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EVALUATION OF THE EFFECT OF OPERATING PARAMETERS ON THE MOVEMENT OF AN INDUSTRIAL VIBRATING SIEVE

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Abstract: In the oil industry, the solids control step is of fundamental importance, as it aims to recover the drilling fluid for reuse in the process and adapt the solid material for an environmentally correct disposal. The vibrating screen is the first equipment used in solids control and its function is to reduce as much as possible the fluid content in the solid destined for the next stages of solids control. Thus, it can be seen that the optimal functioning of the vibrating screen benefits the entire solids control stage. The format of the movement performed by the machine is one of the design elements that interfere in the separation result. In view of the above, this work aims to characterize the movement and evaluate the effect of operational variables on the movement of a vibrating sieve. Results show that the equipment presents progressive elliptical movement, corroborating information provided by the manufacturer, and that the movement is greatly influenced by the presence or absence of fluid on the screen, however, once filled with fluid, variations in operating conditions do not significantly affect the movement.

Keywords: Vibrating sieve; Movement characterization; Solids control.

INTRODUCTION

The drilling of rocks for the extraction of oil is done through a probe, which consists of a set of equipment that makes it possible to apply a rotating action of an existing drill bit at the end of the drill string. Such action generates rock fragments, which must be removed by pumping a drilling fluid (THOMAS, 2001).

According to the American Petroleum Institute (API), drilling fluid is a circulating fluid used to make the drilling operation viable.

Generally, the drilling fluid is reused in the process for reinjection into the reservoir and when the solid material from the drilling is not properly removed, it compromises the physical properties of the fluid. The gravel is removed in a solids control unit, whose objective is to adjust the fluid for reinjection into the reservoir (AMERICAN ASSOCIATION OF DRILLING ENGINEERS, 1999). A solids control unit typically consists of vibrating screens, hydrocyclones and decanter centrifuges.

In addition to the economic aspect, the solids control system is also necessary due to the increasingly strict environmental legislation around the world. According to the US Environmental Protection Agency, the content of synthetic drilling fluid adhered to cuttings discarded on offshore platforms must be less than 6.9% by mass, and the disposal of cuttings impregnated with oil-based fluid is also prohibited (WHITE, 2000).

Vibrating sieves are the first devices to process the fluid, they are responsible for removing particles larger than 74 μm (gravel and grains larger than sand) that are retained on the screen, allowing a large amount of drilling fluid to pass through the screen. to proceed to the next removal steps. Therefore, other solids separation equipment can only operate efficiently if the sieves are working properly. Consequently, they are considered the most important solids control devices in a drilling rig (HOBEROCK, 1980; RAJA, 2012).

Drilling fluid flows down, into and through the screens of the screen. If the screen is stationary, a significant load would need to be applied to the drilling fluid to force it through the screen.

In this sense, it is necessary that vibrating motors be coupled to the system so that they apply a force on the screens of the sieve, causing the fluid to be separated more efficiently.

The upward movement moves the drilling fluid across the screen. Large solids do not follow the screen downwards, so they can be propelled from the surface of the screen. When the screen moves downward, the large solids are suspended above the screen and come into contact with the screen at a point farther towards the discharge end of the agitator. This is the reason why elliptical, circular and linear motion screens transport solids (ASME, 2005).

The movement of the vibrating screen through the drilling fluid causes the screen to cut through the fluid. This lowers the viscosity and is an effective component in allowing the agitator to process the drilling fluid (ASME, 2005).

Screening is the result of using the energy developed by a rotating eccentric mass and applying that force-to a porous surface. The energy causes the screen to vibrate in a fixed orbit or path.

The movement produced by the screens is the result of the combination of the amount and position of the vibrating motors along the equipment. Also according to ASME (2005), there are 4 characteristic movements of sieves: balanced elliptical, unbalanced elliptical, circular and linear.

Given the importance of movement in the solid-fluid separation process in vibrating screens, this work aims to characterize the type of movement of an industrial vibrating screen and to quantify the effects of operational variables on the characteristics of movement through experimental data.

