EFFICIENCY INCREASE IN THE EXTRACTION OF SUGAR CANE MILLS BY MEANS OF THE REGULATION OF HYDRAULIC PRESSURES

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Abstract: In this paper, the distribution of pressure on the bagasse layer in the sugar cane mills and an automatic regulation proposal to increase the efficiency in the extraction of sugar cane juice is approached. An analysis that considers the top shaft-roller as a beam on elastic foundation is carried out. It is possible to determine the pressure distribution on the bagasse layer and the mill bearing reactions. The behavior of the bagasse layer reaction is analyzed for different hydraulic pressures in each side of the mill; being demonstrated, an optimal relationship of pressures to achieve a uniform compression on the bagasse layer. Finally, once this pressure relation in known, a control strategy is developed for each hydraulic cylinder.

Keywords: Mill, extraction, elastic foundation, plant, Adaptive control, controller.

1. INTRODUCTION

This paper presents a new analysis plan and the procedure used to calculate the inner forces in the sugar cane mill shafts. The mill studied has four rollers and inclined "virgin". The reaction of the bagasse layer on the top roller was determined considering it as a beam on elastic foundation.

One of the contributions of this research is to consider the top roller as a beam on elastic foundation. No previous paper determines the variation law of this reaction along the length of the rollers. There can be no doubt that its characterization from the mathematical point of view offers new knowledge about the process of compacting of sugar cane in the mills.

In this research it is proposed to modify the hydraulic pressures due to the load system acting on top shaft causes a non uniform compacting pressure on the bagasse layer. This situation creates different extraction levels. In this way and with the information given by the analysis model, an automatic control is proposed on the hydraulic servo-system.

This control permits to adjust in a continuous way the hydraulic pressures in order to achieve a uniform compacting pressure also increasing the efficiency if it is taken into account that if the compacting pressure increases also the extraction does.

2. ANALYSIS MODEL.

The following loads on the shafts were considered in the analysis plan design:

- Hydraulic force on the top shaft bearings.
- Gear contact forces.
- Contact forces between the top shaft square shaft and coupling box.
- Reaction of the bagasse layer on the shaft rollers.
- Shaft weight and joined elements. Normal forces generated on the "virgin".
- Bearing friction with the "virgin".
- Piston sealed friction with the cylinders walls.

It was possible to measure the instant flotation by means of a resistive transducer, connected to a computer data acquisition card.

The contact forces P_a and P_b are related to the instant torque and instant flotation by:

$$P_a = T_m^{inst.}\left(\frac{1}{l_3} \pm \frac{A_0}{2}\right) \tag{1}$$

$$P_b = T_m^{inst.}\left(\frac{1}{l_3} \mp \frac{A_0}{2}\right) \tag{2}$$

Where:

T_m^{inst} – Instant torque acting on the square shank (kN m).

l_3 – Square shank face (m).

A_0 – Coefficient depending on the instant misalignment ratio (m-1).

Based on the instant flotation measures and the power consumed by the corresponding engines that move the "Guillermo Moncada" sugar factory five mills, it was possible to obtain a simplified load history for the forces acting on the top shaft square shank. Fig. 1 shows a graph with a short time period of load history of the contact forces in the square shank.

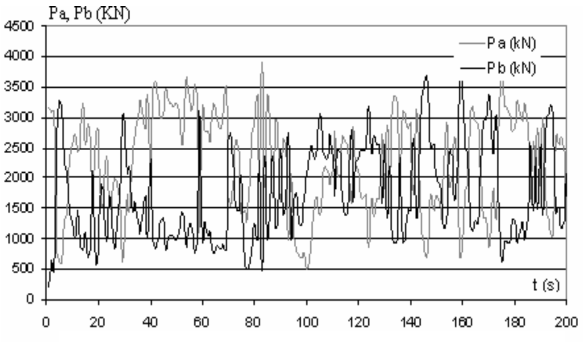

Fig. 1. Contact forces variation in the top shaft square shank.

On the other hand, the bagasse layer reaction on the shafts rollers is a reactive load and has an unknown value, so, it should be determined using the rest of the loads acting on the shaft. It was determined considering the shaft as a beam on elastic foundation so that the bagasse layer reaction is proportional to the shaft deflection for each position (Pisarenko, 1985):

$$q_{R\,(z)} = -\alpha y_{(z)} \tag{3}$$

Where:

$q_{R(z)}$ – Bagasse layer reaction intensity at a z distance from the left end of the roller (kN/m).

α - Foundation rigidity coefficient (MPa).

$y_{(z)}$– Shaft deflection at distance z of the left side (mm).

