Possibility to continuously control the tilt of excavators with an inclinometer

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Abstract: - The main problem, on which emphasis is laid, is how to maintain the stability of rotor excavators, the main machinery of a technological extracting system employed for coal mining, or any other extraction machinery, in balance. The balance survey, respectively that of the stability of these machineries is compulsory because the bearing surface is rather small compared to the other building sub-systems outside the range of the surface, onto which much higher forces operate. The lack of correct balance for the rotor excavators determines their operation in an inadequate dynamic mode, or in extreme cases, there is the danger of losing stability by tilting over the excavator respectively suffering huge material and human loss. Thus, these excavators have a mass of balance theoretically measured during the production process. It is compulsory for the correctness of the position and mass value of balance to be checked because there might be substantial error sources leading to compromise the operation. For the machineries and installations that have a small bearing surface compared to their height, an efficient control of balance can be done only if the angle of tilt of the superstructure is known, and if the angle does not exceed certain values. The limit values of the angle of tilt are determined by one condition, i.e. the composite force of both the interior and the exterior forces should pierce the plan, which is bounded by the props of the machinery. In order to continuously measure the angle of tilt of the superstructure, in any direction possible, recent studies highlight the possibility of using inclinometer to be able to control the balance and respectively the stability of rotor excavators. By measuring the angle of tilt for a structure considered rigid with the help of inclinometers, we are looking to evaluate the movement of the center of gravity toward the interior of the bearing surface, which may have consequences on the stability of the machinery. Thus a continuous control using computers over the tilt of the structure can be made considering the two perpendicular directions, so as the limit value of the angle of stability is not exceeded.

Key-Words: - Barycentre, Inclinometers, Data acquisitioning card, Artificial horizon, Excavator

1 Generalities

Generally working machineries inside quarries and mainly rotor excavators have a rather small bearing surface, and the building parts, which are influenced by great forces, stretch towards the exterior of the surface.

The balance problem of such bearing structures is of utmost importance, because the resultant of all the forces which act on the structure is not allowed to touch or to overpass the perimeter of the bearing surface, consequently leading to the instability of the structure.

The problem is much more difficult because the centre of mass of the rotor excavator is higher than the bearing structure as well as the point where all the exterior forces act on the excavator.

Figure 1 schematically represents the superior part of a rotor excavator. The limits of the bearing perimeter are represented by the numbers 1 and 2, are situated on a distance of 0,5×a from the axis of revolution of the superior part to the axis z of the reference system. The distance between the two bearing perimeters “a” is small compared to the rotor “b” and of the counterweight “c”.

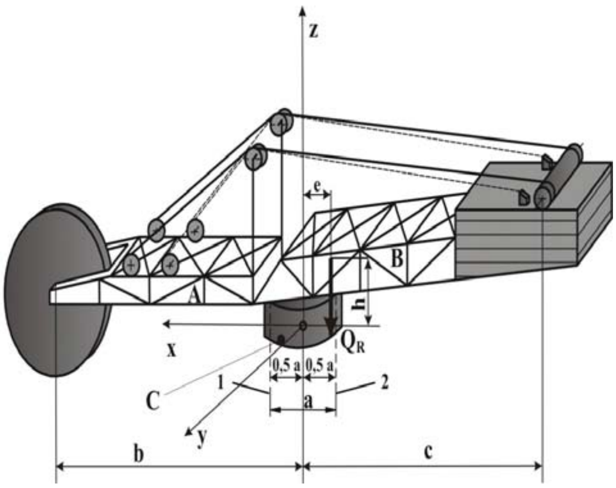

Fig.1 Specific elements of the balance and stability of the superior rotary platform of the rotor excavators

A – rotary arm;
B – counterweight arm;
C – rotary crown of the superior part;
1 and 2 – limits of the bearing perimeter of the superior part.

The centre of mass of the superior part’s weight Q_R is shifted by the extension “e” towards the arm, depending on “z”, at a height “h” from the perimeter of the bearing surface.

These two measures “e” and “h” are not constant and depend on the height where the rotor is lifted, thus “e” is minimum when the arm of the rotor is in horizontal position and once the arm is lifted it rises, and “h” is minimum when the arm is lowered and rises as the arm of the rotor is lifted.

In horizontal position of the working machine, respectively the rotor excavator, and the resultant pierces the bearing surface to a distance “e” and an axis z. When the machinery is tilted, the point where the resultant pierces the bearing surface is shifted, and according to the direct tilt, the distance to the axis may be greater or smaller than “e”.

2 Theoretical and Technical Considerations Regarding the Balance and Stability of Working Machinery

The vertical forces that act over the rotor on the axis (-z) shift the intercrossing point of all the forces toward the bearing perimeter 1, and the horizontal forces which act over the rotor on the axis (-x), only if this is situated under the plane of the bearing surface, producing the same effect.