MATERIALS AND METHODS

EXPERIMENTAL UNIT

The experimental unit used was a MONGOOSE PRO Shaker industrial vibrating sieve produced by the company M-I Swaco, of the Schlumberger group. The sieve consisted of 4 sieving screens, each screen with a length of 0.585 m and a width of 1.165 m, with an opening diameter of 0.075 mm (200 mesh). The equipment also had two vibrating motors with 1800 RPM and 2.5 hp operating in counter-rotation. According to the manufacturer, the equipment can operate in normal mode with a g-factor of up to 6.5, while in capacity mode, the g-factor value can reach up to 7.5. Regarding the screen inclination, according to the manufacturer, the inclination can vary from 2° to 8°.

The vibrating sieve used was installed at the Chemical Engineering Research Unit (UPEQ) of the Faculty of Chemical Engineering of the institution: Universidade Federal de Uberlândia.

The vibrating screen was mounted 3 m above the ground, using a carbon steel support structure, below which there is a mixing tank equipped with a 3,000 L capacity agitator.

The suspension used in the tests was formed by montmorillonite mud and sand, with a mass concentration of sand in the mixture of 2.5%. The granulometric distribution of the sand used followed the RRB granulometric distribution model, adjusted with R^2=0.96 and presented in Equation 1, where D is the diameter of the particles in μm and X is the fraction of solids with a diameter equal to or smaller than the D.

$$X = 1 - exp\left[-\left(\frac{D}{721.14}\right)^{2.54}\right] \quad (1)$$

The motmorillonite slurry used was obtained from the dissolution of montmorillonite in water, the mass concentration of montmorillonite used in the slurry being equal to 3.14%. This mud has rheological characteristics of a pseudoplastic fluid and its apparent viscosity is described by Equation 2.

$$\eta = 0.3169 \cdot \gamma^{-0.6096} \quad (2)$$

In Equation 2, η is the apparent viscosity in "Pa"."s" and γ is the shear rate in . The average viscosity of montmorillonite slurry is 0.012 "Pa"."s", equivalent to 12 cP, by way of comparison, the viscosity of water is 1 cP.

The suspension was pumped by a Warman Weir 4/3C – AH mud pump with a 15 HP WEG engine. The unit used in the experimental tests is schematized in figure 1.

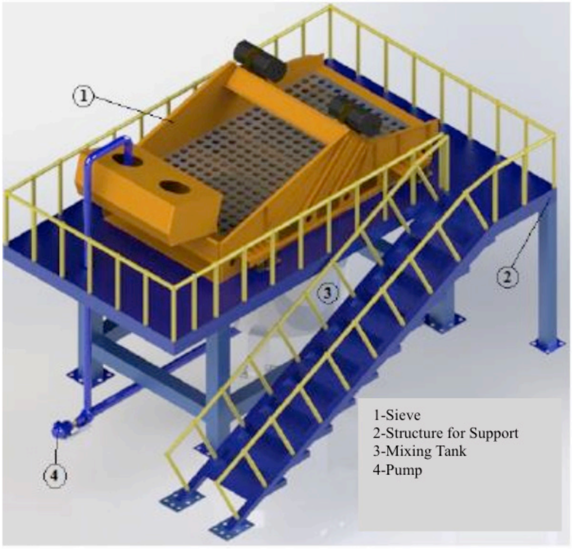

Figure 1: Scheme of the experimental unit used.

To study the characterization of movement, the Adafruit library was used, as well as the accelerometer sensor model MPU-6050, an Arduino board model: Uno R3 and four *jumpers*.

The accelerometer measures acceleration (rate of change of object's velocity). It detects static forces such as gravity (9.8 m/s^2) or dynamic forces such as vibrations or motion. The MPU-6050 measures acceleration in the X, Y and Z axes.

The communication with the microcontroller takes place through the Inter-integrated Circuit (I2C) interface and, therefore, communicates through two channels, one destined to receive and transmit data and the other for communication synchronization. The sensor has eight pins with different functions, as illustrated in figure 2.

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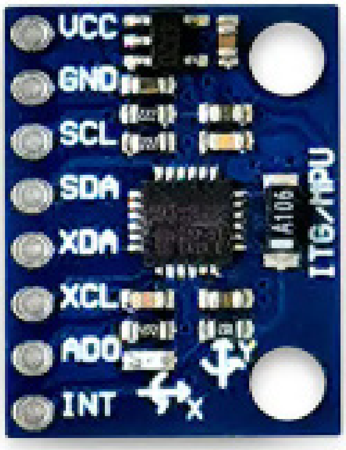

Figure 2: Triaxial accelerometer sensor model MPU-6050.