In order to apply the beam on elastic foundation Model, it is needed to know the rigidity coefficient of the foundation (α), that in this case it is compact bagasse. This coefficient was obtained using Arzola's model (Arzola, 2003).

$$\alpha = \frac{5{,}8 \cdot 10^{-7}\left(84{,}6 - 0{,}4W + 0{,}006W^2 + 4{,}3M\right)}{C_{eq}^{\,7}} \tag{4}$$

Where:

C'_{eq} –Equivalent compression ratio of bagasse in the mill.

W – Bagasse humidity percentage in the mill entrance.

M – Mill position in the Tandem.

The inner forces acting on the shaft cross section could be determined with no difficulty from the left to the right end of the roller using the section approach. The area where the roller is coupled is unknown because it's also unknown the variation law of the bagasse layer reaction. It can be determined using the parameter approach for the solution of the general case of load for a finite beam on elastic foundation (Juvinall, 2000; Okamura, 1972).

The analysis focuses now in the bagasse layer reaction behavior for different relations of applied hydraulic forces on the left and right cylinders. Previous papers state the possible effect of the use of different hydraulic forces for both sides of the mill. It is stated as an approach with which the flotation on both sides of the mill is the same. But, no previous research makes a theoretical analysis to support this behavior and in most of them the bagasse layer reaction is considered as distributed with uniformity (Fernández, 1982; Hugott, 1986). The intensity relation of the left side hydraulic force (q_{hid} 1) with respect to the intensity relation of the right side hydraulic force (q_{hid} 2) is stated as:

$$\lambda = \frac{q_{hid1}}{q_{hid\,2}} \tag{5}$$

The reactions shown in Fig 2 are obtained giving values of 0,75; 1; 1,25 and 1,5 to λ.

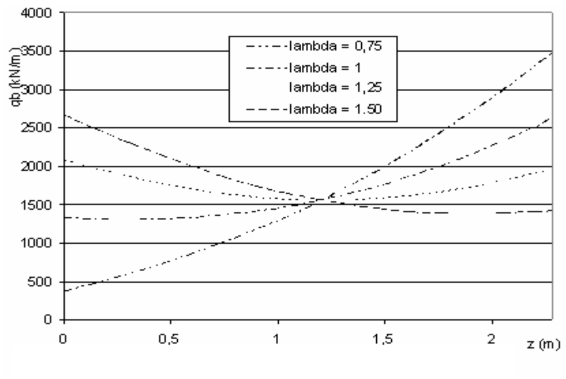

Fig. 2. Bagasse reaction behaviour considering some lambda values.

The obtained result is interesting from the working view point. You can notice that when you apply same hydraulic forces on both bearings, the cane going near the gears side is much more compact than the one going near the extreme side. An even more unfavourable situation could be reached if it is applied a bigger hydraulic force (λ= 0,75) on the right cylinder.

Obviously, if it is intended to reach higher levels of extraction, the pressure on the bagasse layer should be as uniform as possible along the roller width.

The very best hydraulic pressure relation in the analyzed mill is reached for λ=1,24; where the best symmetry is achieved in the bagasse reaction distribution. This parameter (λ) is in correspondence with the uniformity level in the compression that is exerted to the bagasse in the mill. Each mill should be analyzed separately in order to know the best λ value. This optimal value depends on the dimensions, working parameters and loads acting.

It is known that the higher compression pressure, the higher extraction is achieved. Although the relation between the extraction and the applied pressure is not lineal as it is seen in fig 3.

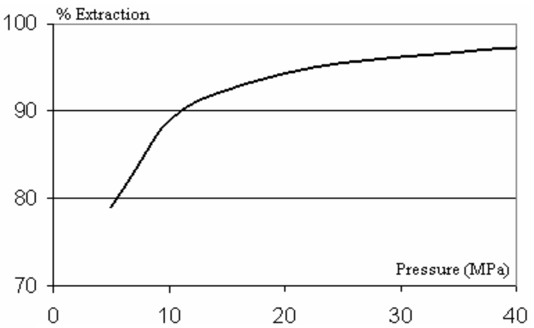

Fig. 3. Extraction behaviour with the applied pressure.

Hugott (1986) offers a group of useful measures to relate these two variables. The following extraction behavior is obtained from the equation:

$$\mathrm{Ext} = 68{,}82 + 8{,}75\ln(\mathrm{PHE}) \tag{6}$$

Where:
Ext – Extraction percentage (%).
PHE – Specific hydraulic pressure (MPa).

It is necessary to check the behavior of the global extraction for equal hydraulic pressures and for a relation between them that reaches a pressure on the bagasse layer as uniform as possible (λ= 1,24), keeping in both cases a total hydraulic pressure of the same magnitude.