The forces that act inside the rotor on the (+z) axis, respectively the forces inside the counterweight arm on the (-z) axis, shift the intercrossing point of all the forces toward the the bearing perimeter 2, and the horizontal forces which act inside the rotor on the (+x) axis, only if they act under the plane of the bearing surface and the forces on the (-x) axis producing the same effect if they act above the plane of the bearing surface.

An absolute operation of the excavator is possible only if the intercrossing point of the resultant of all the forces is situated inside the bearing surface delimited by 1 and 2.

Even in the most unfavourable situations of external forces manifestation, forces which might occur during operation, the intercrossing point of the resultant is not allowed to overpass the bearing perimeter, because otherwise not only the machinery might turn over, damaging the excavator, but also endangering the lives of human operators.

In order to tackle with the problem of stability, subsidiarily that of balance, the forces that act on the rotor excavator may be divided into two groups:

- All the forces which act continuously and constantly on a construction are part of the first group;
- All the forces which do not act continuously (i.e. all the exterior forces), and also the forces determined by the tilt of their own weight, are part of the second group.

The forces comprised in the first group are forces created by the weight of each component on the (-z) axis. For this kind of forces, the place of the centre of mass can be found out with the masses of the building parts in composition. Thus, some errors might turn up due to a high number of components which may not have an exact mass. It is recommended for the position of the centre of mass, given by the own mass, to be determined after having installed all the components by weigh in and only then to establish the necessary mass of the counterweight because it is interdependent to the position of the centre of mass. In order to be able to modify the mass of the counterweight from construction it is recommended to take into account for the design phase of a variation domain of ±10 % for the mass of balance determined theoretically. Due to the utmost importance of the size of the mass for the operation of the excavator, this has to be clearly specified in its technical documentation. Its size has to be clearly and visibly written on the exterior of the construction. The forces comprised in the first group are forces that give stability, due to their not modifying the size and position and continuously act on the (-z) axis. Due to these forces on the bearing surface the stability moments tend to appear.

The forces comprised in the second group are forces that tend to tilt over the machinery, developing around the bearing surface the moments, which may be theoretically calculated out of the individual forces. It is still in this group that the forces that appear due to the blocking of the rotor in the massif or due to the rotor's suspension on the slope.

Be it the case of suspension of the superior platform onto a ball bearing the perimeters are clearly being determined by the centre line of the rolling surface of the bearing. A clear improvement of safety can be obtained with the help of catch hooks (rams), between the superior rolling surface and the inferior rolling surface of the bearings.

Be it the case of special constructions for the rotary platforms, which can undertake traction forces, the edges of the bearing surface are situated outside the centre line of the rolling surface of bearings and is oriented in such a way that it is able to undertake moments trough the rotary platform.

If it is necessary to ensure similar conditions to the ball bearing normal rotary platforms it can be made only with the help of a construction with catch hooks that is able to undertake and transmit high traction forces between the superior and the inferior rotary part.

Such constructions with catch hooks operate only after the platform has already tilted, that is why its operation in combination of charges where no rotary movement will take place has to be limited.

On the machineries where the superior part of the rotary structure is fixed on a revolving base plate by spherical articulations, which permits the tilt, it is necessary to obtain a certificate of stability for the plane of the articulations.

Due to the fact that the articulations of tilt in most of the cases are closer to the rotary axis than the exterior perimeter of the bearing trajectory the certificate of stability is no longer necessary for the plane of the rotary binding.

For the plane of the fulcra of the inferior construction on the crawler belt system, depending on the rolling system, different forms of supporting perimeters may exist. In figures 2, 3 and 4 different forms of support types can be seen.

The inferior construction offers a constant value in order to determine the moment M_S, while for the superior part the different rolling positions need to be analysed.

Also for the moments M_r the most unfavourable position of the rolling part confronted to the bearing perimeter of the inferior part.

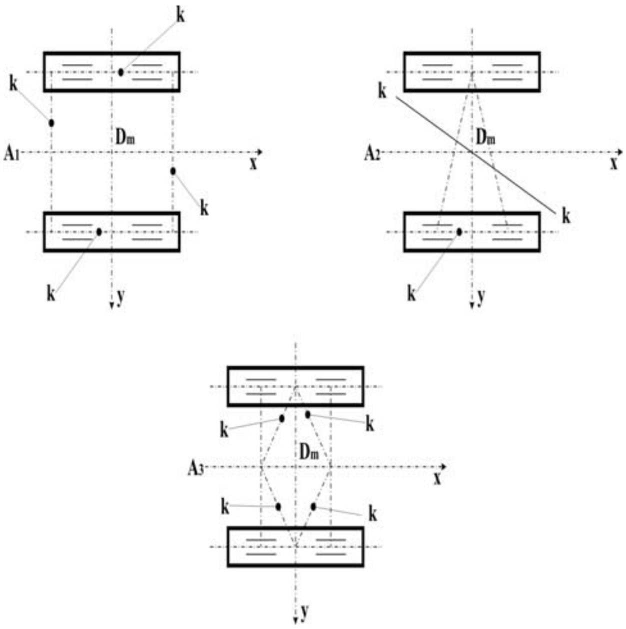

Fig.2 Support types for the rolling system with 2 crawler belts.

