time monitoring of both hydraulic cylinder pressure and mast inclination during hoisting. In this context, the present article aims to contribute to that gap by proposing a monitoring system that enables early detection of critical events during the mast hoisting process and establishes the groundwork for the future development of predictive models and automation systems adapted to the operational conditions of field drilling equipment.

## 3. MATERIALS AND METHODS

### 3.1 Problem Description

In NOV Rapid Rig 13 drilling rigs, mast lifting is performed using two double-acting, three-stage hydraulic cylinders mounted respectively at the DS (Driller Side) and ODS (Off Driller Side) ends of the rig [15]. The hoisting process is carried out manually by the operator, who uses two independent levers on the control console, each associated with a proportional valve that regulates the hydraulic flow sent to the cylinders. While this method is functional, technical and operational limitations have been identified in practice.

One of the main challenges lies in the asynchrony between the cylinders, caused by uncoordinated manual control. This results in pressure imbalances that may lead to transverse tilting of the mast during lifting. Such deviations cause irregular redistribution of forces throughout the structure, affecting the overall stability of the system and increasing the risk of structural damage. Additionally, the location of the control console does not provide the operator with direct visibility of the mast's transverse axis, as shown in Fig. 1. As a result, assistance from a second worker is required—this person, positioned in front of the rig, gives visual or manual signals to indicate necessary adjustments. This working scheme generates dependency on communication between operators, increases the likelihood of human error, and reduces the efficiency of the hoisting procedure.

***Fig. 1.*** *Operator's perspective at the mast hoisting controls – limited visibility for transverse leveling.*
***Source:*** *Authors.*

Hydraulic pressure is a key indicator of the internal behavior of the cylinders, and its continuous monitoring is essential for detecting anomalous conditions such as overloads, sudden pressure drops, internal leakage, or imbalances between working chambers. Similarly, the mast's transverse inclination is an external parameter reflecting synchronization or imbalance between the cylinders. Integrating these two types of data allows for real-time operation monitoring and establishing technical criteria to identify misalignments, prevent overloads, assess maneuver efficiency, and detect structural deviations that could compromise system stability.

### 3.2 Methodology for Problem Solving

According to the definition provided in the Frascati Manual [16], this paper falls within the scope of applied research, as it focuses on designing, developing, and implementing a specific technological solution to address a concrete operational problem. Fig. 2 presents a schematic representation of the methodological phases developed in this work for the design, implementation, and validation of the proposed monitoring system.

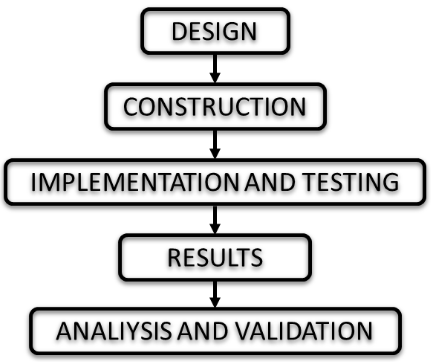


***Fig. 2.*** *Flowchart of the methodological phases for the design, implementation, and testing of the monitoring system.*
***Source:*** *Authors.*

#### *3.2.1 Monitoring System Design*

The design of the monitoring system is based on the selection of robust, precise, and rapidly integrable industrial components, focused on meeting the technical requirements of the operational environment. The sensors, controllers, and the user interface are characterized by using criteria such as accuracy, latency, compatibility, and environmental conditions.

A biaxial SICK TMM88B-ALC090 sensor is selected to measure the mast's inclination angle. This device can detect angles up to ±90°, with a resolution of 0.01° and a typical accuracy of ±0.1°. Its compact housing, IP67 rating, and operating range from –40 °C to +80 °C make it suitable for demanding industrial environments. A key advantage of this device is its configurability via the PGT-12-Pro programmer, which allows for zero-point adjustment and redefinition of the measurement range. It was specifically configured to concentrate its 0–10 V output within a reduced operational range of –15° to +15° on the transverse axis, and 0° to +90° on the longitudinal axis, thereby optimizing the system’s sensitivity and resolution without requiring hardware modifications [17].

Pressure measurement in the hydraulic cylinders of the mast hoisting system is carried out using Trafag EPI 8287 transmitters, designed to operate up to 3600 psig (~250 bar). These devices offer a 4-20 mA output signal, a typical accuracy of ±0.3% F.S., IP65 protection, and temperature operation ranges from –40 °C to +125 °C, with vibration resistance up to 25 g. Their selection was based on field-proven stability, accuracy, and mechanical robustness [18].

