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MECHANICAL-STRUCTURAL MONITORING SYSTEM BASED IN MODEL ANALYSIS FOR BUCKET WHEEL EXCAVATORS

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Abstract. *Bucket Wheel excavators play a very important role in handling ore material in mining sites. These machines possess many structural and mechanical components that work regularly under stringent operating conditions. The development of more precise and accurate procedures to predict the mechanical behavior of mining machine components and to provide technical data for more efficient maintenance programs is crucial for large mining companies. This work deals with a numerical analysis based on the finite element method devised to identify the critical components of mining machines that must be monitored during their operating cycles. Continuous monitoring systems provide technical data about the mechanical condition of component, leading to more precise estimates of operational parameters, useful life, and damage detection. The procedure implemented in this work is capable of predicting the stress and strain levels of the mechanical and structural parts of Bucket Wheel Excavators under heavy loads, allowing the selection of the locations for measuring the mechanical response of the system and mounting the associated transducers. The finite element model can generate strain and vibration data to help selecting the monitoring variables and to specify and configure the sensors used in the monitoring system. The experimental data collected from the predicted critical points of the machine are analyzed to produce indicators of the machine condition, which can be used to detect potential failures, improve the maintenance plans, and to estimate the remaining useful life of components.*

Keywords: *Structural Health Monitoring, Failure detection, Bucket Wheel Excavator, Stockyard Machine.*

1. INTRODUCTION

Bucket Wheel Excavator (BWE) is a type of stockyard machine, which is a mobile equipment, rail-mounted, and used for continuous handling of bulk materials on mining industries. Due to its high production capacity and size, it is essential to develop monitoring systems for this type of machine, in order to evaluate its mechanical and structural condition.

The failure of large industrial equipment, such as reclaimers, attracts a lot of attention from all parties involved in the process, including technical managers, engineers, manufacturers, and insurance companies. The loss of productivity caused by unexpected interruption of a large machine can be enormous. Such equipment can produce up to 10,000 tons per hour, and a loss can create bottlenecks at the plant ore supply. In addition, downtime, and repairs (or replacements) generate large economic and time losses (Araujo, 2012).

One of the most widely employed monitoring systems for large machines is the Structural Health Monitoring (SHM). SHM is a system developed based on failure detection strategies for mechanical, civil, and aerospace structures. This monitoring system evolves dynamic observations of the mechanical and structural system performing periodic measurement and analyzing failure patterns, damage detection, and current levels of structural integrity (Sohn et al., 2004).

The development of SHM techniques is motivated by the need of supervising the types of deterioration along time experienced by machines and structures. Thus, it is essential that engineers have information about the structural and mechanical condition of the components, level of deterioration, the effects of those components on the service life and operating capacity, generating sufficient information for decision-making in operation (Karbhari, 2009).

A SHM is focused on evaluating parameters and conditions variables with a series of approximations, using statistical analysis methods on the measured data to estimate the system condition and the damage detection (Farrar, 2003). Designing a SHM involves determining machine condition variables, the quantities and types of sensors that will be used, mounting locations, and data processing system. Moreover, it is also necessary to define the frequency at which data will be collected. In some cases, it is recommended to collect data immediately before and at time intervals after the occurrence of a critical event. However, some parameters require continuous monitoring, such as fatigue, as it is necessary to count stress cycles continuously to estimate damage and predict remaining fatigue life (Sohn et al., 2004).

Ciang (2008) presents a SHM for wind turbines and states that frequent monitoring is necessary to improve safety conditions, reduce sudden breakdowns, minimize major unscheduled maintenance, optimize logistics and maintenance

processes. Catbas (2009) describes the application of SHM for large bridge structures with special methods for data analysis. Wong (2009) shows a complete SHM system for monitoring a cable supported bridge in Hong Kong.

The objective of this study is to develop a mechanical-structural monitoring system for large and heavy equipment, using a Bucket Wheel Excavator as an example of application. The finite element method is applied to generate a discrete model of a BWE to study the mechanical and structural behavior of the machine under operational conditions and determine the critical regions for monitoring. From the predictions rendered from the numerical analysis, it is possible to estimate the more susceptible regions to failures and select the more appropriate locations for installing sensors to monitor the structural and mechanical condition of the machine. Furthermore, methods of damage detection and prognosis are presented to evaluate the mechanical and structural components condition.

1.1 MECHANICAL-STRUCTURAL CONTINUOUS MONITORING SYSTEM

The architecture of a mechanical-structural continuous monitoring system or SHM design is illustrated on Figure 1.