k – supporting perimeter;
A_1 – rolling system with 2 rigid crawler belts; guidance tilt roller;
A_2 – rolling system with 2 crawler belts; a immobile crawler belt and a revolving one;
A_3 – rolling system with 2 revolving crawler belts; balanced guidance rollers (compensating)

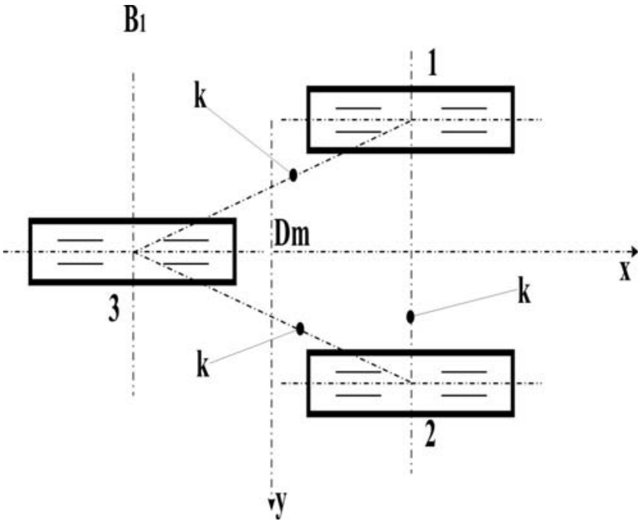

Fig.3 Support types for rolling systems with 3 crawler belts.

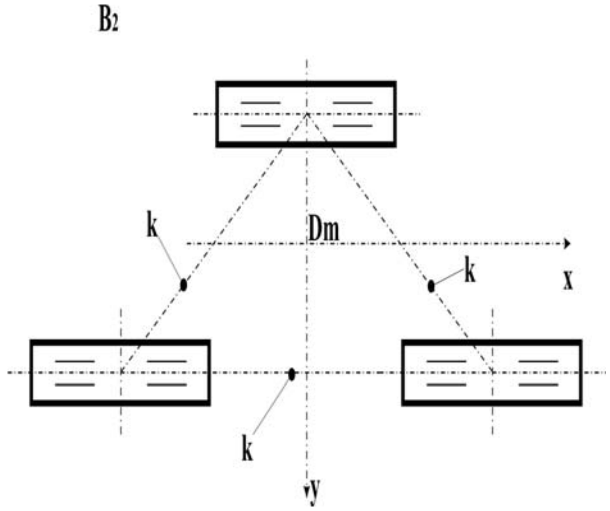

Fig.4 Support types for rolling systems with 3 crawler belts.

B_1 – rolling system with 3 controlled crawler belts; compensated guidance rollers;
B_2 – rolling system with 3 crawler belts, 2 controlled crawler belts; compensated guidance rollers.

The inclination forces have an acute tilt effect because the bearing plan is situated lower, under the barycentre of the masses, respectively that of the rolling platform.

Mainly the weights of the building ensemble of the crawler belts does not have to be used for determining the safety to tilt in the supporting points of the inferior part because in most of the cases the building of the supporting points of the inferior part cannot undertake high traction forces. Only one stabilizing force of the supporting point of the inferior part can be taken into consideration, and which can be transferred through extension from the building of the supporting point to the building of the crawler belts.

Because the position of the barycentre may be influenced by the masses situated on the arm of the rotor and on the counterweight arm it has to be taken into consideration that the heavy objects which are not part of the construction of the excavator but which are necessary for repair works not to be left there when the excavator is in operation and to be discarded after these works have been done. If there is the need for some of these elements to be installed afterwards either on the arm of the rotor or on the counterweight arm then the weight of these elements needs to be balanced through a corresponding correction. This kind of corrections for the counterweight, need to be mentioned into the technical documentation of the machinery.

Be it the case of repair works where large masses are discarded, e.g. dismantling the operation of the rotor, stability measures need to taken (e.g. discarding a counterweight part, or butting it).

For the deposit or interchanging machineries, stability researches need to be done similar as for the rotor excavators. Both for the excavators as well as for the interchanging machinery, both the horizontal impulse as well as the supplementary vertical charge, need to be taken into consideration when calculating the stability.