The control system is structured around a Delta DVP20SX2 PLC, featuring four analog inputs and two analog outputs, along with 16k-step memory, electromagnetic immunity, and I/O expansion capabilities. This PLC was chosen for its native integration with ladder logic development software and compatibility with standardized industrial devices [19]. The selected human-machine interface (HMI) is the Delta DOP-107EG, a 7” touchscreen communicating with the PLC via RS-485 Modbus RTU protocol. This HMI enabled the implementation of graphical visualization, alarm management, data logging, and trend display using the DIAScreen environment—a free embedded SCADA solution [20].

The total system latency analysis—considering sensor response times, PLC scan time, and screen refresh rate—yielded an estimated range of 120 to 200 ms, fulfilling the criteria for soft real-time monitoring (<500 ms). This performance ensures adequate supervision of the hoisting process without impairing the operator's response capability.

Fig. 3 shows the P&ID diagram of the designed monitoring system, displaying the main connections between sensors, PLC, HMI, and hydraulic components.

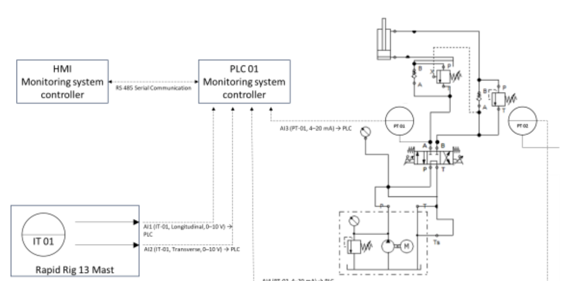


***Fig. 3.*** *P&ID Diagram of the Monitoring System.*
***Source:*** *Authors.*

### *3.2.2 Construction and Implementation of the Monitoring System*

During the construction of the monitoring system for mast hoisting, priority was given to meeting the technical requirements established in the Technical Regulation for Electrical Installations (RETIE), ensuring a safe installation in compliance with current regulations in Colombia. Additionally, guidelines from the National Electrical Code (NEC – NFPA 70), widely adopted in oil & gas industrial facilities, are considered to ensure high standards of electrical protection and operational reliability.

Once the system integration was completed, as shown in Fig. 4, functional tests were conducted under the safety protocols defined by the organization. The procedure began with the management of authorizations, which included detailed technical documentation regarding the interventions made to the hydraulic system, accompanied by a Job Safety Analysis that identified potential hazards and established preventive controls. Subsequently, the corresponding work permit was processed and validated by internal authorities.

***Fig. 4.*** *Mast Hoisting Monitoring System.*
***Source:*** *Authors.*

Field installation of the system involved adapting the pressure measurement points on the DS and ODS cylinders of the NOV Rapid Rig 13 unit, using high-pressure quick couplings to ensure firm and reliable connections, as shown in Fig. 5. With the mast positioned and secured on the substructure, the inclination sensor was then mounted, preceded by a visual inspection to verify structural conditions before starting the hoisting process.

With the monitoring system connected in the field, the proper operation of the sensors and the visualization interface was verified. Before initiating the mast hoisting, a comprehensive review of operational safety was conducted, during which associated risks and emergency response protocols were reviewed, according to the company's procedures [4]. Critical variables—hydraulic pressure and angular inclination—were recorded and displayed in real time during the maneuver. This allowed for on-site evaluation of measurement accuracy and system responsiveness to the process's dynamic changes.

***Fig. 5.*** *Pressure sensors installed at the outlet of the 'mast raising' console valves.*
***Source:*** *Authors.*

## 4. RESULTS

### 4.1 Static Pressure Graph

The static pressure graph was built from the minimum values recorded under no-motion conditions, reflecting the ideal theoretical behavior of the hydraulic cylinder pressure as a function of the longitudinal inclination angle of the mast. This representation is a reference point for the hysteresis phenomenon observed during mast hoisting, since actual pressures during dynamic operation remain slightly above the estimated static values.

Due to the geometric complexity of the mast and the difficulty in theoretically determining its weight and center of mass, an experimental measurement is chosen to obtain the weight, as shown in Fig. 6. For this purpose, field values are recorded using telescopic cranes equipped with calibrated LMI (Load Moment Indicator) systems, from which the load weights were extracted, ensuring reliable data.