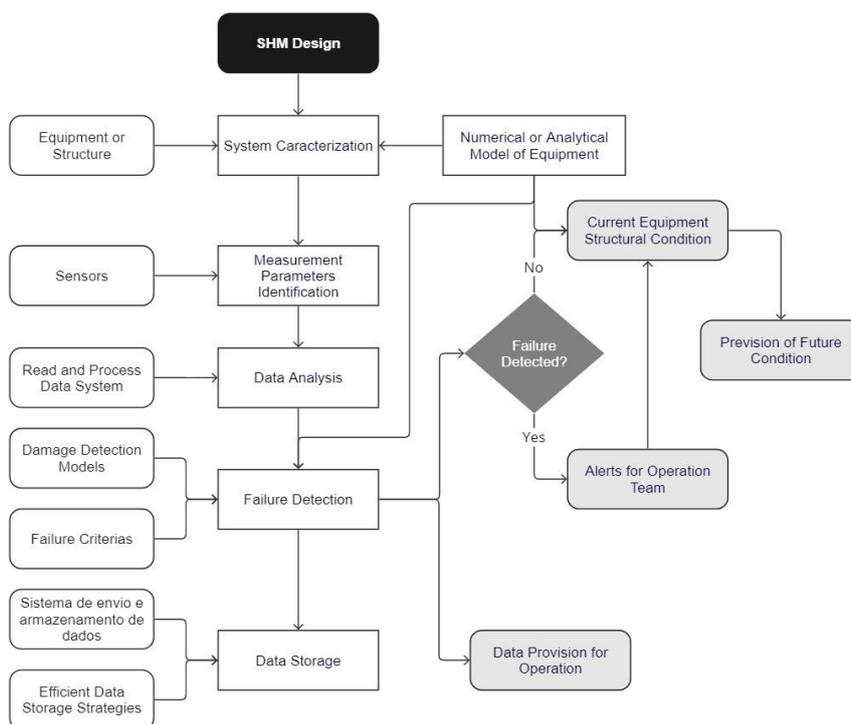


Figure 1. Schematic diagram of a structural health system.

The characterization of the mechanical-structural system consists of analyzing and understanding its function and the objectives of implementing the monitoring system. Firstly, an effort is necessary to obtain the relevant technical data associated with the mechanical-structural system, such as design and manufacturing drawings, photographs, inspection documents, failure history, maintenance and mechanical or structural modifications already performed.

Analytical models of a machine are considered during the structural characterization stage, which are fundamental to predict the mechanical response of this machine. These models are employed to provide useful data for the instrumentation of the equipment to be monitored. Besides, after implementation of the measurement system, these models can be refined and calibrated with the measured experimental data, in order to represent the current condition more precisely and to obtain a reference for determining potential changes in the mechanical-structural response, in the performance and in the fatigue life (Catbas, 2009).

1.2 Damage Detection

A SHM requires procedures to perform a fault analysis, which can provide data for failure detection. According to Worden (2006), the methods for detecting failures in SHM are divided into four levels of hierarchy. As the level increases, the system becomes more complex.

- Level 1 – Detection: method generates a qualitative indication of the possible presence of damage.
- Level 2 – Location: method generates an indication of the possible location of the damage.
- Level 3 – Assessment: method generates an estimate of the size and type of the damage.
- Level 4 – Prognosis: method generates information about the component operational integrity and residual life.

The development of damage detection strategies depends on the type of damage, the influence of the failure on the mechanical-structural system, the consequences of the failure, and the determination of the range of condition variables for operation without failures. The finite element model of the machine can be used to analyze the condition variables that play important roles in the system response.

1.3 Failures in Bucket Wheel Excavators

According to Rusinski (2009), excavator machines are subjected to time-varying loads, mainly due to the excavation and disposal of transported material. These load variations can cause mechanical and structural degradation, which can be observed through small cracks in the regions of welded joints. Also, the machine can operate at frequencies close to some natural frequency, generating cyclic deformation that can accelerate the degradation.

According to the categorization proposed by Jovancic (2011), the structure of a Combined Stacker and Reclaimer machine can be divided into five groups, listed in hierarchical order of importance. The presence of failures in the components can cause instability on the system and lead to a global collapse. The region of each group can be seen in Figure 2, for the SRs 2000 model of Combined Stacker and Reclaimer machine. The components of each region are described as follows: 1. connection rods at bucket wheel and counter-weight beams, 2. all lug connections of bucket wheel and counter-weight beams and pylon, 3. load-bearing structure of lifting components, 4. joint of slewing deck and pylon, 5. travelling bogies. Additionally, some parts deserve special attention, although they do not impact the overall stability of the equipment, such as the structure of the operator cabin, whose failure can lead to fatalities.