The scope of measuring the angle of tilt of a structure considered rigid is to evaluate the movement of the barycentre towards the interior of the bearing surface, which may have consequences on the stability of the machinery (Figure 5).

Thus, taking into consideration the facts presented above, if the value of the angles of tilt with the vertical inside both a longitudinal (x) and a transversal (y) plane are known, then the determination of the movement of the barycentre of the structure towards the interior of the bearing surface is possible, ordered by the bearing system. Figure 6 represents a simplified angle of tilt with one of the considered axis.

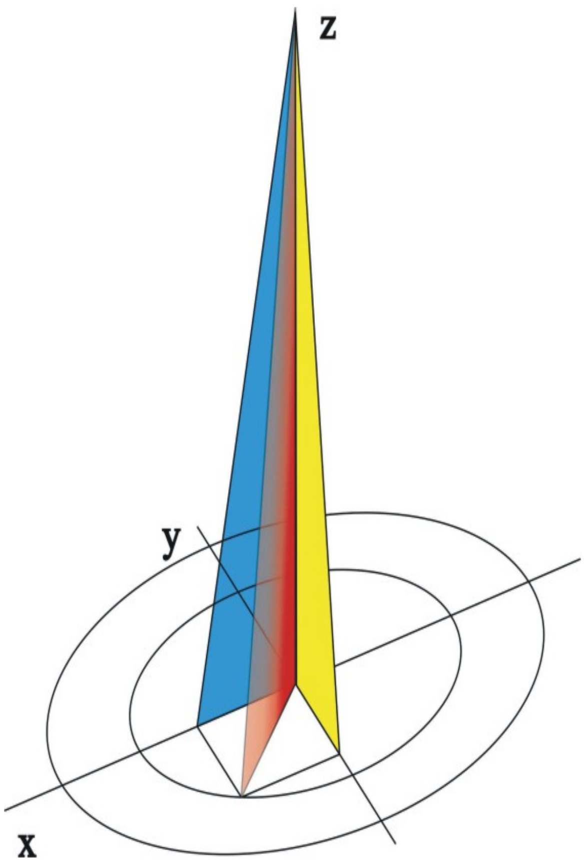

Fig.5 Top view of the angle of tilt
Red – Structure's angle of tilt, blue, yellow – axes projection of the angle of tilt

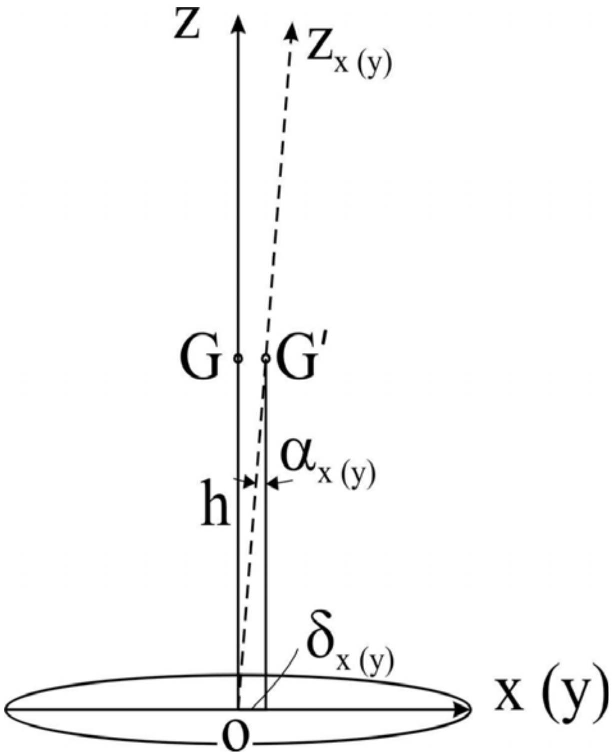

Fig.6 Projection movement of the barycentre

Where:
x – longitudinal axis;
y – transversal axis;
z – vertical axis;
G – barycentre;
G' – displaced barycentre;
G" – barycentre projection on the bearing surface;
h – barycentre height over the bearing surface;
α_x – angle of tit in longitudinal plane;
α_y – angle of tilt in transversal plane;
δ_x – barycentre project displacement in longitudinal plane;
δ_y – barycentre project displacement in transversal plane.

$$\delta_x = h \cdot \sin\alpha_x \tag{1}$$

$$\delta_y = h \cdot \sin\alpha_y \tag{2}$$

Taking into consideration the two displacements, δ_x and δ_y, we are able to calculate the barycentre's projection inside the bearing surface, as shown in figure 7.