In this study, only four pins were used, namely: "VCC", "GND", "SCL" and "SDA". The "VCC" pin provides the circuit power, the "GND" the system ground, the "SCL" is the timer while the "SDA" is the data transmitter. It can be seen that the sensor has in its structure the identification of the direction and direction of the x and y axes, which must be respected at the time of data collection.

The Arduino board used in this study was the R3 model which, like the sensor, has communication with the microcontroller via I2C interface.

In the studies carried out, it was decided to evaluate only the normal mode of operation, which, according to the manufacturer, guarantees a g-factor of up to 6.5 and presents a progressive elliptical movement, but does not present further details regarding this movement.

In this study, the sensor was positioned in the sieve basket in two positions, one at the beginning, close to the suspension feed, and one at the end, close to the solids discharge, as shown in Figure 3.

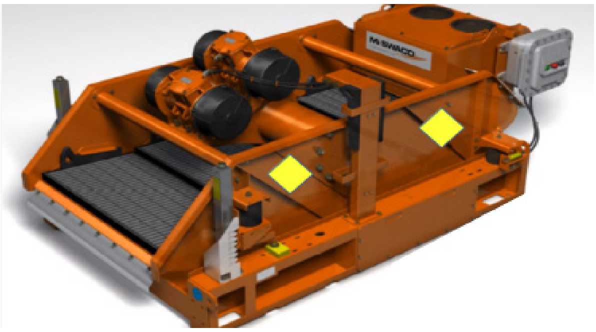

Figure 3: Basket positions (yellow diamonds) where the accelerometer sensor was attached.

There are different ways to get sensor readings. In this work, the Adafruit_MPU6050 library was used.

The first step of programming code is to include the libraries that will be useful. In this case, in addition to *Adafruit_MPU6050*, Adafruit_Sensor, math.h and wire.h were used. The wire.h library allows communication between I2C devices, while the math.h library provides a set of functions for mathematical operations.

Due to the noise present in the signal captured by the sensor, it was necessary to calibrate the low-pass filter at 260 Hz. As the noise has a much higher frequency than the signal of interest, the filter allows only lower frequencies to pass in the final signal, retaining the higher frequencies. This way, the noise present in the signal is eliminated.

The acceleration *range* was set at 8G, that is, up to eight times the gravity value. This value was defined according to the sieve's specifications, which determine the operating range at 6.5G.

The main lines of code have the "*loop* ()" function. This function is a repeat task command. Therefore, recurring sensor readings were obtained and displayed on the Arduino Serial *Monitor*. Acceleration was measured in m/s^2 every 100 milliseconds.

MOVEMENT CHARACTERIZATION

With the data collected, it is possible to characterize the movement of the vibrating sieve through mathematical equations. To characterize the movement, it is necessary to define the ellipses that represent this movement. First, it is important to define the parameters of the canonical equation of the ellipse, represented in Equation 3.

$$\left(\frac{a'_x}{m}\right)^2 + \left(\frac{a'_y}{M}\right)^2 - 1 = 0 \quad (3)$$

On what:

$$a'_x = a_x cos\theta + a_y sin\theta \quad (4)$$

$$a'_y = a_y cos\theta - a_x sin\theta \quad (5)$$

Equations 4 and 5 are linear transformations for a rotation of θ in the Cartesian plane, where a_x and a_y are the values of the system accelerations collected by the accelerometer sensor. As the sensor is fixed parallel to the surface of the basket, which is flat, then $a_z \approx 0$. In Equation 3, m and M are, respectively, the minor and major semi-axes.

The characterization of the motion requires the determination of the parameters θ, m and M. It is observed that Equation 15 is equal to zero and that for each line of the available data set of accelerations, it is possible to write this equation and obtain a value for its left side, this assigning values to the unknown parameters. If all the "left sides" resulting from Equation 3, applied to each line, are summed in modulus, the result must be minimal when the unknown parameters are correct. Therefore, an optimization problem must be solved, whose objective is to minimize the sum in modulus of the aforementioned "left sides", determining the optimal values of θ, m and M. Or, in mathematical terms, one has to solve the problem of Equation 6.

$$F(\theta, m, M) = min{:} \sum_i \left| \left(\frac{a'_{xi}}{m}\right)^2 + \left(\frac{a'_{yi}}{M}\right)^2 - 1 \right| \quad (6)$$

After the optimization process, we have the canonical equation of the defined ellipse; however, in terms of usefulness for application in models and analysis of external effects, the canonical equation is not very useful, and, therefore, the parametric equation of the ellipse must be determined. The parametric equations define the trajectory of accelerations as a function of time.