1.4 Fatigue Failures

Arsic (2018) indicates that the most critical regions of the mechanical-structural components of yard machines are the welded connection joints which represent almost 80% of occurrence of cracks.

Rusinski (2009) describes a failure analysis of a BWE caused by the rupture of the BWE linkage of counter-weight connection rod. Araujo (2012) reports a failure due to rupture in the connection rod of the boom during commissioning stage, that also generated instability and global collapse. Bosnjak (2013) presents an analysis that shows frequent cracks in the pylon, in a support region of the counter boom of a BWE, associated with high cyclic stress concentration in the damage location. Several works have shown the occurrence of small cracks on different structural components of BWE that lead to catastrophic failure (Arsic, 2010; Bosnjak, 2008; Rusinski, 2010; Jovancic, 2010). The fatigue analysis on the critical points of a BWE is vital to implement a reliable monitoring system.

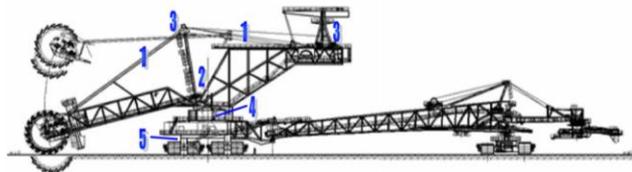


Figure 2. Basic structure of a structural monitoring system (Jovancic, 2011).

1.5 Stability Failures

The position of large machine center of mass must be carefully determined to avoid impacts on the stress levels and prevent failures due to local and global instability. Reliable measurement procedure is required to determine the global center of mass of the system (Moczko, 2019). Experimental measurements for weighing and estimating the position of the center of mass in Stockyard Machines can be performed through several methodologies.

- Weighing structures with three or more hydraulic cylinders equipped with pressure or force transducers.
- For rail mounted machines, weighing can be determined measuring deformation in the rails caused by each of the machine wheels, using strain gages.
- Weighing by measuring the deformation of structural elements, which is the most difficult to execute and is characterized by having the most estimation error compared to the other methods, but measurements can be performed in a continuous monitoring system.

1.6 Slewing Bearing Failures

Slewing bearings often endure harsh conditions and present high costs of replacement. A monitoring system of large bucket excavators must be capable of detecting premature damage on the bearing system (Caesarendra, 2015). Some analyses of the slewing bearings have shown that failures on the gears of the supporting system have forced the interruption of a BWE after 5,000 hours of operation (Arsic, 2019). Vibration and acoustic emission measurements have been used to monitor low speed slewing bearings for BWE (Caesarendra, 2015).

1.7 Operational parameters monitoring

Monitoring operating conditions is fundamental for SHM systems. Stockyard machines are subjected to stringent and varying conditions that can reduce the useful life of their components. Also, the operating parameters can be used to help in the identification of failures and in the decision-making process for operational strategies.

2. BUCKET WHEEL EXCAVATOR MODEL ANALYSIS

A finite element model with 315011 plate elements, 13511 beam elements, 3190 bar elements is implemented using the package FEMAP/NASTRAN (Siemens, version 2020.2) to represent the most relevant mechanical and structural components of the machine. The bucket wheel structure and non-structural parts (geared motors, slewing bearing, wheels, hydraulic parts, electric rooms, cabin, belt conveyor components, chutes, walkways, etc) were inserted into the model with mass elements connected to structural parts with rigid links (see Figure 3).