Thus, the coordinates for the projection of the barycentre inside the bearing surface are the following.

$$R = h\sqrt{(\sin\alpha_x)^2 + (\sin\alpha_y)^2} \tag{3}$$

$$\varphi = \text{arctg}\frac{\sin\alpha_y}{\sin\alpha_x} \tag{4}$$

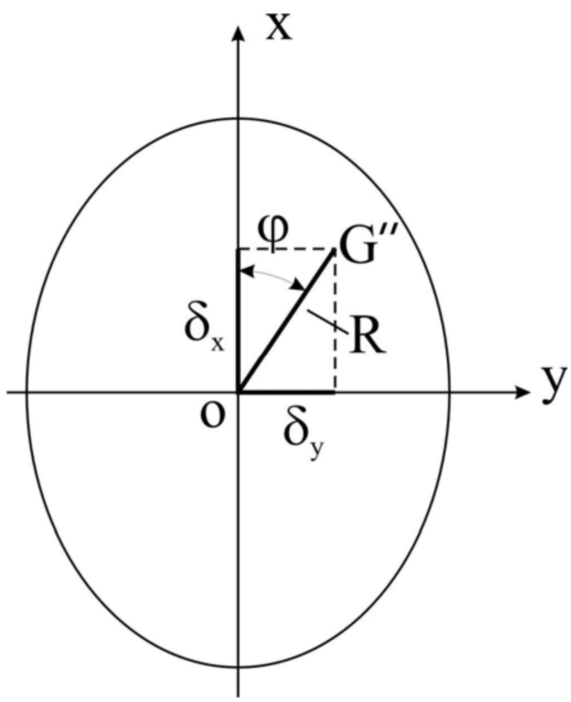

Fig.7 Barycentre's projection inside the bearing surface

3 continuously control the balance of rotor excavators with an inclinometer

Inclinometer devices are being used in order to measure the angle of tilt with the vertical of the surface; depending on the solution we are trying to find and the precision of the measurement, the sensors of the device will be set in the following technologies: accelerometer, electrolytic, quicksilver, gas bubble, and pendulum. In order to measure the angles of tilt inside the planes X-Y, 2, type 4 Rieker inclinometers will be used.

3.1 H4 Inclinometer

These devices (figure 8) are single axis inclination type inclinometers, metallically manufactured, with a IP66 protection degree, and a range of +/- 30^o.

Depending on the chosen measurement device, the output may be either analogue (0 – 5V) or digital (transmitted through a serial port). One specification should be made when using an analogue type, i.e.

the module NV8 for signal filtering and conditioning is necessary. A computer has to be also preset in measuring design, computer which will have connected to its COM1 and COM2 serial ports the 2 inclinometers. The installation of the 2 devices will be made with the help of a metallic cube, in order for the axes of the devices to parallel with the longitudinal axis of the machinery, respectively with its transversal axis. Such an installing device can be seen in figure 9, used to hold 3 sensors (3 axes).

Fig.8 H4 Series Inclinometer

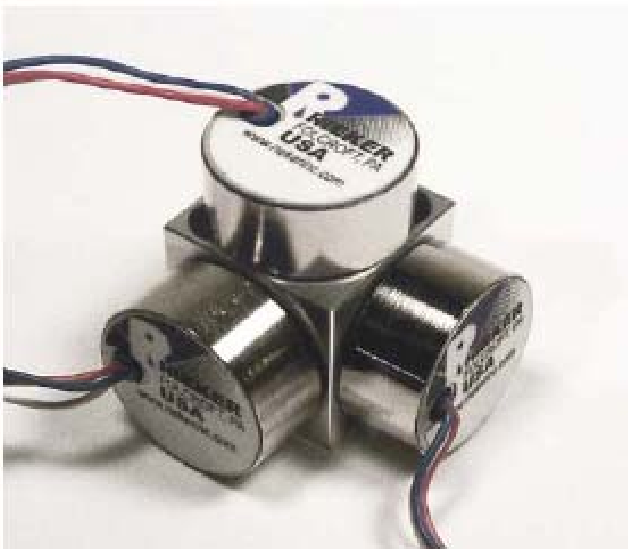

Fig.9 Device for 3 sensors

The technical characteristics of such a transmitter are presented in the table 1.

Table 1

Input Parameters	
Measuring Range	+/- 30^o
Measuring Axes	1
Power Supply	8-30V DC
Output Parameters	
Non Linearity	< 0.5% of the Measuring Range
Null Repeatability	0.05^o
Transverse Sensitivity	< 1^o at a 30^o tilt
Sensitivity	< 300mS
Optional Temperature Compensation Drift	< +/- 1.0^o over full operating temperature
Operating Temperature	-40^{o}C ... +85^{o}C
Analog Output (0... 5V)	
Zero offset	2.5V
Analog Voltage Output	0 ... 5V DC
Voltage Sensitivity	66.7mV/^{o}
Temperature Compensation	< +/- 0.5^o
Resolution	< 0.02^o
Current Consumption	10mA
Digital Output	
Temperature Compensation	< +/- 0.5^o
Resolution	< 0.02^o
Current Consumption	10mA typical
Output Format	ASCII decimal
BAUD rate	9600
DATA bits	8
PARITY	none
STOP BITS	1