The parametric equation for the x direction is given by Equation 7 and in the y direction by Equation 8.

$$a_x = -\omega^2 A_x sin(\omega t + \gamma_x) \quad (7)$$

$$a_y = -\omega^2 A_y sin(\omega t + \gamma_y) \quad (8)$$

Here, ω=2πf is the angular velocity, with f being the vibration frequency given by the frequency inverter associated with the sieve in Hz, A_x e A_y are the vibration amplitudes in the x and y directions given in meters, respectively, y_x and y_y are the phase angles.

The equation used to obtain the parameters of the parametric equation of the ellipse in the x and y directions was adapted from Chen et al. (2020).

As the vibrating screen rotates clockwise, the phase angles for the x and y directions are calculated, respectively, by Equations 9 and 10.

$$\gamma_x = \operatorname{atan}\left(\frac{M}{m} cot\theta\right) \quad (9)$$

$$\gamma_y = -\operatorname{atan}\left(\frac{M}{m} tan\theta\right) \quad (10)$$

The amplitudes in x and y are calculated from Equations 11 and 12.

$$A_x = \frac{\sqrt{(mcos\theta)^2 + (Msin\theta)^2}}{\omega^2} \quad (11)$$

$$A_y = \frac{\sqrt{(msin\theta)^2 + (Mcos\theta)^2}}{\omega^2} \quad (12)$$

With the parameters already established, the parametric equations of the accelerations are defined, which can be plotted against the experimental data.

ANALYSIS OF THE EFFECT OF OPERATING VARIABLES ON MOVEMENT

In terms of the operation of the vibrating screen used in this study, the operating conditions that can be manipulated are: tilt of the screen of the screen, rotation frequency of the screen motors and frequency of the system feed pump.

The alteration of these operational variables allows to obtain a better condition for the operation, in terms of solid-liquid separation. The manipulation of these operating conditions also influences the amount of material retained on the sieve screen and, in turn, this amount of material influences the movement performed by the sieve.

Due to the dynamics of the process, it is not possible to directly determine the amount of material on the sieve screen, therefore, to evaluate the effect of the suspension mass on the sieve screen on its movement, a central composite planning was elaborated. (PCC), in order to analyze the effects of operational variables on the movement performed by the vibrating sieve.

The experimental planning matrix adopted is presented in Table 1.

N° Experiment	X_1 (Inclination)	X_2 (Freq. engines)	X_3 (Freq. bomb)
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1
9	0	0	0
10	-α	0	0
11	α	0	0
12	0	-α	0
13	0	α	0
14	0	0	-α
15	0	0	α
16	0	0	0

Table 1: Experimental design matrix used.

The variables X_1, X_2 and X_3, which represent, respectively, screen inclination, rotation frequency of the sieve motors and frequency of the feed pump, are coded. The coding formulas are presented in Equations 13, 14 and 15.

$$X_1 = \frac{\text{Inclinação}(°) - 5°}{1.5°} \quad (13)$$

$$X_2 = \frac{f_{motor}(RPM) - 1400RPM}{227RPM} \quad (14)$$

$$X_3 = \frac{f_{bomba}(Hz) - 13Hz}{1.5Hz} \quad (15)$$

For the case of central composite planning with 3 factors, a central point in cubic planning (2^k) and a central point in the second part of the planning (experimental design used), the value of α in the planning matrix is α = 1.763834.

As response variables, the parameters that define the parametric equations of motion were used, that is, A_x, A_y, y_x and y_y. For the analysis of the effects of the operational parameters in the movement, the accelerometer sensor was kept fixed only in the final part of the screen of the sieve.

RESULTS AND DISCUSSIONS

MOVEMENT CHARACTERIZATION

In the characterization of the movement, the vibrating screen was not being fed, that is, it was operating empty, therefore, the parameters obtained are not a function of the operating conditions. For the characterization of the movement, the vibrating motors were operating with a rotation frequency of 1870 RPM, or 31.17 Hz, which is equivalent to the maximum value reached by the equipment.

To obtain the parameters that characterize the movement, 400 data collected by the accelerometer sensor were used. The optimization problem was then formulated in a spreadsheet software and solved using the differential evolution algorithm.