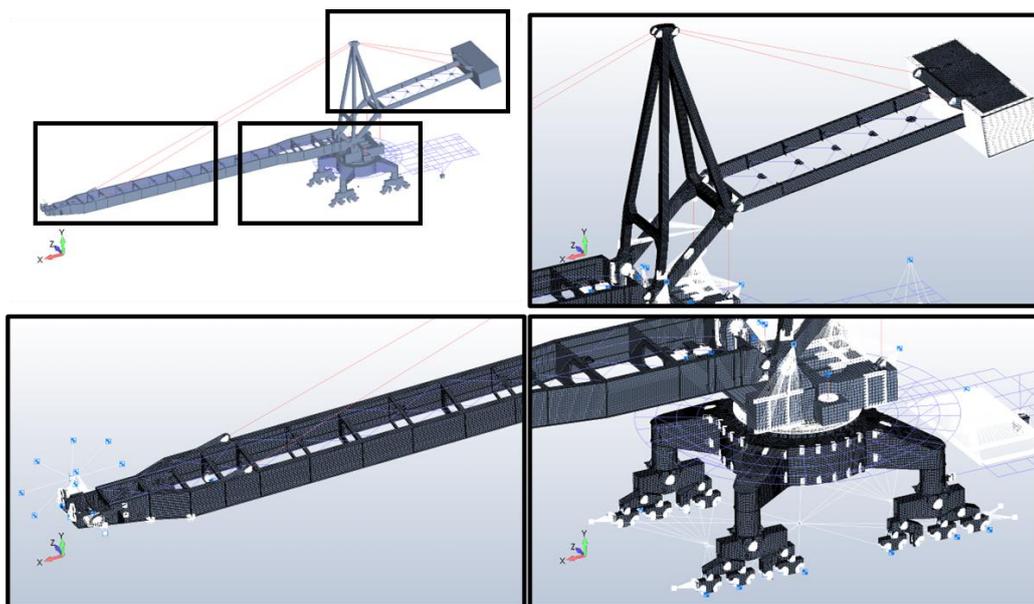


Figure 3. Finite element mesh.

A linear static analysis is performed for all load combinations according to FEM 2 131/2 132 standard. The load on the components of the BWE and the kinematic constraints are selected to represent different operating conditions. The loads acting on the machine during some operating cycles and the maximum wind loads on the steady machine are employed in the finite element model to perform the stress analysis. Technical data of machine is described in Table 1.

Table 1. Machine technical data.

Main dimensions (length x width x height)	50,6 x 12,6 x 23,3 m
Weight	535,5 t
Reclaimed material (specific gravity)	Coal (0,8 t/m ³)
Reclaimed capacity	600 t/hr
Traveling speed	30,9 m/min
Slewing speed	0,154 rpm
Luffing speed	6,0 m/min
Bucket revolution speed	6,2 rpm

According to FEM 2 131/2 132, the structural calculations for Stockyard machines must account stresses developed during operation and out of service with maximum wind conditions. Loads are categorized according to their frequency: main, additional, and special loads. Main loads are all loads which occurs under normal operational conditions. Additional loads can occur intermittently during operation or out of service. Special are loads that should not be present in equipment but the calculations must account its effects. The list of loads is shown in Table 2.

Table 2. Loads for Bucket Wheel Excavators.

Main loads

Dead loads, material loads, incrustation, digging forces, forces on conveyor, permanent dynamic effects, forces due inclination level

Additional loads

Wind loads, snow and ice loads, temperature effects, abnormal digging forces, bearing friction and rolling resistances, perpendicular forces to the rail due travelling (skewing effects), non-permanent dynamic effects

Special loads

Clogging of chutes, resting of reclaiming device or boom on material pile, failure of load limiting devices, blocking of travelling devices, lateral collision of the bwe with the slope, abnormal wind load, buffer effects, loads due to earthquakes, loads during machine erection

3. MONITORING SYSTEM

3.1 Fatigue life monitoring

Previous works on failure analysis of stockyard machines have indicated that the most common source of damage is associated with the fatigue of welded joints. Thus, the most critical places in the structure are points where the stress level reaches large values during the machine operation.

To estimate the most critical points based on numerical model analysis only the main loads are considered since other loads occur infrequently and its influence on fatigue assessment can be disregarded. An operational load cycle is obtained with machine in four different slewing positions and three luffing angles. The finite element predictions of the maximum stress ranges estimated by the von Mises criterion are depicted on Figure 4.

In total twenty points is selected as critical points for monitoring, the first sixteen points is selected based on stress range distribution, and number seventeen to twenty are chosen to represent all cases of failures reported in the technical literature.