3.2 NG360 Inclinometer

These inclinometer is a liquid capacitive based inclinometer used for measuring the tilt angle of any object with respect to gravity within a 0 to 360° (Figure 10). The basic sensor consists of four separate sensing elements whose outputs are combined to provide a highly accurate linear output over a complete 360° tilt range. An inclusive EEPROM stores the calibration data and dynamic control functions. The embedded software virtually eliminates total errors by compensating temperature drifts and sets the sensor dynamics for specific customer applications. It provides a very accurate 360° angle output with a RS485 interface. When used along with the SC485B (RS232/RS485) converter the user has the possibility of connecting up to 78 units on the same communication line.

Fig.10 NG360 Inclinometer

3.3 Digital Inclinometer, RDI Series LCD display

The RDI provides both single or dual axis inclination sensing in a rugged environmentally protected housing (Figure 11). The sensing package incorporates a modular design allowing the user to select the measurement range and temperature compensation that best suits the individual application. Input ranges of ±10°, ±30° and ±70° are standard for both single and dual axis models, however, special single axis ranges up to ±130° can easily be accommodated. Non-symmetrical ranges such as -10° to +50° are available for applications that only tilt in one direction. Multiple output configurations have been incorporated in the RDI. The box can be supplied with any combination of digital LCD display, analog 0.25 to 4.25V output, RS232 output, and up to four (4) open collector outputs providing the maximum functionality. These switch outputs operate like an "on/off" function allowing for activating external buzzers or lamps or turning equipment on or off. Also available with fully adjustable trip angle settings along the full range of the sensor.

Fig.11 Digital Inclinometer, RDI Series

The LCD display can be configured to display degrees, percent grade, or inch per foot rise with either 0.1° or 0.01° resolution. The display model comes standard with green, yellow, and red LEDs. These are set at predefined angles within the requested measurement range - providing the operator a bright visual signal. The digital display model also provides relative zero and min/max functions. The relative zero allows the operator to temporarily zero the digital readout to obtain relative slope changes. The operator will always know when the device is in the REL mode by the (*) symbol that is displayed after the angle. The min/max function provides the smallest and largest angle the device has sensed since the last reset. The analog output is available as either temperature compensated or non-temperature compensated depending on the required accuracy for the specific application. A 12 bit digital to analog converter is used to perform the conversion. The RS232 output is presented in decimal format in degrees, percent grade, or inchper foot rise. The output is formatted one reading per line for single axis units and two readings per line for dual axis units. The first reading for a dual axis unit represents channel 1 (normally side to side) and the second reading represents channel with both channels reading the same direction for redundancy in safety applications.

4 Experimental research

As shown in the paragraphs above, if the value of the angles of tilt with the vertical inside both a longitudinal (x) and a transversal (y) plane are known, then the determination of the movement of the barycentre of the structure towards the interior of the bearing surface is possible. This means the installation of two inclinometers, which will measure the corresponding tilt of the two axes.

Thus, one of the inclinometers will measure the tilt along the longitudinal axis of the excavator, and the other one will measure the tilt along the transversal axis or as put in other words front / back and tilt left / right.

For realizing a soft application the Analogical Output H4 Type Inclinometer has been taken as model. The power supplied, by this type of inclinometer was accepted by a numerical calculator through a data acquisitioning card (Figure 10).

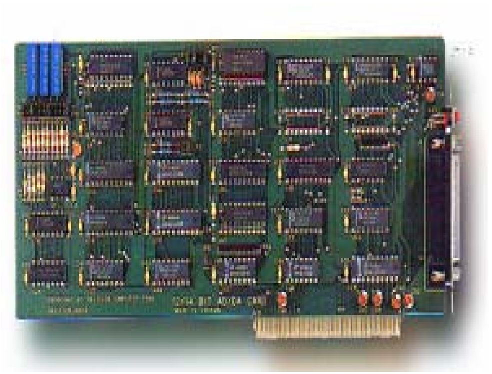

Fig.10 A/D – D/A 12 bits Card

This type of card allows 2 digital-analogical outputs (unipolar and bipolar) and 16 analog-digital simple inputs or 8 analog-digital differential inputs, all of these having a 12 bits resolution. The Technical data of this card are the following:

D/A

– resolution	12 bits;
– number of channels	2;
– power output:	
- unipolar output	0 at 2,5 V, 0 at 5 V, 0 at10 V;
- bipolar output	-2,5 at 2,5 V, -5 at 5 V, -10 at 10 V;
– conversion time	< 2 μs ;
– output impedance	> 2 kΩ ;

A/D:

– resolution	12 bits;
– power input	
- unipolar input	0 at 2,5 V, 0 at 5 V, 0 at 10 V;
- bipolar input	-2,5 at 2,5 , -5 at 5 V, -10 at 10 V;
– conversion time	< 22 μs (for each channel);
– maximum power allowed	12 V.

