IN SITU MODAL TESTING METHODS FOR HUGE STRUCTURES. APPLICATION TO SURFACE MINING MACHINES

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Abstract: The paper deals with a simple and practical method for the equilibrium stability determination for the huge mining machinery structure by a defining stability index, using the reaction forces in the machinery bearings measured by strain gauge montages applied on the supported beams of the bearings. The methods was tested with good result on numerous machineries including bucket wheel excavators, store yielding machine with bucket wheel and large spreaders used in open pit mines.

Key words: strain gauges**,** open pit mining**,** signal processing

1. APPLICATION

For strain gauge measuring systems, it was developed, in cooperation between Vibration Testing and Research Laboratory of University “Politehnica” Timişoara and Detronic Electronics Timişoara, a wireless data acquisition system for multiple strain gauges which offer the possibility to collect and measure simultaneously the strain gauges signals placed on an area up to 10 sq. km. Each mobile equipment contain an analog to digital converter of 24 bits and a radio transmitter (radio frequency: 2.4 GHz) to a PC control receiver placed in aria of 1.5 km line of sight open field.

In figure 1a are presented the time history of the signals $u_A(t)$ and $u_B(t)$ from the two pseudosensors in bearings A and B the excavator arm sweeping in rotation from position $\phi = 0^0$ to $\phi = 180^0$ during 450 sec. Even for a very low speed of excavator arm rotation the two signals are not smooth, each containing two components. one an quasi static ($u_As(t)$ and $u_Bs(t)$) and the second ($u_Av(t)$ and $u_Bv(t)$) time variable by excavator structure modal components laws. The two components can be separated, the quasi static $u_As(t)$ and $u_Bs(t)$ are obtained by an average discrete form

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$$u_w s(i) = \frac{1}{n_m} \sum_{k=\frac{n_m}{2}-i}^{\frac{n_m}{2}} u_w(k) \quad (w = A, B) \tag{1}$$

where $u_w(k)$ being the signal sampling at time k.Δt of sampling time increment Δt. n_m being the number of sampling in averaging processing around the sampling i. The modal components are obtained by substation operation

$$u_w v(i) = u_w(i) - u_w s(i) \quad (w = A, B) \tag{2}$$

and the time history of the separated signals look as in figure 1.b.

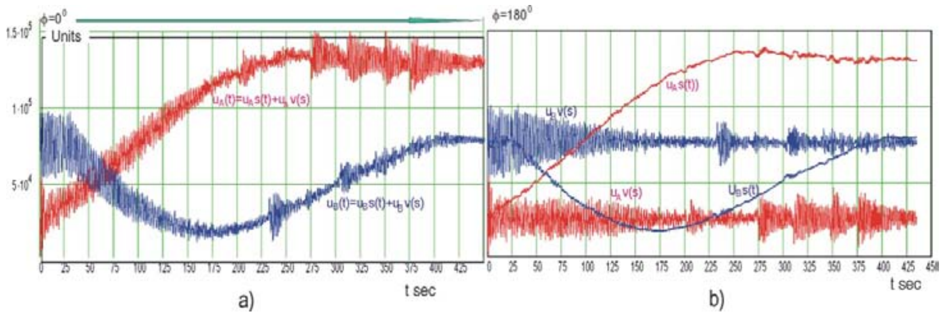

Fig. 1. Time history of recorded reaction signals $u_A(t)$ and $u_B(t)$

Correlating the component signals $u_A s$(t) $u_B s$(t) with the different angle positions $\phi(t)$ of the excavator's arm and using the equation (5) as fitting equation, solved in a least square manner, it is determined the best fitted values for u_{wo} u_{wx} and u_{wy} (w=A,B) and harmonics laws of reaction forces

$$Rh_w(\phi) == \frac{1}{k_w}\left(u_{wx}\cos(\phi) + u_{wy}\sin(\phi)\right) \quad (w = A, B) \tag{3}$$

which drawn in the figure 2 marks very god fitting, the deviations between those and the experimental values drown by stem with boxes being neglected.