The parameters of the parametric equations of the ellipse obtained are shown in Table 2.

Position	y_x (-)	y_y (-)	A_x (m)	A_y (m)
Start	1.4388	-1.3303	0.0372	0.0495
Final	1.2672	-1.2669	0.0421	0.0421

Table 2: Parameters of the parametric equations of the ellipse in the x and y directions.

With the parameters that describe the movement, it was possible to plot the experimental data and the models obtained at the beginning and at the end of the vibrating sieve, these graphs are, respectively, represented by figures 4 and 5.

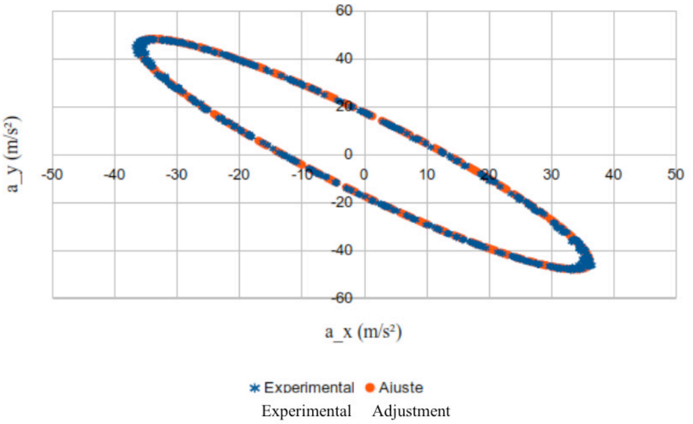

Figure 4: Motion obtained experimentally and adjusted by the parametric equations at the beginning of the sieve.

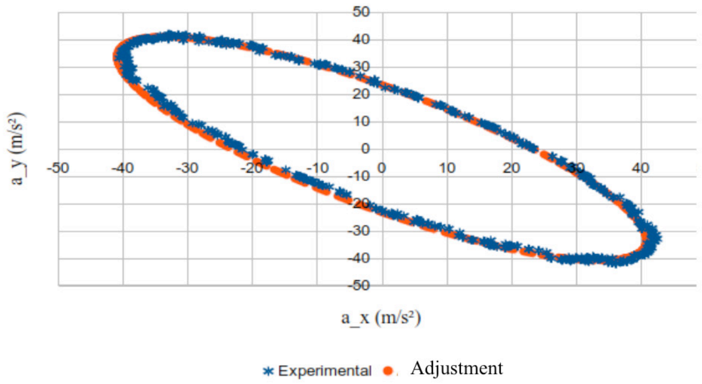

Figure 5: Motion obtained experimentally and adjusted by parametric equations at the end of the sieve.

The movement identified coincided with the characteristic described by the manufacturer, the progressive elliptical movement was observed, that is, at the beginning of the screen the ellipse is narrower while at the end of the screen the ellipse is wider.

It was also observed that the model fitted by the parametric equations of the ellipse describes the movement well due to the proximity of the experimental and fitted curves. It was not possible, in this study, to numerically quantify the error between the fitted and experimental curves, this occurs because the sensor sampling time does not coincide with the time of the parametric equations, since, although a time t = 0 has been adopted, this instant is just a reference, since the sampling is started at a random time instant of the trajectory.

As indicated in the parameters of Table 2, at the beginning of the vibrating sieve, the acceleration in the y direction is more accentuated than in the x direction, which favors a greater flow of passing fluid, at the end of the screen, there is a movement that favors a greater residence time, which is justified due to the lower fluid content in the solid in the final parts of the separation screen during a real operation.

ANALYSIS OF THE EFFECT OF OPERATING VARIABLES ON MOVEMENT

With the system operating in the separation of solid-liquid from the suspension described in the Materials and Methods section, the motion was characterized for each experimental condition presented in Table 1. The parameters of the parametric equations of the ellipse for each operational condition adopted are presented in the Table 3.