If you divide the area under the selected curves into many sectors, it is possible to calculate the specific pressure for every sector as:

$$PE_n = \frac{\bar{q}_n}{0{,}1D} \tag{7}$$

Where:
PE_n – Specific pressure on the n sector of the bagasse layer (MPa).
$\bar{q}_n$ – Average distributed load on the n sector of the bagasse layer (MN/m).
D – Mean diameter of the rollers (m).

Calculating the extraction in each sector *n* by means of equation 6 and determining its value for all the length of the roller it is obtained:

$$EG = 68{,}82 + \frac{1}{n}8{,}75\sum_{i=1}^{n}\ln(PE_n) \tag{8}$$

Where:
EG – Mill global extraction percentage (%).

We can see from the calculations that the global extraction has a value of 92.7 % for equal hydraulic pressures and for hydraulic pressures that exert a hydraulic pressure as uniform as possible on the bagasse layer, the global extraction is 93.3 %. It can be noticed that the increase in the extraction efficiency is 0.6 %. Other calculated values in the increase of the extraction efficiency have been found between 0.5 % and 1 %.

3. AUTOMATIC CONTROL.

One of the main aspects to be considered when designing an automatic control is the good comprehension of the plant to be studied. In our case, the analysis is centered in two main parts: the plant to be controlled formed by hydraulic servo-system and the interpretation of the mill load diagram.

The mathematical model which describes the pressures in both ends of the mill is represented as follows:

$$\begin{aligned}
M_1 &= -q_{hid1}C_1 + q^y_{ncp}C_2 + C_3 \\
V_1 &= -q_{hid1}C_4 + q^y_{ncp}C_5 + C_6 \\
M_2 &= -q_{hid2}C_7 - q^y_{ncb}C_8 + q^y_{ncc}C_9 + \\
&\quad + P_bC_{10} - P_aC_{11} + C_{12} \\
V_2 &= q_{hid2}C_{13} - q^y_{ncb}C_{14} - q^y_{ncc}C_{15} + \\
&\quad + P_b - P_a + C_{16}
\end{aligned} \tag{9}$$

Where:
M_1, M_2, V_1, V_2 -Bending moments and shear forces in the roller ends.

The highlighted terms are constants that depend on the load system, the mill geometry and the physical-chemical properties of the material. The other parameters are variables that relate the hydraulic pressures with the roller flotation and the electric current consumed by the mill.

Analyzing the model to determine the variables that take part in the control, then it is obtained:

$$\begin{aligned}
M_1 &= f(p_1, I_M) \\
V_1 &= f(p_1, I_M) \\
M_2 &= f\left(p_2, I_M, f^{inst}\right) \\
V_2 &= f\left(p_2, I_M, f^{inst}\right)
\end{aligned} \tag{10}$$

Where:

p_1, p_2 – Hydraulic pressures to be apply on the mill ends.

I_M – Consumed electric current by the electric engine that moves the mill.

f^{inst} – top shaft instant flotation due to bagasse layer fluctuation.

Once it is known that the main problem lies in achieving uniformity in the bagasse layer compression, the following condition is determined to calculate the pressures.

$$M_1 - M_2 + (V_1 + V_2)\frac{L_4}{2} = 0 \tag{11}$$

Finally the equation (12) is obtained considering C_a, C_b as constants.

$$C_a p_1 + C_b p_2 = f\left(I_M, f^{inst}\right) \tag{12}$$

From the mechanical point of view, the total hydraulic pressure can have a magnitude as high as desired, as long as the mechanical resistance condition is achieved for the mill components. Once this was determined by the tensional state, the equation to calculate the optimal pressures to be applied on the mill is obtained.

$$C_c p_1 + C_d p_2 = C_{ten} \tag{13}$$

The constant C_{ten} depends on the loads, geometry and mechanical properties of the material. C_c and C_d are constants.

Finally, the optimal pressures are determined by means of the equation system of (12) and (13). As it is observed in (10), the calculus of the optimal pressures to be applied on the mill is influenced directly by the electric current and the top roller flotation on the bagasse layer. That continuous measure of these variables will be considered in the control implementation.

Once the mathematical process is explained for the calculation of the optimal hydraulic pressures, the analysis should be focused in the modelling and control of the hydraulic servo-system. The dynamic of it will determine the requirements of the design. In this case it is more complex, due to the dynamic of the cylinder-valve assembly is highly non lineal and relatively hard to control. The servo-system model used in the control is:

$$Wp(s) = \frac{Kp}{s^3 + ap_1 s^2 + ap_2 s} \tag{14}$$

Where Kp, ap_1 y ap_2 are parameters that change according to the position of the cylinder. More details are offered in Perez, (2004).

