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PREDICTIVE MAINTENANCE OF HYDRAULIC AND ROTATING SYSTEMS IN MOBILE CRANES: A CONDITION-MONITORING FRAMEWORK BASED ON VIBRATION AND OIL ANALYSIS

MANUTENÇÃO PREDITIVA DE SISTEMAS HIDRÁULICOS E ROTATIVOS EM GUINDASTES MÓVEIS: UMA ESTRUTURA DE MONITORAMENTO DE CONDIÇÕES BASEADA EM ANÁLISE DE VIBRAÇÃO E DE ÓLEO

MANTENIMIENTO PREDICTIVO DE SISTEMAS HIDRÁULICOS Y ROTATIVOS EN GRÚAS MÓVILES: UN MARCO DE MONITORIZACIÓN DEL ESTADO BASADO EN EL ANÁLISIS DE VIBRACIONES Y DE ACEITE

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ABSTRACT

Mobile cranes concentrate in a single machine a diesel power unit, high-pressure hydraulic circuits, slewing and hoisting gearboxes and safety-critical structural elements. Most of their failure modes are not age-related, which limits the effectiveness of purely time-based preventive maintenance. This paper proposes a condition-monitoring framework for the predictive maintenance of the hydraulic and rotating systems of mobile cranes, built on a review of the literature published up to 2022. The framework combines the P-F interval concept, vibration severity assessment based on ISO 10816-3, fluid cleanliness control based on ISO 4406, oil analysis, thermography, and the six-layer data-processing architecture of ISO 13374. It is complemented by a matrix that links the main failure modes of crane subsystems to the monitoring techniques capable of detecting them, and by implementation guidelines for fleets operating in dispersed job sites. Published evidence indicates that predictive programmes reduce downtime by 30% to 50% and extend machine life by 20% to 40%, but these benefits depend on correct technique selection, inspection intervals shorter than the P-F interval and disciplined data management.

Keywords: Predictive Maintenance. Condition Monitoring. Mobile Cranes. Hydraulic Systems. Vibration Analysis. Oil Analysis.

RESUMO

Guindastes móveis concentram, em um único equipamento, um conjunto motor a diesel, circuitos hidráulicos de alta pressão, mecanismos de giro e elevação, além de elementos estruturais críticos para a segurança. A maioria de seus modos de falha não está relacionada à idade do equipamento, o que limita a eficácia de uma manutenção preventiva baseada puramente no tempo. Este artigo propõe uma estrutura de monitoramento de condições para

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a manutenção preditiva dos sistemas hidráulicos e rotativos de guindastes móveis, fundamentada em uma revisão da literatura publicada até 2022. A estrutura combina o conceito de intervalo P-F, a avaliação da severidade de vibração (conforme a norma ISO 10816-3), o controle da limpeza de fluidos (conforme a norma ISO 4406), a análise de óleo, a termografia e a arquitetura de processamento de dados de seis camadas definida pela norma ISO 13374. O modelo é complementado por uma matriz que associa os principais modos de falha dos subsistemas do guindaste às técnicas de monitoramento capazes de detectá-los, bem como por diretrizes de implementação voltadas para frotas que operam em locais de trabalho dispersos. Evidências publicadas indicam que programas de manutenção preditiva reduzem o tempo de inatividade em 30% a 50% e prolongam a vida útil do equipamento em 20% a 40%; contudo, esses benefícios dependem da seleção correta das técnicas, da definição de intervalos de inspeção inferiores ao intervalo P-F e de uma gestão de dados rigorosa.

Palavras-chave: Manutenção Preditiva. Monitoramento de Condições. Guindastes Móveis. Sistemas Hidráulicos. Análise de Vibração. Análise de Óleo.