*Fig. 6. Mast hoisting using telescopic cranes — procedure used to obtain the weight of the NOV Rapid Rig 13 mast.* ***Source:*** *Authors.*

Based on the previous procedure, Fig. 7 presents the geometric analysis of the distances involved, showing the position of the cylinders and the angles.

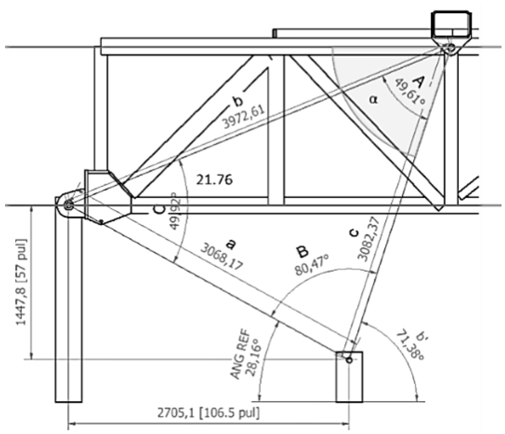


*Fig. 7. Geometry diagram of the mast hoisting system, showing the position of the cylinders, angles, and distances involved in the movement.* ***Source****: [12].*

Likewise, to calculate the forces, a force and moment analysis is conducted through a simplified free body diagram, as illustrated in Fig. 8, considering the summation of moments equal to zero, integrating factors such as the location of the center of mass and the lever arms of the acting forces.

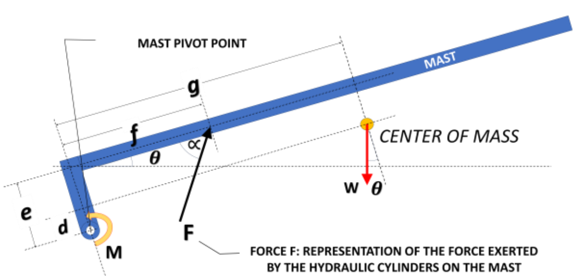


*Fig. 8. Free body diagram for the analysis of mast motion dynamics, showing the forces and moments involved in the system.* ***Source:*** *Authors.*

Below are the measured and calculated values for the distances and forces shown in Fig. 8:

$$w = 42{,}547\ Metric\ ton = 93{,}736\ Klbf$$
$$g = 12\ m$$
$$f = 3{,}68\ m$$
$$e = 1{,}47\ m$$
$$d = 0{,}74\ m$$
$$\alpha = 21.76 + A$$

where A depends on the variation of angle θ and is calculated using the law of cosines.

Considering the summation of moments equal to zero, the force value of the cylinders at any angle can be calculated using equation (1):

$$F = \frac{w(-g \cdot \cos\theta + d \cdot \sin\theta)}{(-f \cdot \text{sen}\,\alpha + e \cdot \cos\alpha)} \qquad (1)$$

From equation (1), the system force data for each mast inclination angle is obtained and plotted below in Fig. 9.

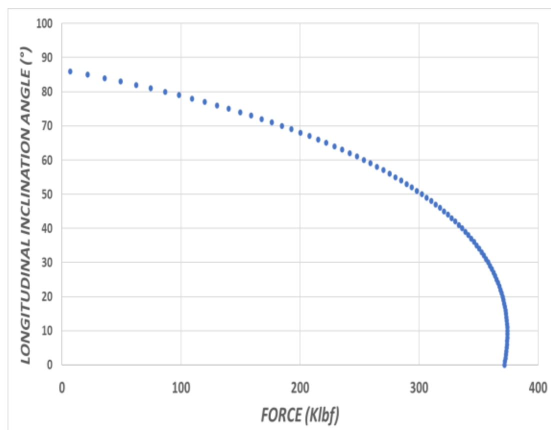


*Fig. 9. Behavior of the total cylinder force for each mast inclination angle.*
***Source:*** *Authors.*

Finally, the pressure-force relationship data for the hydraulic cylinders is obtained according to the effective areas of each cylinder stage, taken from the manufacturer's tables [15]. This information made it possible to plot the baseline curve of pressure behavior versus the mast inclination angle, as shown in Fig. 10. This graph represents a three-stage telescopic hydraulic cylinder and is key for understanding force and pressure transitions during mast hoisting and associated gravitational influences.