Experiment	A_x (mm)	A_y (mm)	(-)	(-)
1	1.2683	1.3687	1.5368	-1.2260
2	1.3004	1.3228	1.5338	-1.2281
3	1.2087	1.4337	1.5552	-1.2092
4	1.2633	1.3507	1.5528	-1.2485
5	1.2422	1.3779	1.5378	-1.2144
6	1.2636	1.3406	1.5355	-1.2096
7	1.2369	1.3966	1.5541	-1.2228
8	1.2643	1.3268	1.5522	-1.2439
9	1.2592	1.3619	1.5469	-1.2388
10	1.2287	1.3638	1.5474	-1.2211
11	1.2961	1.3125	1.5447	-1.2536
12	1.2054	1.2572	1.5182	-1.2163
13	1.2148	1.4269	1.5579	-1.2437
14	1.2752	1.3576	1.5465	-1.2448
15	1.2576	1.3447	1.5464	-1.2364
16	1.2581	1.3570	1.5468	-1.2378

Table 3: Parameters of the parametric equations of motion obtained for each experimental condition used.

With the experimental results in hand, the statistical treatment was performed using the R language and using the RStudio graphical interface, through the RSM library (LENTH, 2009). The statistical treatment aimed to analyze the effects of each parameter of the models obtained by regression in a confidence interval of 90%, with the non-significant effects for the model being removed one by one.

The regression models obtained are presented in Equation 16.

$$
\begin{bmatrix} A_x \\ A_y \\ \gamma_x \\ \gamma_y \end{bmatrix} =
\begin{bmatrix}
1.2671 & 0.0179 & -0.0060 & 0 & 0 & 0 & 0.0115 & 0 & -0.0162 & 0 \\
1.3562 & -0.0230 & 0.0279 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1.5469 & -0.0010 & 0.0099 & 0 & 0 & 0 & 0 & 0 & -0.0026 & 0 \\
-1.2309 & -0.0081 & -0.0067 & 0 & -0.0079 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \cdot
\begin{bmatrix} 1 \\ X_1 \\ X_2 \\ X_3 \\ X_1 \cdot X_2 \\ X_1 \cdot X_3 \\ X_2 \cdot X_3 \\ X_1^2 \\ X_2^2 \\ X_3^2 \end{bmatrix} \qquad (16)
$$

As a metric to assess the goodness of fit, the mean relative error (MRE) was used. Let ŷi be the predicted value and yi the actual value, the ERM is defined by Equation 17.

$$ERM(\%) = \frac{1}{N}\sum_1^N \left|\frac{\hat{y}_i - y_i}{y_i}\right| \times 100\% \qquad (17)$$

Table 4 shows the ERM value calculated for each model obtained.

Model	*ERM (%)*
A_x	0.76
A_y	1.42
y_x	0.07
y_y	0.56

Table 4: Mean relative error calculated for each identified model.

Analyzing the models obtained from the regression of experimental data, differently from what would be expected, the feed flow, indirectly related to the frequency of the feed pump (X_3) practically had no influence on the movement, appearing only in an interaction parameter with the frequency of the motors (X_2). However, analyzing the results presented in Table 2, in which the sieve screen was empty, and the results of Table 3, there is a great variation in the parameters that characterize the trajectory of the equipment, it is worth noting that the amplitude units are different, but carrying out the proper conversion, it is observed that the amplitudes of the movement in the sieve filled with the suspension are inferior to the amplitude of the empty sieve, for both directions, x and y. Thus, it is concluded in relation to the feed flow that, once the screen is already filled, changes in flow do not affect the characteristics of the sieve movement.

Regarding the other two variables, namely: screen inclination and motor rotation frequency, it can be seen that they do not have a great influence on the parameters, since the coefficients associated with these parameters are very small compared to the constant value of the polynomial.

CONCLUSIONS

Based on the study developed in this work, it was possible to characterize the movement of the equipment through the detection of accelerations by the accelerometer sensor and to discuss, from a theoretical point of view, the drainage of the suspension on the screens.

The ellipses constructed from the experimental results presented an excellent approximation to the ellipses plotted from the mathematical manipulations.

The movement identified in this study was the progressive elliptical. This movement explains the greater potential for solid-liquid separation at the beginning of the sieve, where the liquid concentration is high, and a longer residence time at the end of the sieve, which favors the deposition of less humid solids in the discharge region.

Regarding the analysis of the effects of the operational variables, the description of the effects was possible to be carried out through an experimental design, obtaining regression equations that describe the influence of the screen inclination, rotation of the sieve motors and rotation frequency. of the pump on the movement characteristics.

A great difference was observed in the parameters of the parametric equations of the ellipses for the empty sieve and for the system operating with the suspension of montmorillonite mud and sand. However, once the screen has been filled, large variations in motion are not observed with changing operating conditions.

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