RESUMEN

Las grúas móviles integran en una sola máquina una unidad de potencia diésel, circuitos hidráulicos de alta presión, mecanismos de giro y elevación, y elementos estructurales críticos para la seguridad. La mayoría de sus modos de fallo no están relacionados con la antigüedad, lo que limita la eficacia del mantenimiento preventivo basado exclusivamente en el tiempo. Este artículo propone un marco de monitorización del estado para el mantenimiento predictivo de los sistemas hidráulicos y rotativos de las grúas móviles, fundamentado en una revisión de la literatura publicada hasta 2022. El marco combina el concepto del intervalo P-F, la evaluación de la severidad de las vibraciones según la norma ISO 10816-3, el control de la limpieza de los fluidos conforme a la norma ISO 4406, el análisis de aceite, la termografía y la arquitectura de procesamiento de datos de seis capas definida en la norma ISO 13374. Se complementa con una matriz que vincula los principales modos de fallo de los subsistemas de la grúa con las técnicas de monitorización capaces de detectarlos, así como con directrices de implementación para flotas que operan en emplazamientos dispersos. La evidencia disponible indica que los programas de mantenimiento predictivo reducen el tiempo de inactividad entre un 30 % y un 50 %, y prolongan la vida útil de la maquinaria entre un 20 % y un 40 %; no obstante, estos beneficios dependen de una selección adecuada de las técnicas, de intervalos de inspección inferiores al intervalo P-F y de una gestión rigurosa de los datos.

Palabras clave: Mantenimiento Predictivo. Monitorización del Estado. Grúas Móviles. Sistemas Hidráulicos. Análisis de Vibraciones. Análisis de Aceite.

1 PREDICTIVE MAINTENANCE OF HYDRAULIC AND ROTATING SYSTEMS IN MOBILE CRANES: A CONDITION-MONITORING FRAMEWORK BASED ON VIBRATION AND OIL ANALYSIS

Predictive, or condition-based, maintenance is the strategy in which the decision to intervene on an item is based on the measured state of that item rather than on elapsed time or usage (CEN, 2017). Its theoretical justification comes from the observation that most complex items do not show a clear wear-out age: in the classic airline study by Nowlan and Heap (1978), only 11% of the items analysed displayed age-related failure patterns, while 89% failed in a random manner or after an initial period of infant mortality. For such items, scheduled replacement does not reduce the probability of failure, but monitoring the condition can reveal the onset of a failure early enough to plan a corrective intervention (Jardine et al., 2006; Moubray, 1997).

Mobile cranes are a demanding field of application for this strategy. They combine a diesel power unit, hydraulic pumps, motors and cylinders working at high pressure, slewing and hoisting gearboxes, brakes, wire ropes and electronic safety devices, all operating under variable loads in outdoor job sites. A sudden failure in these systems can drop a load or cause loss of stability, with severe consequences: the U.S. Bureau of Labor Statistics recorded 297 crane-related occupational deaths between 2011 and 2017 (BLS, 2019). In this context, predictive maintenance is not only a cost decision but also a safety barrier.

This paper proposes a condition-monitoring framework for the hydraulic and rotating systems of mobile cranes. It draws on the maintenance and reliability literature published up to 2022 and on the international standards for condition monitoring. The paper first reviews the theoretical basis of predictive maintenance, then presents the monitoring techniques most relevant to cranes, the data-processing architecture, a failure-mode-to-technique matrix and implementation guidelines.