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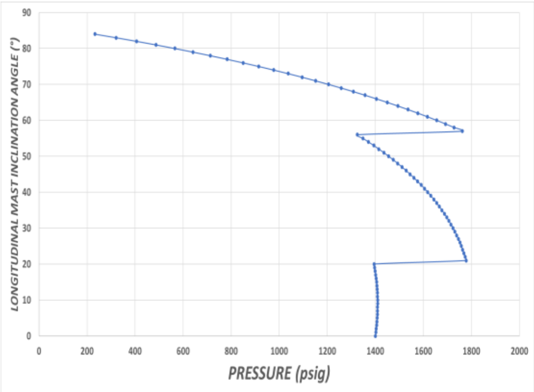


***Fig. 10.*** *Pressure behavior in a hydraulic cylinder versus mast inclination angle.*
***Source:*** *Authors.*

The development of this curve constitutes a significant advancement, as it establishes a reference framework for future research and optimization strategies in mast hoisting processes. The three key regions identified in the graph are analyzed below:

*First Stage (0° to ~20°):* The cylinder operates with its largest-diameter stage, generating maximum force at lower pressure due to the larger effective piston area. Pressure remains relatively constant, as the horizontal component of the mast's weight is low and the cylinders lift the mast's full weight. This phase stands out for its energy efficiency and the consistent pressure behavior concerning inclination angle, which is also a consequence of the system geometry.

*Second Stage (~20° to ~56°):* When the second, smaller-diameter stage is activated, higher pressure is required to compensate for the load. This transition introduces pressure fluctuations due to fluid redistribution and internal seal resistance. At the start of this stage, a peak pressure near 1800 psig is recorded. Furthermore, the pressure-angle curve shows nonlinear behavior during this phase.

*Third Stage (~57° to ~86°):* In this stage, pressure decreases sharply due to changes in the gravitational component. As in the previous stage, a pressure peak is recorded at the beginning, slightly below 1780 psig. Throughout this stage, the pressure graph—though not perfectly linear—exhibits more linear behavior compared to previous stages. This may be attributed to the reduced variation in effective mast weight on the cylinders as it approaches the vertical position [21]. It is also important to note that after 86 degrees of inclination, the theoretically calculated pressure yields negative values. This occurs because at this angle, the mast's center of mass has already passed the pivot point, and from that moment, the cylinders stop applying upward force and instead begin to support the mast.

### 4.2 Measured Pressure Graph in DS and ODS Cylinders as a Function of Mast Inclination Angle

The graph obtained through the monitoring system validated its capability to record, in real time, the pressure in the hydraulic cylinders and the mast inclination during the NOV Rapid Rig 13 hoisting process. Fig. 11 shows the collected field data, which revealed key behavior patterns in the pressures of the DS and ODS cylinders. Specifically, pressure peaks were identified, associated with transitions between the stages of the telescopic cylinder [6].

During the first 20° of inclination, the pressures in both cylinders remained stable within the 1400 to 1500 psig range, indicating adequate initial load compensation.

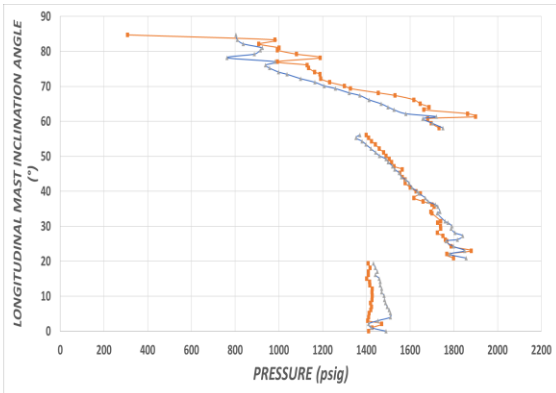


***Fig. 11****. Measured pressure graph in DS and ODS cylinders as a function of mast inclination angle, obtained from real-time values recorded by the monitoring system.*
***Source:*** *Authors.*

Around 20°, the first pressure peak occurred in both cylinders, reaching up to 1856 psig in the DS cylinder and 1767 psig in the ODS cylinder. This abrupt increase coincides with the transition from the first to the second stage of the telescopic cylinder. This moment requires a temporary rise in pressure to overcome the system's initial resistance and ensure the extension of the next cylinder segment.

Following this peak, pressure in both cylinders stabilized and progressively decreased until 56°, when a second peak appeared, corresponding to the transition to the third cylinder stage. In this phase, pressures reached significant values before starting their final decline.

During the final hoisting phase, after 60°, the ODS cylinder maintained higher pressure levels until the last degrees of inclination and then dropped to minimal values, reaching only 308 psig at 84°. This suggests a progressive load transfer to the DS cylinder in the final stages of hoisting.