Also, it can be observed the phase between the two harmonics keeping the same geometrical phase between point *A* and *B* of 120^0. The values of the amplitudes

$$Ro_w = \frac{1}{k_w}\sqrt{u_{wx}^2 + u_{wy}^2} \quad (w = A, B) \tag{4}$$

of bearings harmonically variations are near the same, Ro_A = 437 kN and Ro_B = 443 kN corresponding to a percent deviation of 1.4%, which for an in situ field test is an very good result. For pseudosensors calibration is used a load F_e applied on the arms placed along the given bearing at the distance Lb to bearing by a manual pulley tackle Pl, (Fig. 2), the load being using a special wireless strain gauge sensor S_F.

Also, the radius r_G of mass centre trajectory can be determine using form (6), resulting for this case r_G = 511.6 mm from signal recorded of the pseudosensor from bearing A and r_G = 518.8 mm by signal recorded of the pseudosensor from bearing B.

The static stability of excavator structure depend of values the three charge loads in the bearings A, B and C. If one, as bearing A, tend to be unloaded R_A—>o the line BC become a overturning axis, the stability index defined as

$$i_d s = \min\left(\frac{R_A}{\frac{m_r g}{3}}\right) == \min\left(1 + 3.\frac{r_G}{a}\cos(\phi + \beta)\right) = 1 - 3.\frac{r_G}{a} \qquad (5)$$

for the case studied resulting the static stability index $i_d s$ = 0.862.

In Figure 7a are presented two characteristic positions of the excavator arm; (P1) the mass centre G being on the line AA_o at arm position $\phi=27^0$ where angular deviation of mass centre G position is $\beta=157^0$, on the balancing arm (6). The same results are obtaining taking in account the position P_2 the arm where the mass centre is on the line BB_o. and the signal of reaction R_B being processed.

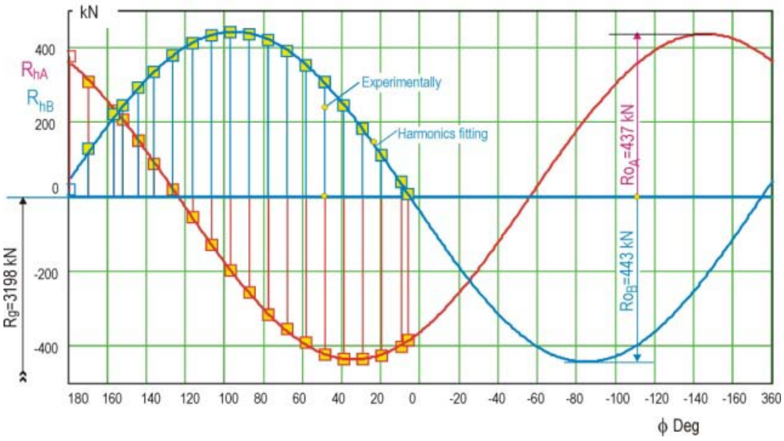

Fig. 2. Harmonic variations of the reactions forces $Rh_A(\phi)$ and $Rh_B(\phi)$

2. DYNAMIC STABILITY DETERMINATION

The mining machineries are very low damped structures so that the light perturbation can induce significant dynamics effect and large vibration levels. Even for a simple rotation of the arm, as in figure 1, occurs notable vibration level. The perturbation can become very strong in the working time, (fig.1a), figure 5 presented the time history of the reaction forces R_A and R_B.

In this case the analytical forms of for the three reactions (1) become

$$R_A = \frac{1}{3} m_r g + m_r g . \frac{r_G}{a} \cos\left(\phi + \beta\right) + R_{mA}(t)$$
$$R_B = \frac{1}{3} m_r g + m_r g . \frac{r_G}{a} \cos(\phi + \beta + 120^0) + R_{mA}(t) \qquad (6)$$

$R_{mA}(t)$ and $R_{mB}(t)$ being modal components excited by excavation processed.