2 THEORETICAL BACKGROUND

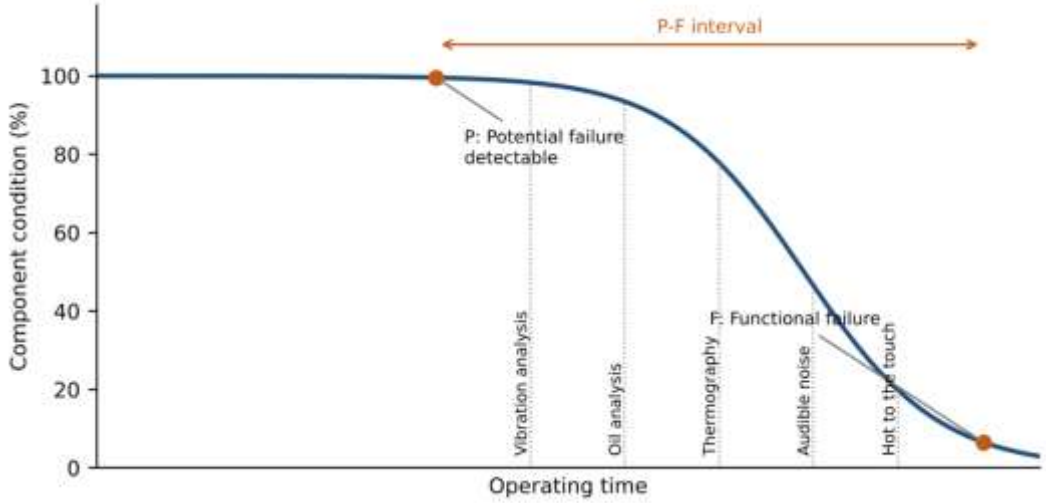
2.1 THE P-F INTERVAL

The central concept of condition-based maintenance is the P-F interval, the time between the point at which a potential failure becomes detectable (P) and the point at which it becomes a functional failure (F) (Moubray, 1997). Different techniques detect the same

degradation at different points along this curve (Figure 1). Vibration analysis and oil analysis typically reveal bearing or gear deterioration much earlier than thermography, audible noise or heat felt by touch (Mobley, 2002; Scheffer & Girdhar, 2004). Two practical rules follow. First, the inspection interval must be shorter than the P-F interval, and Moubray (1997) suggests using about half of it to ensure that the potential failure is detected with enough time to act. Second, the earlier the technique detects the failure, the longer the window available for planning, ordering parts and scheduling the crane out of service.

Figure 1

The P-F Curve and the Relative Detection Point of Condition-Monitoring Techniques



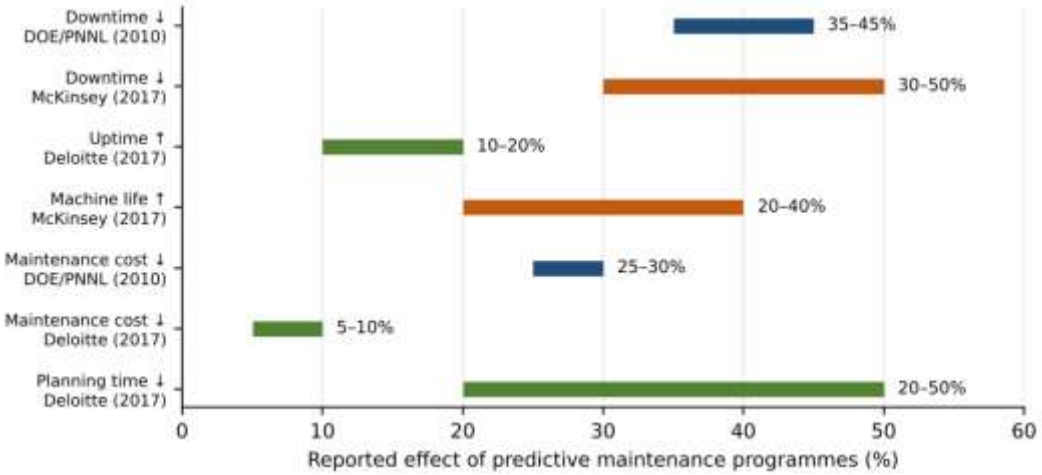
Note. Conceptual diagram prepared by the author based on Moubray (1997) and Mobley (2002). The positions of the techniques are illustrative of their typical sequence, not measured values.