The reading, interpreting and display of monitored values program was realized in C language on a DOS platform. Monitoring the angles of tilt (front/back and left/right) was materialized with the help of an artificial horizon. The Figures 11, 12, and ??? represent two print screens representing different situations referring to the tilt of an excavator.

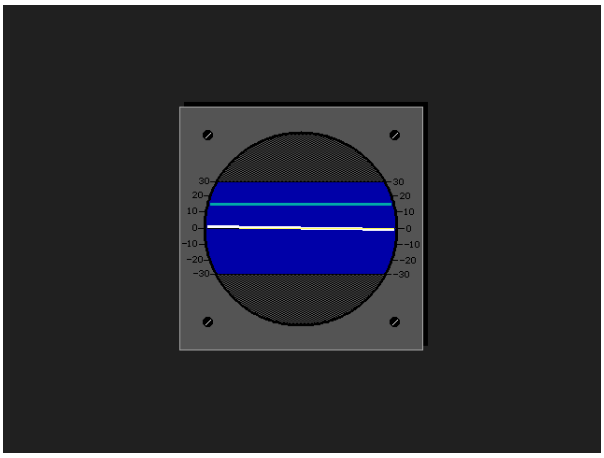

Fig.11 Front tilt – Left/right null

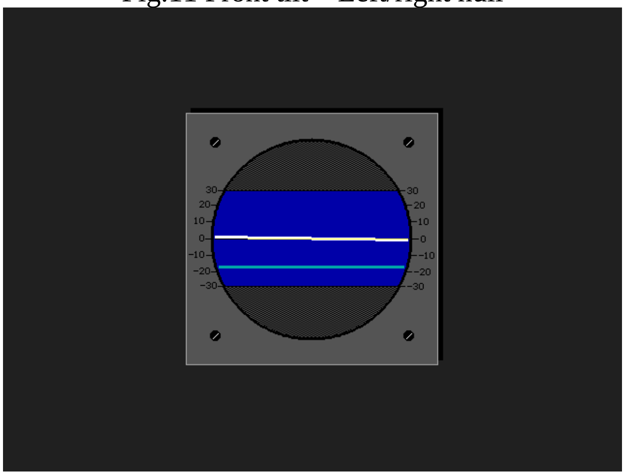

Fig.12 Back tilt – Left/right null

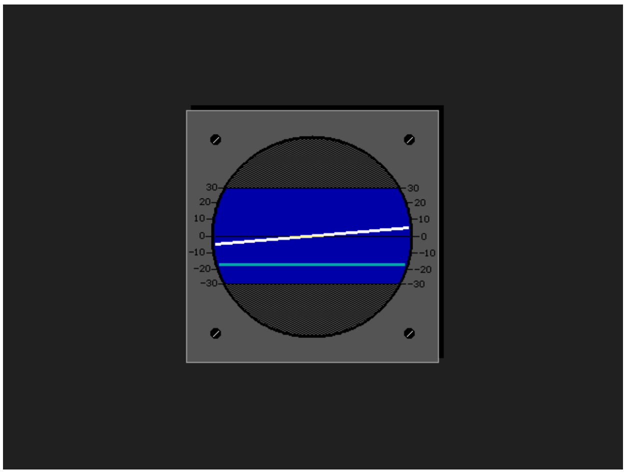

Fig.13 Back tilt – Left tilt

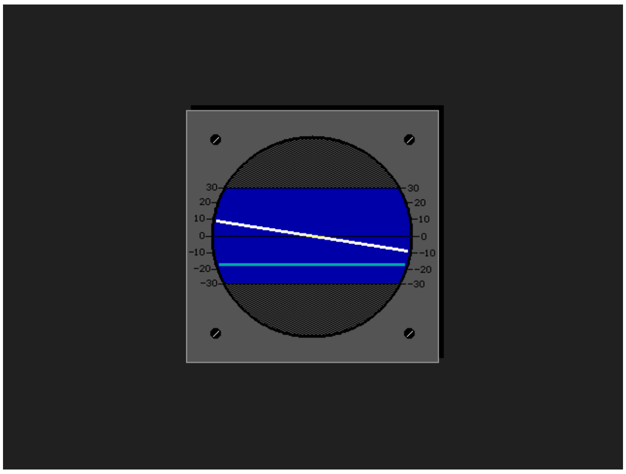

Fig.14 Back tilt – Right tilt

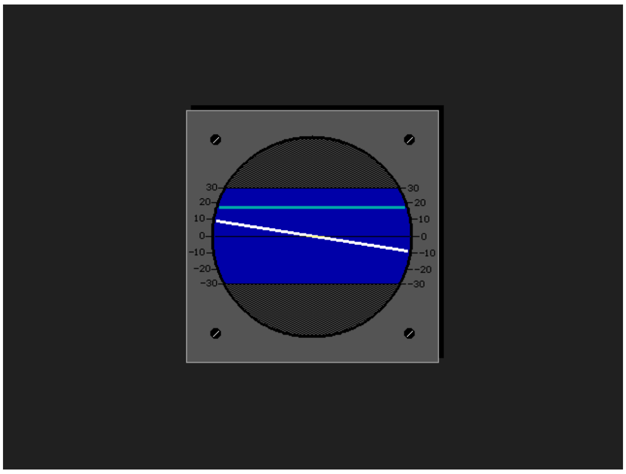

Fig.15 Front tilt – Right tilt

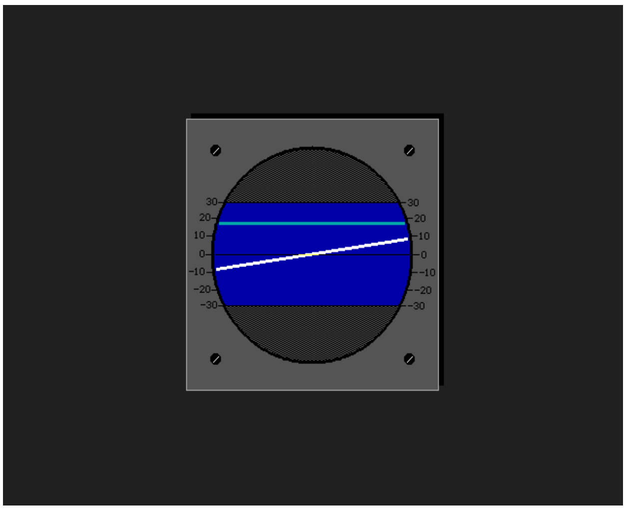

Fig.15 Front tilt – Left tilt

5 Conclusions

Emphasis is laid on the problem of balance and stability not only of the rotor excavators, which represent the main machinery in a coal mining technological system, but also of other machineries employed in excavations.

The balance survey, respectively that of the stability of these machineries is compulsory because the bearing surface is rather small compared to the other building sub-systems outside the range of the surface, onto which much higher forces operate. The lack of correct balance for the rotor excavators determines their operation in an inadequate dynamic mode, or in extreme cases, there is the danger of losing stability by tilting over the excavator respectively suffering huge material and human loss.

Thus, these excavators have a mass of balance theoretically measured during the production process. It is compulsory for the correctness of the position and mass value of balance to be checked because there might be substantial error sources leading to compromise the operation. In order to solve this problem there are several methods, one of them based on the weighing the entire equipment installed on the superior part of the excavator.