By zooming between time t=220 to 320 sec, (Figure 6), and from Fourier spectrum it can be observed that only a modal component occurs, of the modal frequency f=0.392 Hz obtained by applying a circle fitting algorithm [1]. As a result the modal components can be approximate

$$R_{mA}(t) = Ro_A(t)\cos(2\pi f t)$$
$$R_{mB}(t) = Ro_B(t)\cos(2\pi f t + \pi) \qquad (7)$$

the two components being in opposite phase between, normally, because in the recorder time the excavator works in arm range position P_3 (Figure 7) ϕ=30^0 to 60^0 the reaction F_C of excavation force loaded bearing A and discharge the bearing B.
$Ro_A(t)$ and $Ro_B(t)$ are the magnitudes of the modal components which are determined by the signals envelope on the lover side of time histories.. Also, an dynamic stability index is defined for bearing A

$$i_d d_A = \min\left(\frac{R_w}{\frac{m_r g}{3}} \right) == \left(1 + 3.\frac{r_G}{a}\cos(\phi + \beta) + 3.\frac{\min(Ro_A(t)\cos(2\pi f))}{m_r g} \right) \qquad (8)$$

resulting the value $i_d d_A$ =0.636 and in the same mode the dynamic stability index for bearing ini$_d$d$_B$=0.507. This the last value can be more lover if is taken in consideration the constant component of the excavation force F_c

3. CONCLUSIONS AND FUTURE STUDY TO BE DEVELOPED

The above study gives a simple and practical method for the equilibrium stability determination for the huge mining machinery structure by a defining stability index, using the reaction forces in the machinery bearings measured by strain gauge montages applied on the supported beams of the bearings. The methods was tested with good result on numerous machineries including bucket wheel excavators, store yielding machine with bucket wheel and large spreaders [3].

The signals recorded in the testing time, for different operations contain only a few modal components especially the first mode being the main excited. The natural frequency of the first mode being very low, in range of 0.4 to 0.6 Hz, for all machinery

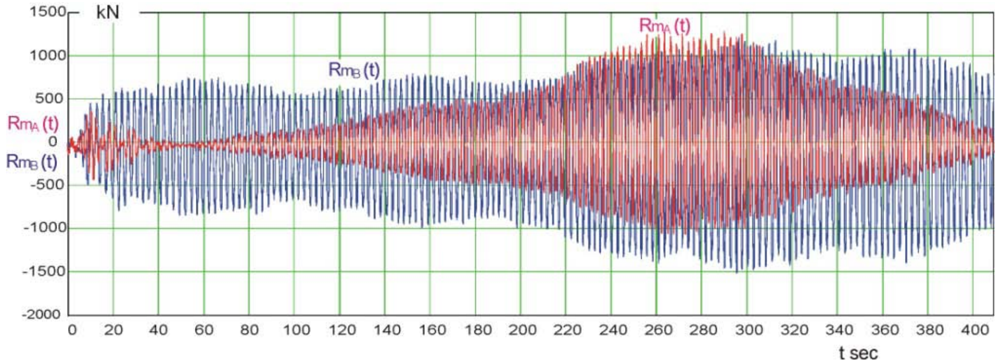

Fig. 5. Modal components $R_{mA}(t)$ and $R_{mB}(t)$ time history

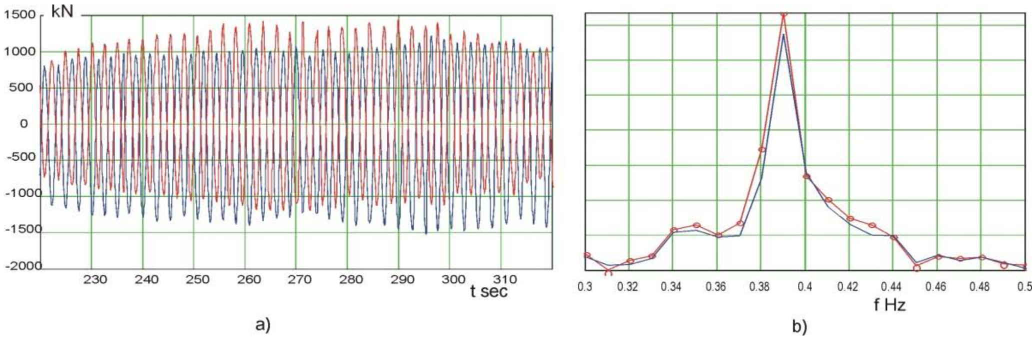

Fig. 6. a) Zooming of time history from Figure 5 and b) Fourier spectrum of the modal components $R_{mA}(t)$ and $R_{mB}(t)$