2.2 EVIDENCE ON THE BENEFITS OF PREDICTIVE PROGRAMMES

Published estimates of the benefits of predictive maintenance vary by source and industry, but they consistently point in the same direction (Figure 2). The U.S. Department of Energy best-practices guide reports reductions of 25% to 30% in maintenance costs, 70% to 75% in breakdowns and 35% to 45% in downtime for predictive programmes (Sullivan et al., 2010). Dilda et al. (2017) reported that predictive maintenance typically reduces machine downtime by 30% to 50% and increases machine life by 20% to 40%. Coleman et al. (2017) estimated increases of 10% to 20% in equipment uptime and reductions of 5% to 10% in maintenance costs and of 20% to 50% in maintenance planning time.

Figure 2

Reported Effects of Predictive Maintenance Programmes



Note. Prepared by the author with data from Sullivan et al. (2010), Dilda et al. (2017) and Coleman et al. (2017). Ranges are as reported by each source and refer to different industries and samples.

These figures should be read with caution. They come from consultancy reports and compilations of industrial case studies rather than from controlled studies of crane fleets, and the reviews by Carvalho et al. (2019) and Zonta et al. (2020) show that results depend heavily on the quality of data and on the maturity of the organisation. They nevertheless justify the effort of structuring a programme, provided it is targeted at failure modes in which early detection is possible and economically relevant.

3 MONITORING TECHNIQUES RELEVANT TO MOBILE CRANES

3.1 VIBRATION ANALYSIS

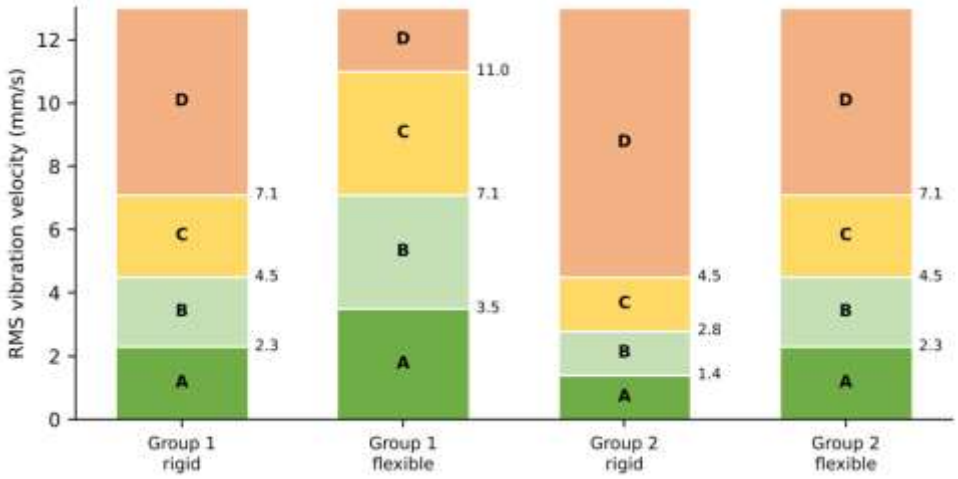
Vibration analysis is the most established technique for rotating machinery. It detects unbalance, misalignment, looseness, bearing defects and gear-mesh problems by analysing the amplitude and frequency content of the vibration signal (Randall, 2011; Scheffer & Girdhar, 2004). In mobile cranes, the relevant rotating assemblies are the engine-pump drive, the hydraulic pumps and motors, the hoisting and slewing gearboxes and the slewing bearing.

For the overall vibration level, ISO 10816-3 defines evaluation zones for machines measured in situ, expressed as RMS vibration velocity (ISO, 2009). Zone A corresponds to newly commissioned machines; zone B to machines acceptable for unrestricted long-term operation; zone C to machines that should not operate continuously for long periods; and

zone D to vibration severe enough to cause damage. The limits depend on machine size and on support flexibility (Figure 3). The standard was conceived for industrial machines on fixed foundations and was replaced by ISO 20816-3 in 2022; for crane components it should be used as a reference for trend analysis rather than as an absolute acceptance criterion, and the most reliable indicator is the change of each machine relative to its own baseline (Scheffer & Girdhar, 2004).