It is obviously necessary to lift the entire platform with the help of linear motor hydraulic force elements (hydraulic cylinders) and to determine the value of the developed forces on the points where these devices are installed. Taking into consideration the forces developed and the points of installation of the force elements by a calculus method the place and the weight value of the excavator may be determined (as a vector). In present there is the tendency to use either a simpler hydraulic system manually operated construction lifting device, or more complex centralized command lifting devices fitted with measurement devices, i.e. force transmitters, emplacement transmitters, the centralization and rehash of the information being made with the help of computers based on special software.

Another way of solving the problem is that based on strain measurements. The strain measurement unit ensures the possibility of measuring the energy in any point on the metallic construction of the excavator when this is imposed by the adequate application of tensiometric stamps and their connection, with the help of an electronic computer interface, to signal amplifiers ant to tensiometric power. If the continuous quality control system of stability based on the application of tensiometric stamps on the inferior side of the mobile platform is implemented, there is the need to use a tensiometric bridge of at least 12 channels (i.e. 12 active channels + 4 set apart), which will permanently belong to the excavator next to the cable raceways, signal amplifiers, data acquisition board and the computer inside the cabin of the operator.

Analyzing the paragraphs above we have reached the conclusion that the stability (equilibrium) may be monitored correctly with the help of inclinometers which will measure the angles of tilt front / back respectively left / right. As a solution to the experiment we have chosen the analogical output H4 Type Inclinometer.

The soft application allows the measurement of tilt through an artificial horizon. Both the front / back tilt and the left / right tilt can be measured simultaneously. The display of the tilt being intuitive for the operator of the excavator, thus allowing him to take immediate and efficient action in order to avoid a dangerous tilt which might lead to a malfunction or in some extreme cases to a possible overturn f the excavator.

This method is convenient due to its degree of simplicity, control possibility and cost in regard to the other methods mentioned before (i.e. weighing and tensiometric measurements).

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