On the other hand, knowing the input signal changes continuously, the control should be able of assuring a perfect tracking of the input signal without obtaining instability due to the mechanical conditions.

Taking into account these peculiarities, a Model Reference Adaptive Control (MRAC) considering the way proposed by Slotine and Li (1991) combined with a feedforward signal calculated from tracking control. Fig. 4 shows the adaptive control loop.

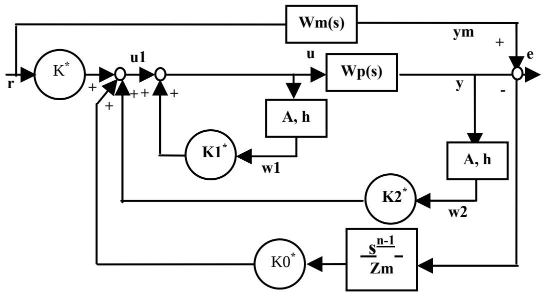

Fig. 4. Model referente adaptive control.

The objective of the design is to determine a control law, and an associated adaptation law, so that the plant output (y) asymptotically approaches (ym). The blocks for generating the signals $\mathbf{w_1}$ and $\mathbf{w_2}$ represents an (n-1)th order dynamics, which can be described by:

$$\overset{*}{\mathbf{w}}_1 = \mathbf{A}\mathbf{w}_1 + \mathbf{h}\mathbf{u} \qquad \overset{*}{\mathbf{w}}_2 = \mathbf{A}\mathbf{w}_2 + \mathbf{h}\mathbf{y}$$

Where $\mathbf{w_1}$and $\mathbf{w_2}$ are an (n-1)x1 state vectors, **A** is an (n -1)x(n -1) matrix and **h** is a constant vector such that (**A**, **h**) is controllable.

The poles of the matrix **A** are chosen to be the same as the roots of the polynomial Zm(s) (numerator of the reference model).

Assuming the plant parameters unknown, the control law can be described by:

$$u = \mathbf{K}^T(t) \cdot \mathbf{w}(t) \tag{15}$$

Where the controller parameters and the state vectors are:

$$\mathbf{K}(t) = [k(t) \quad k1(t) \quad k2(t) \quad k0(t)]^T \qquad \mathbf{w}(t) = [r \quad w1 \quad w2 \quad y]$$

The goal of this law is to become the close loop transfer function into the reference model. Because of the plant parameters are changing with the position of the cylinder, the controller parameters are adjusted by means of an adaptation law like the equation (16) such that the following error asymptotically converges to zero.

$$\dot{\mathbf{\Phi}}(t) = -\operatorname{sgn}(k) \cdot \delta \cdot e \cdot \mathbf{w}(t) \tag{16}$$

With δ being a positive constant that represents the adaptation gain.

we can now analyze the system's stability and convergence behaviour using Lyapunov theory. In order to achieve this purpose is calculated a feedforward signal using trajectory control because of the servo-system's models has relative degree greater than one.

Fig. 5 shows the control loop to carry out the automatic regulation of the mill. As it can be observed, every hydraulic system has its own control loop, in which the input signal is the optimal pressure to be applied in every instant calculated with the mathematical process unit. This unit relate the equations (12) and (13), and taking into account the interaction between each control loop.

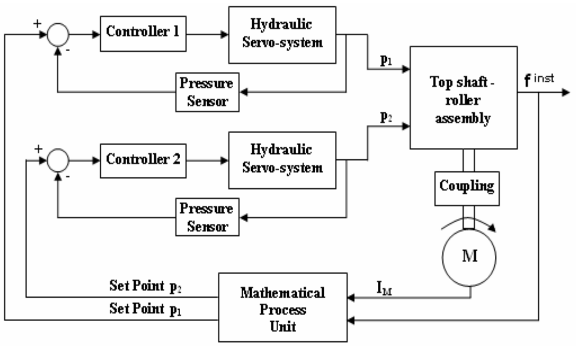

Fig. 5. Automatic control loop.

4. CONCLUSIONS.

- The use of an analysis plan permits to define, for a certain mill, the intensity relation of hydraulic forces on the top shaft bearings. Conclusions on the hydraulic load intensity relation to achieve a compression as uniform as possible of the layer all along the rollers, are also obtained.
- The use of a hydraulic pressure relation with which is achieved a compacting as uniform as possible, causes an increase in the sugar-mill extraction efficiency between 0.5 % and 1 % for an equal total hydraulic force.
- Considering the non lineal characteristics of the hydraulic servo-system and the mill mechanical conditions, the proposed control strategy achieves the needed requirements for optimal regulation of hydraulic pressures and in addition, the efficiency increase in the extraction of sugar cane juice.

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