Figure 3

Vibration Severity Zones of ISO 10816-3



Note. Prepared by the author with the zone boundaries of ISO 10816-3:2009. Group 1: large machines with rated power above 300 kW; Group 2: medium-sized machines from 15 kW to 300 kW.

The slewing bearing deserves particular attention. It rotates slowly and intermittently, which makes conventional vibration analysis difficult. For this component, the literature recommends combining periodic measurement of tilting clearance with grease analysis for wear metals, since increases in iron content and in clearance indicate raceway wear (Mobley, 2002).

3.2 OIL AND HYDRAULIC FLUID ANALYSIS

Contamination of the hydraulic fluid by solid particles, water and air is widely recognised as a leading cause of hydraulic component failure (Totten, 2011). Oil analysis therefore serves two purposes: it monitors the condition of the fluid itself and it detects wear

of pumps, motors, valves and gearboxes through the debris they release (Toms & Toms, 2008). A typical analysis programme for cranes includes:

- particle count expressed as an ISO 4406 cleanliness code, which reports the number of particles per millilitre larger than 4, 6 and 14 μm(c) (ISO, 2021);
- spectrometric analysis of wear metals (iron, copper, chromium, aluminium) and contaminants (silicon, indicating dust ingress);
- viscosity and water content, which reveal fluid degradation, mixing of fluids and condensation;
- ferrography or particle quantifier index for gearboxes, which indicates abnormal wear before it becomes visible.

Cleanliness targets should be set according to the most sensitive component in the circuit, such as proportional valves, and to the operating pressure. When the cleanliness code exceeds the target, the corrective action is not only filtration but also identification of the source of contamination: worn rod seals, damaged breathers or contaminated top-up oil (Toms & Toms, 2008; Totten, 2011).

3.3 THERMOGRAPHY AND OPERATIONAL PARAMETERS

Infrared thermography, standardised by ISO 18434-1, detects abnormal temperatures in electrical panels, brakes, bearings and hydraulic components (ISO, 2008). In hydraulic circuits, localised heating of a valve or relief block may indicate internal leakage, which also appears as a loss of pressure or speed. Modern cranes record operating parameters such as pressure, oil temperature, engine load and working hours through their controllers and telematics systems. These records allow trend analysis without additional sensors, provided the data are extracted and reviewed systematically (Lei et al., 2018).

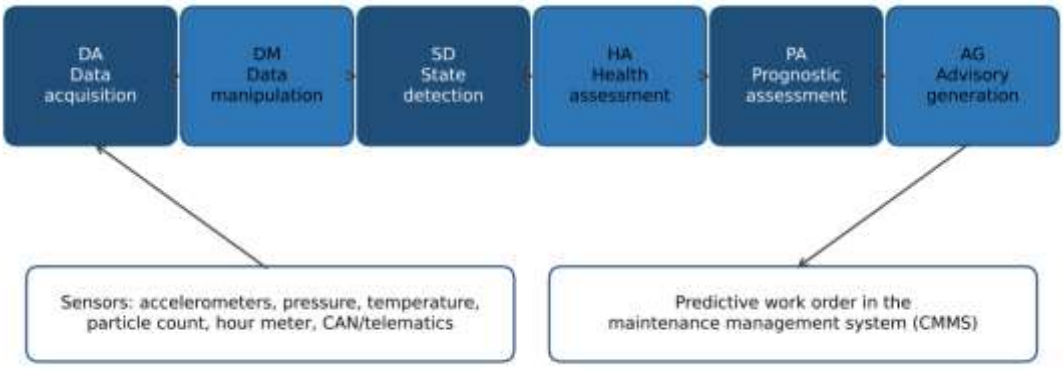
4 DATA ARCHITECTURE FOR CONDITION MONITORING

Collecting measurements is not enough; data must be transformed into maintenance decisions. ISO 13374-1 proposes six functional layers for condition-monitoring systems (Figure 4): data acquisition, data manipulation, state detection, health assessment, prognostic assessment and advisory generation (ISO, 2003). In a crane fleet, the first layers can be implemented with portable data collectors and laboratory reports, while the last layers

depend on the integration of results into the computerised maintenance management system (CMMS), where an alarm becomes a work order with defined priority and deadline.