This load redistribution behavior is characteristic of hydraulic systems operating under structural or alignment conditions that are not perfectly symmetrical. The pressure drop and erratic values recorded by the monitoring system at angles greater than 86° indicate that the mast's weight begins to be primarily supported by the rig's fixed structure, gradually reducing the load applied to the cylinders.

The statistical summary of the variables is presented below in Table 1 and Table 2.

***Table 1:** Average values of pressure error and standard deviation associated with the DS and ODS hydraulic cylinders.*

| DATA | VALUE |
|---|---|
| Average pressure error DS | *35,1 psig* |
| Average pressure error ODS | *56,2 psig* |
| Standard deviation DS | *109,5 psig* |
| Standard deviation ODS | *139,7 psig* |

***Source:*** *Authors.*

***Table 2:** Average error and standard deviation of the mast's transverse inclination calculated from the data recorded during the hoisting maneuvers.*

| DATO | VALOR |
|---|---|
| Average error | *0,0838°* |
| Standard deviation | *1,049°* |

***Source:*** *Authors.*

## 4.3 Validation of Results

The system validation results are presented in Table 3. For this comparative analysis, the theoretical data obtained from the baseline curve (Fig. 10) and the data recorded in real time by the monitoring system (Fig. 11) are considered.

***Table 3:** Validation of results from the baseline curve and the data recorded in real time by the monitoring system*

| THEORETICAL DATA (BASELINE CURVE) | REAL-TIME DATA (DS AND ODS CURVES) |
|---|---|
| *Initial hoisting zone (0° - 20°)* | |
| Pressure remains slightly above 1400 psig | Maintains a similar range, with minor fluctuations between 1400–1500 psig in DS and ODS cylinders. However, the ODS cylinder exhibits higher pressure values than the DS. |
| The behavior of the theoretical and real data curves is similar, suggesting that the system is operating within the expected margin. | |
| *First cylinder stage transition (~21°)* | |
| Shows a sudden pressure increase up to 1778 psig, confirming the transition to the second stage. | Registers an abrupt rise in DS and ODS cylinders, reaching 1856 psig (DS) and 1798 psig (ODS). |
| In this first transition, both curves behave similarly, suggesting correct system operation within expected margins. | |
| *Intermediate stability (22° - 56°)* | |
| Maintains a progressively decreasing trend between 1700–1300 psig. | DS and ODS cylinders show relative stability. Despite some dispersion, the curve descends gradually within 1800–1400 psig. |
| The theoretical and real data curves show similar behavior. However, oscillations in the real data may be attributed to the real hydraulic system compensating to maintain stability or to the operator's performance while controlling the valve. | |
| *Second cylinder stage transition (~57°)* | |
| Another sharp increase up to 1763 psig is recorded, indicating the transition to the third stage.. | A pressure increase is observed in DS and ODS cylinders, although with more dispersed values. |
| Both curves confirm the transition to the final stage. However, pressure variability in real data suggests the real system does not respond as uniformly as the theoretical model. | |
| *Final hoisting phase (60° and above)* | |
| Gradually decreases to negative values after 86°, indicating the cylinder should no longer contribute to the load. | DS cylinder pressure decreases to 803 psig at 84°, suggesting continued structural effort. ODS pressure drops rapidly to 308 psig at 84°, indicating it stops contributing earlier. After 85°, erratic values oscillate toward negative pressure. |
| Real pressure does not drop as quickly as the theoretical values, indicating additional factors (residual structural resistance, mast guide friction, pressure regulation effects, etc.). However, both data sets show the end of cylinder action beyond 85° of inclination. | |

***Source:*** *Authors.*

Based on the data obtained during mast hoisting and considering the manufacturer's recommendations, several critical situations have been identified that may compromise the safety and stability of the hydraulic system. For each of these conditions, the monitoring system—via its HMI visualization panel—provides specific alarms that enable early detection and informed decision-making:

- *Exceeding maximum working pressures:* the system triggers an overpressure alarm, warning of conditions that could compromise the integrity of the hydraulic cylinders [7].

- *Incorrect extension sequence of the cylinders:* an incompatibility alarm is generated, alerting to a mismatch between the inclination angle and the expected pressure in the DS and ODS cylinders, thereby preventing potential structural failures [7].

- *Cylinder partially extended without pressure:* a pressure drop alarm is activated, indicating a possible leak or malfunction that could affect hoisting stability [7].