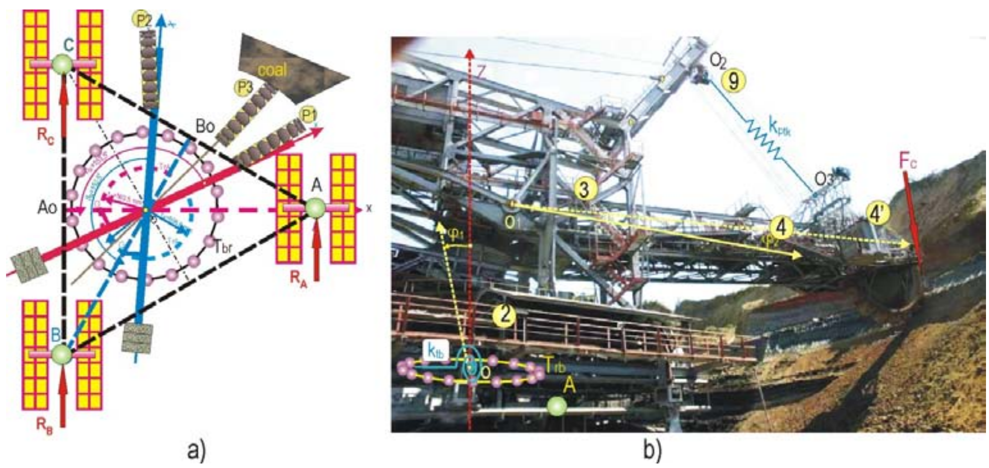

Fig. 7. a) Three characteristic angular positions of the excavator arm; P_1,P_2 and P_3
b) Illustration of the excavator main motion lows. $\varphi_1(t)$ elastic rocking in the trust ball bearing of stiffness constant $k_{tb;}$ $\varphi_2(t)$ relative pitch motion due to elastic deformation of the pulley tackle wires of stiffness constant k_{plk}

structures tested, so there are same problems to measure the structure vibration using seismic accelerometers with DC components (as strain gauge or capacitive accelerometer): in this frequency range it is very hard to separate the components due to translation from the components due to rotation.

To overcome this difficult problem it is applied a digital image processing. On the structure is fixed a panel P_{nl} (Fig. 8) with a drawing grid of gap d, and with Sony DCR TRV120E Digital Camcorder, Cam, placed at about 30 m distance to the panel Plt, were focalized to point P_1 and P_2 and recorded images with 25 frame/ sec

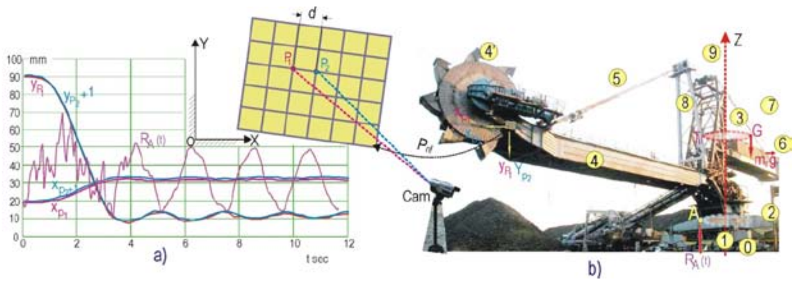

Fig. 8. Illustration of vibration measurement using digital image processing.
a) Displacement time histories; b) shortly setup.

Using a special algorithm developed in VTRL for this application in Figure 8a is presented the motion time histories of the two points P_1 and P_2; $y_{P1}(t)$ and $y_{P2}(t)$ vertical motions and $x_{P1}(t)$ and $x_{P2}(t)$ horizontal motions. It can be notices that motion lows of two points are the same and in view to be separated they were distanced with 1 mm. The record sequence presents a machine arm down motion of 80 mm with a final break, follow by free decay vibration motions inertial excited by the first mode of 0.51 Hz frequency, the first mode being pregnant presented in the signal of reaction force R_A, synchronized with the image record. The method can be improved using more one camcorder, which for this application, can be a customary one which is not expensive. In this mode can be represent the real motion of the machinery structure both components: cinematic motion according to machinery mechanism and the elastic deformation occurring from different excitations as the inertial which can be determined from cinematic motions. Also, the deformation shape of the machinery structure will be used to obtain a hybrid simplified dynamic model using experimental and design data, model necessary to be simulated different dangerous excitations.

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