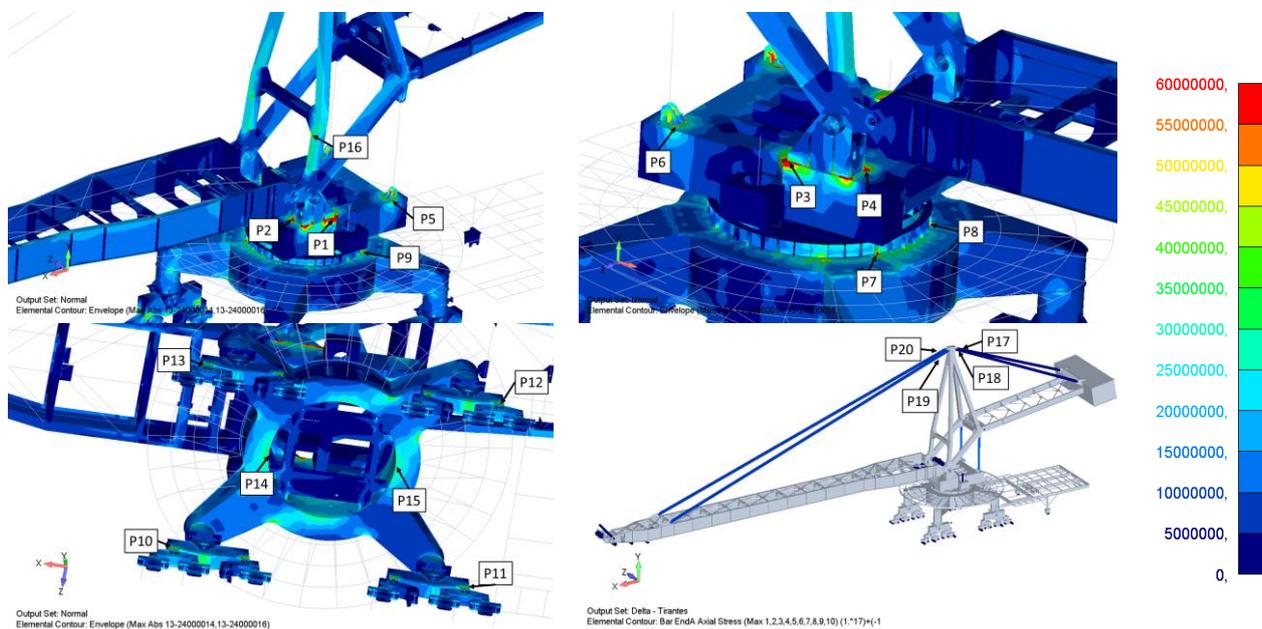


Figure 4. Distribution of stress range for operational cycles of a BWE (MPa).

The finite element model renders the values of the von Mises stress at the selected points during an operating cycle of the machine. The variation of stress at each point is used to estimate the stress cycle. Afterwards, a cycle count is performed using the Rainflow method. Fatigue life is estimated using the nominal stress method and hot spot method (IIW, 2016). The predictions of fatigue life for selected points are listed in Table 3.

Table 3. Estimated fatigue life for the selected points of the BWE.

Estimated fatigue life (in 1,000 hours)							
P1	35.8	P6	12086.1	P11	2135	P16	55345
P2	142.7	P7	212836.2	P12	6242	P17	“Infinite life” ⁽¹⁾
P3	60.3	P8	59877.4	P13	8710	P18	“Infinite life” ⁽¹⁾
P4	22.5	P9	8972.4	P14	45311	P19	“Infinite life” ⁽¹⁾
P5	6347.0	P10	1093.7	P15	60450	P20	“Infinite life” ⁽¹⁾

(1) Infinite life is considered for points which fatigue life is greater than 10⁹ cycles.

This study considers the use of strain gage as the most recommended method to predict fatigue life in a Structural Health Monitoring of Bucket Wheel Excavators (Lee et al., 2005).

3.2 Global stability monitoring

Experimental values of strain can be employed to analyze the global stability of heavy machines. A first step is to obtain the center mass position of the equipment and the locations of the supporting system (travelling wheels) on the horizontal plane. Center mass position can be computed from the balance of vertical reaction forces on the wheels. Eq. (1) and (2) are used to determine the center mass position of the equipment on the horizontal plane, on which x holds for the longitudinal direction and z for the lateral direction.

$$x_{cg} = \frac{\sum_{i=1}^n F_{vi}x_i}{\sum F_{vi}}, \tag{1}$$

where, x_{cg} , F_{vi} , x_i and n are the center mass position on longitudinal direction (x axis), vertical force on i^{th} wheel, distance in x axis from origin to position of i^{th} wheel, and number of wheels, respectively. The origin is on the center of the slewing bearing.

$$z_{cg} = \frac{\sum_{i=1}^n F_{vi}z_i}{\sum F_{vi}}, \tag{2}$$

where, z_{cg} and z_i are the center mass position on lateral direction (z axis), and distance in z axis from origin to position of i^{th} wheel, respectively.

In order to monitor the global stability, the FEM model is employed to estimate the locations and directions along which strains have a linear correlation to the vertical loads on wheels. Four regions are chosen for monitoring, two in each side of the machine, as illustrated in Figure 4.

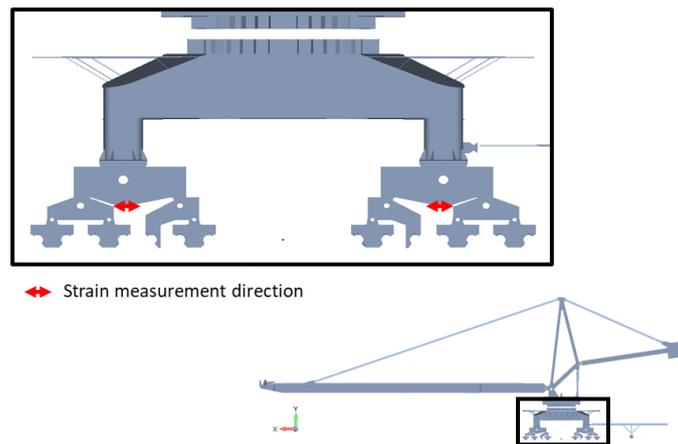


Figure 4. Locations for measurements of strain to estimate the center of mass.