- *Mast misalignment:* the system generates a leveling alarm, allowing the operator to correct any anomalous tilt that could compromise structural safety in real time.
- *Overpressure in one of the cylinders:* an unequal pressure alarm is triggered, detecting a load imbalance between the DS and ODS cylinders, which may indicate weight distribution issues or faults in the hydraulic system [7].

The implementation of these alarms reinforces the usefulness of the monitoring system as a tool for optimizing operational decision-making and risk prevention.

The results presented in this article conclusively validate the correlation between the theoretical reference curve and the curve obtained in the field, demonstrating that the developed system accurately captures the critical transitions between the stages of the telescopic hydraulic cylinder. This functionality provides operational insight that was previously unavailable to operators of the NOV Rapid Rig 13.

## 5. DISCUSSION

The results obtained during the implementation of the NOV Rapid Rig 13 monitoring system provide insight into several technical and scientific implications relevant to the hydrocarbon industry. While the validation confirmed the system's functionality and accuracy, a broader analysis of the data and the experimental process offers valuable contributions for future applications and similar developments.

Firstly, the hoisting maneuver revealed how slight imbalances in hydraulic pressure can generate measurable transverse tilting of the mast. The real-time capture of these variations—previously dependent solely on operator judgment and visual cues—represents a significant advancement over traditional methods. This observation aligns with the findings reported by [22], who emphasize that systems lacking sensor-based feedback are vulnerable to critical deviations that are difficult to detect in time.

Additionally, the real-time data collected during mast hoisting show a hydraulic behavior pattern consistent with the theoretical curve of an ideal system, but with systematic deviations that reflect the influence of unmodeled factors (such as mechanical play, nonlinear friction, or fluid compressibility). This finding opens the possibility of using captured data to build more accurate dynamic models that better describe system behavior under real loading conditions, in line with proposals like those of [8] and [11], who advocate for the use of disturbance observers and pressure-based prediction techniques to anticipate failures.

Another relevant aspect is the applicability of this system to other drilling rigs. Although the system was designed explicitly for the NOV Rapid Rig 13, its modular architecture and portability make it adaptable to other hoisting environments with similar hydraulic systems. This aligns with approaches like that of [10], who emphasize the importance of flexible solutions in variable industrial contexts. However, widespread implementation would require adjustments based on structural geometry, hoisting system configuration, and the specific safety standards of each rig.

From an operational perspective, this system represents an intermediate step between traditional manual control and future automation schemes. The data collected enhances real-time decision-making and could feed automatic control algorithms or predictive diagnostics. In this regard, the article serves as a technological foundation for exploring the development of synchronized cylinder control systems, such as those proposed by [9], but applied in real—not simulated—conditions.

Finally, this paper focused on a single experimental case under specific operational and structural conditions. While the results are promising, further testing on different rigs and under varied conditions is required to generalize the findings. Moreover, the long-term stability evaluation of the system is not addressed, which presents an opportunity for future research.

## 6. CONCLUSIONS

The comparative analysis between the theoretical data from the baseline curve and the records from the real-time monitoring system allowed the identification of critical behaviors, particularly the pressure peaks during transitions between stages of the telescopic cylinder. These results validate the correlation with the theoretical static pressure graph and the effectiveness of the implemented monitoring system.

The results show a pressure imbalance between cylinders, with higher overpressure in the ODS cylinder, suggesting asymmetric loading during hoisting. The high fluctuations recorded, especially in the ODS cylinder, could affect lifting synchrony and increase the risk of undesired tilting or irregular stresses on the mast.

The mast's transverse inclination showed a slight tendency toward the DS cylinder side, accompanied by high stage variability. In the final hoisting phase, a sustained tilt to the same side was observed, which could reflect hydraulic imbalance or performance differences between cylinders, increasing structural risk during the most critical stage of the maneuver.

The portable and adaptable design of the monitoring system demonstrates its viability for implementation in other drilling rigs with multistage hydraulic cylinder-based hoisting systems, offering a versatile tool for analyzing and controlling operational variables.

This research represents an original contribution to the empirical application of hydraulic monitoring systems in land drilling mast hoisting—an area scarcely documented in current scientific literature.

Finally, this paper establishes a solid foundation for the future development of automated mast hoisting systems and predictive maintenance strategies, contributing to improved safety and efficiency in critical operations within the hydrocarbon industry.

## 7. REFERENCES

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