Figure 4

Functional Layers of a Condition-Monitoring System



Note. Prepared by the author based on ISO 13374-1:2003.

Machine-learning methods have been widely proposed for the state-detection and prognostic layers. Carvalho et al. (2019) found that random forests, neural networks and support vector machines are the most frequent methods in predictive-maintenance studies, and Lei et al. (2018) reviewed the full chain from data acquisition to remaining-useful-life prediction. However, these methods require large volumes of labelled failure data, which small and medium fleets rarely have. For such fleets, rule-based alarms on trends and thresholds, reviewed by an experienced engineer, remain the most practical approach (Ahmad & Kamaruddin, 2012; Zonta et al., 2020).

5 FAILURE-MODE-TO-TECHNIQUE MATRIX

Table 1 links the main failure modes of crane hydraulic and rotating systems to the monitoring techniques that can detect them and to the recommended action when the alarm is triggered. It is intended as a starting point for an RCM analysis (Moubray, 1997; SAE, 2009), not as a substitute for it.

Table 1

Failure Modes of Crane Hydraulic and Rotating Systems and Applicable Monitoring Techniques

Component	Failure mode	Detection technique	Action on alarm
Hydraulic pump	Internal wear, cavitation	Particle count, wear metals, case-drain flow, vibration	Investigate contamination source; plan pump overhaul
Hydraulic cylinders	Seal wear, rod scoring	Drift test, particle count, visual inspection	Replace seals; filter fluid
Hoisting gearbox	Gear pitting, bearing wear	Vibration spectrum, ferrography	Schedule gearbox inspection
Slewing bearing	Raceway wear	Tilting clearance, grease analysis	Re-measure; plan replacement
Engine-pump drive	Misalignment, coupling wear	Vibration analysis	Realign; replace coupling
Brakes	Lining wear, overheating	Thermography, holding test	Adjust or replace linings
Electrical panels	Loose connections	Thermography	Retighten; replace terminals

Note. Prepared by the author based on Mobley (2002), Scheffer and Girdhar (2004), Toms and Toms (2008) and Totten (2011).

6 IMPLEMENTATION GUIDELINES

Based on the literature reviewed, five guidelines are proposed for implementing predictive maintenance in mobile crane fleets:

1. *Prioritise by criticality.* Start with components whose failure affects safety or causes long downtime, such as hoisting gearboxes, main pumps and slewing bearings (Moubray, 1997).
2. *Establish baselines.* Record vibration, cleanliness and temperature values when each crane is new or after overhaul, and evaluate trends against that baseline (Scheffer & Girdhar, 2004).
3. *Set intervals from the P-F interval.* Define sampling and measurement intervals shorter than the expected P-F interval and adjust them as data accumulate (Moubray, 1997).
4. *Close the loop in the CMMS.* Every alarm must generate a work order and every confirmed finding must be recorded with failure mode and cause, so that the programme can be audited (ISO, 2003; ISO, 2016).
5. *Measure results.* Track MTBF, MTTR, availability and the share of failures detected before functional failure to verify that the programme delivers the expected benefits (Sullivan et al., 2010).

7 CONCLUSION

Predictive maintenance is well suited to mobile cranes because most of their critical failure modes are random and develop over a detectable P-F interval. Vibration analysis, oil and fluid analysis, thermography and the trending of operating parameters cover most of these modes in the hydraulic and rotating systems. Their value depends less on sophisticated algorithms than on correct technique selection, inspection intervals consistent with the P-F interval, and the integration of results into maintenance planning. Combined with statutory inspections and a structured post-service analysis of every failure, the framework presented here can raise both the safety and the availability of crane fleets.

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