The FEM predictions for the center of mass can be compared with the estimates rendered by the strain measurements, for different load conditions on the BWE. Figure 5 illustrates the curves for the horizontal coordinates of the center of mass on the x and z axes, obtained by the FEM model and by the strain measurements. Figure 6 shows the relative difference for the positions of the center of mass depicted on Figure 7.

It is noteworthy to say that installation of strain gages must be performed for the machine thoroughly free of load. For that, it is required to lift the slewing deck structure and relieve the pressure on the cylinders of the supporting system.

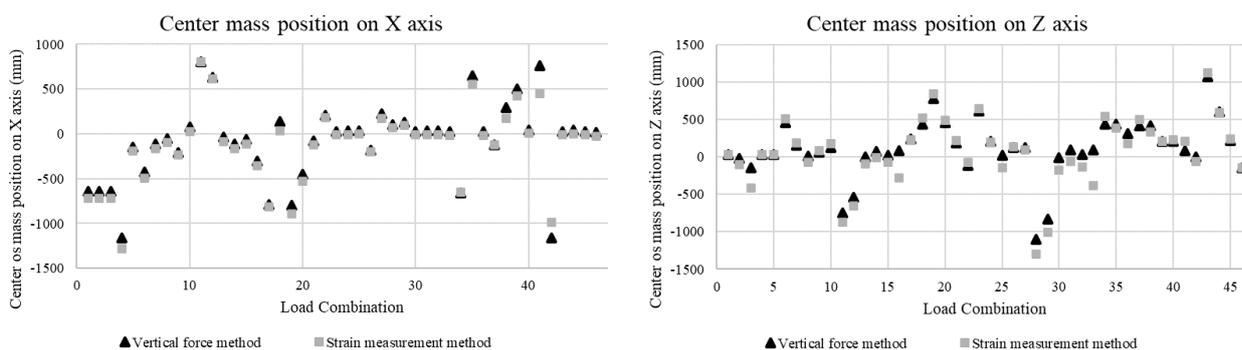


Figure 5. Comparative values of the horizontal coordinates x and z for the center of mass estimated by the force balance via FEM model and by strain measurement.

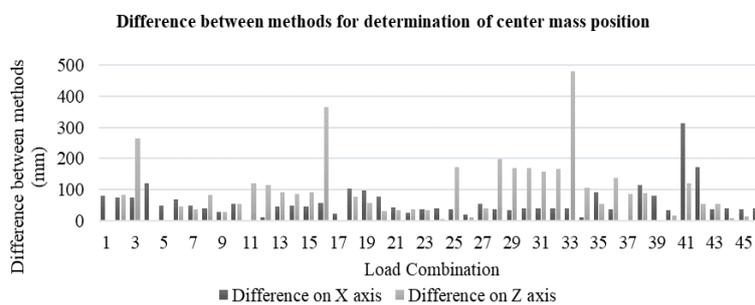


Figure 6. Relative difference for the center of mass position estimated by the force balance using the FEM Model and by strain measurements.

3.3 Damage monitoring on the slewing Bearing

Based on the work presented by Caesarendra (2015), acoustic emission is a signal preferable than vibration signal to monitor low speed bearings. To monitor the slew bearing condition, two acoustic emission transducers will be used, mounted on the slew bearing basis, as shown in Figure 7.

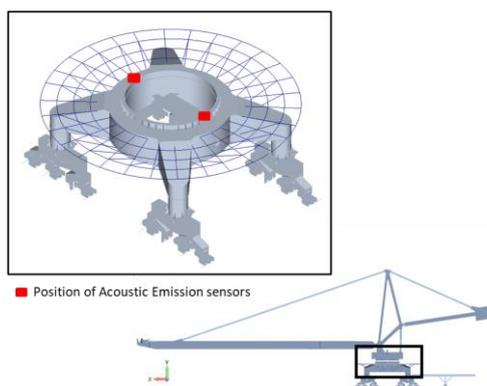


Figure 7. Position of acoustic emission sensors on the slewing bearing.

3.4 Operational parameters monitoring

The influence of the operational parameters on the mechanical and structural condition has been evaluated by the finite element model, to identify the main loads that cause large variations of forces and stresses on the components. The most important operating parameters for diagnosing structural and mechanical condition are listed in Table 4. The recommended monitoring methods for each operating parameter are described. Locations for mounting the sensors for monitoring operational conditions are illustrated in Figure 8, in which the sensors are identified by ID number.

Table 4. Operational parameters for continuous monitoring.

ID	Parameter	Method of measurement
1	Material loads	2x Load cells mounted on caring roller structure of conveyor belt
2	Cutting force	1x Engine electrical current and voltage measurements on Bucket Wheel drive system
3	Elevation of superstructure	1x Inclinometer mounted on boom structure
4	Angular position of superstructure	1x Rotary encoder mounted on slewing bearing
5	Force on elevation hydraulic cylinder	2x Pressure transducers mounted in each elevation cylinder system
6	Linear and angular impacts	2x Triaxial accelerometers mounted on center of superstructure and close to Bucket Wheel
7	Wind velocity and direction	Anemometer mounted on top of pylon
8	Position of equipment	High precision GPS
9	Operational Hours	1x Hour meter on drive system

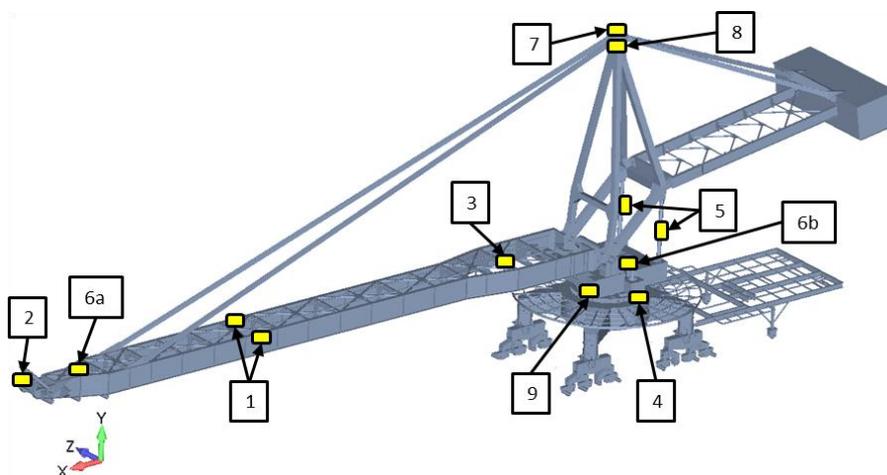


Figure 8. Sensor’s installation positions for monitoring operational conditions.

3.5 Damage detection strategies

For components subjected to fatigue, the recommended strategy for damage detection is based on cycle counting and cumulative damage estimate, which can be evaluated by Eq. (3). When cumulative damage (D_c) reaches the estimated value of fatigue damage (D_r), the SHM system must send an alarm for inspection on the region. To avoid unscheduled stops of the entire equipment for inspection only on some regions, SHM system must perform a prognosis analysis to predict the remaining fatigue life. If the remaining fatigue life is smaller than the scheduled inspection time interval, the inspection must be rescheduled before the damage compromises the mechanical integrity (see Figure 9).

$$D_c = \sum_{i=1}^j \frac{n_i}{N_i} \leq D_r = 1, \tag{3}$$

where D_c , n_i , N_i , j , and D_r are the cumulative damage, number of cycles of a stress range, number of cycles to failure at the stress range, estimated value fatigue damage, respectively.

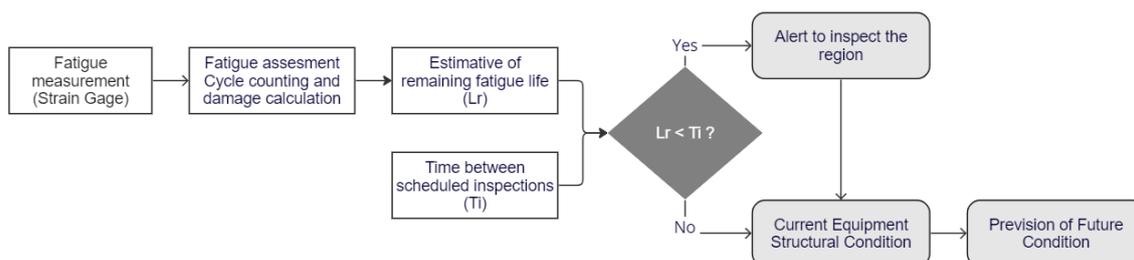


Figure 9. Fatigue damage detection system.

The detection of the machine instability requires a reliable estimate of the coordinates of its center of mass, which must be inserted in the stability polygon (geometry formed from the interconnection of the support points of the structure). For convenience, in this work, a design factor of 1.5 is employed to determine the stability polygon, since the machine monitoring must be continuous ($FS_s = 1.5$).

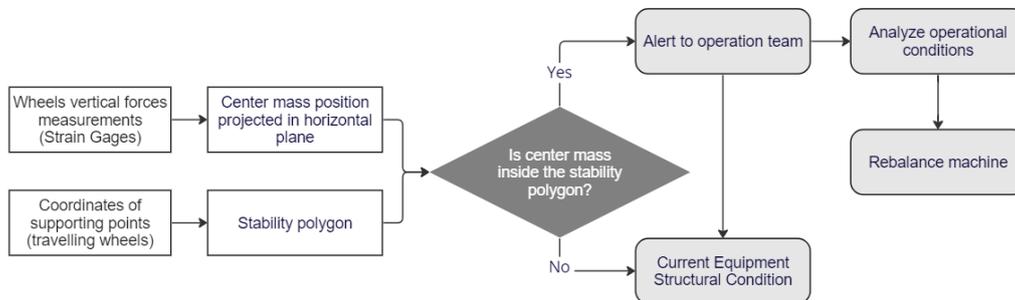


Figure 10. Global stability detection system.

For the damage detection of the slewing bearing with some acoustic emission (AE) technique, numerous experimental tests must be performed to correlate the AE signal with the bearing failures. The main characteristics to be extracted from the measured AE signal are count, energy, duration, amplitude, average signal level (ASL) and RMS.

The amplitude feature is the maximum absolute value of AE signal excursion during and AE hit. The amplitude is expressed in decibel (db) and can be obtained from Eq. (4).

$$db = 20 \log_{10} \left(\frac{V_{max}}{10^{-6}} \right) - G_{preamp}, \quad (4)$$

where db , V_{max} , and G_{preamp} are amplitude expressed in decibel (db), maximum absolute signal in volts, and preamplifier gain in decibel, respectively.

The RMS is a measure of the continuously varying signal into the AE system. The RMS of raw AE signal (AE_{rms}) can be expressed as Eq. (5).

$$AE_{rms} = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} V^2(t) dt} = \sqrt{\frac{1}{T} \sum_{i=1}^N V^2(i)}, \quad (5)$$

where V , T , t_0 , and N are the voltage signal, integration time of signal, initial time, and number of discrete AE data within the interval T , respectively.

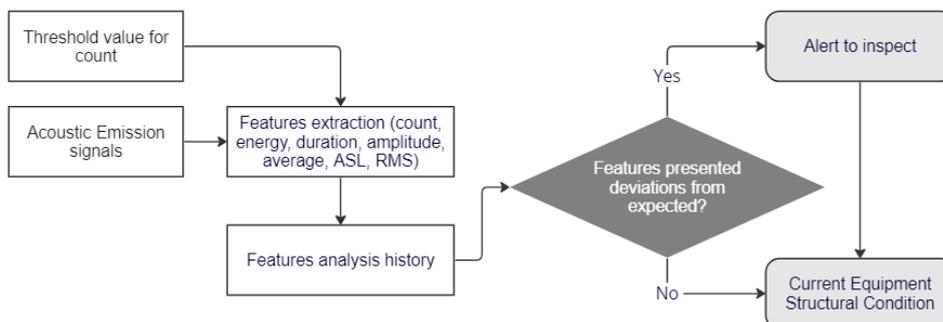


Figure 11. Slewing bearing damage detection system.

4. CONCLUSIONS

Several aspects of the development of a mechanical-structural monitoring system have been discussed for a bucket wheel excavator. A finite element model is implemented to estimate the stress levels on several regions of the machine under different operating conditions. The predicted values of stress are employed to analyze the fatigue life and support the development of a damage monitoring system and the identification of the critical locations for sensor mounting. A damage detection and prognosis strategy are developed based on cycle counting and linear damage theory, generating

alerts for operation teams to inspect the regions with low residual fatigue life and estimating future condition of monitored regions.

For the global stability monitoring, a system using strain measurements on the travelling system is discussed. The relations between the experimental values of strain and the vertical forces on the supporting wheels are evaluated using the FEM model. The comparative values of the center of mass coordinates on the horizontal plane indicate that is possible to monitor global stability using strain gages on the regions of interest. In the analysis of stability, the center of mass coordinates can be monitored, and its position can be compared to the polygon of stability to estimate the risks of global instability in real time.

The types of slewing bearing damage monitoring are also discussed. Acoustic emission techniques are the most recommended experimental procedure for detecting failures on large bearings with very low speed. Some functions for the AE signal employed for damage detection are amplitude, RMS, count, energy and ASL.

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