DETERMINING DEFORMATIONS OF A ROTARY KILN

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ABSTRACT

Deformations of a rotary kiln of a cement plant were determined by a special photogrammetric method. The uninterrupted rotations of the kiln, it stops only once in several years for maintenance purposes, causes continuous changes in the deformations of the foundations and the shell of the kiln and prevents determining coordinates of points on the kiln in a ground system by common methods of analytical photogrammetry. For that reason, the coordinate determination was disposed of and a procedure was devised for computing parameters of functions describing circles and ellipses in space. The deformations of the kiln were then determined by analyzing the shapes of those curves. The accuracy of the deformations so obtained was within a range of 2-4 milimeters. The method is advantageous in two additional respects: it enables to determine deformations under regular operational conditions without necessitating to stop and cool the kiln, and it provides a means to discriminate between permanent deformations of the shell and elastic deformations due to the kiln's weight.

INTRODUCTION

Cement is being produced in a nearly horizontal rotary kiln made of steel. The kiln in question is of a cylindrical shape, about 120 meters long and 3.80 meters in diameter. It is supported every 30 meters by five wheels - "tires" which are concentric with the cylinder. A segment of the kiln between two tires is depicted in figure 1. Each of the five tires rests on two smaller wheels, about 1.0 meter in diameter, which function as roller bearing on which the kiln rotates. (see figure 2). Each bearing can be shifted to the left or to the right with respect to the axis of symmetry of the cylinder, thus permitting to adjust the spacial positions of the tires in order to align the centers of the tires on one straight line collinear with the kiln's axis of symmetry.

As said above the cement production is a continuous process which is interrupted only for carrying out the necessary maintenance works. During the time elapsed between two consecutive stops of the kiln's operation (about five years), the foundations of the bearings may become displaced, both horizontally and vertically. Hence changes in the positions of the centers of the tires may occur which in turn deform the cylinder's axis of symmetry. Such a deformation causes small stresses in the steel of the shell. The kiln rotates with an angular velocity of one rotation in 50 seconds. Hence, the stresses due to the deformations of the axis vary cyclically, which may cause fatigue ruptures.

Besides the mentioned above, two other types of deformations, deviations from an ideal cylindrical shape, have to be considered:

a. Permanent deformations.
These are small irregularities in the shape of the pipe (cylinder). They are independent of the rotational movement and do not cause any varying stresses in the shell. However they affect unfavorably the determination of the cyclical deformations.

b. Elastic or cyclical deformations.
These are the deformations of the pipe's cross sections and its axis of symmetry due to the weight of the pipe and the material in it.

Fig. 1. A section of the rotary kiln.

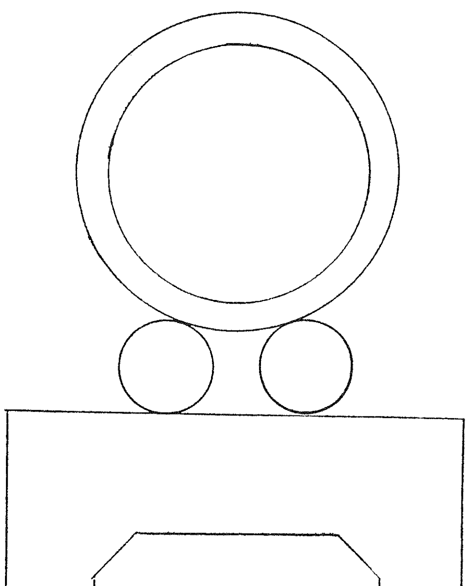

Fig. 2. A cross section of a tire and a roller bearing

To an observer outside the kiln it appears that the elastic deformations do not vary in time, while the permanent deformations seem to be changing cyclically. On the contrary, an observer rotating together with the kiln perceives the irregularities of the shell as being permanent, whereas the deformations caused by the weight appear to him as variables in time.

Deviations of the centers of the tires from a straight line can be compensated for by adjusting the position of the bearings. That can be done even while the kiln is rotating. Cyclic deformations and stresses caused by the weight cannot be eliminated, unless the structure of the kiln is altered, but since they are small, there is no danger of damaging the shell. Nevertheless, knowing the size of these can assist considerably in deciding whether an adjustment of the bearings is required or not.

Determining deformations of the kiln by a method other then photogrammetric is possible only when the kiln is cool and at rest. Stopping and cooling the kiln and then heating it up to a temperature of 150CC may take a week during which the production process is terminated. Moreover, when the kiln is at rest it becomes difficult to distinguish between its permanent and cyclic deformations. The special photogrammetric method described in the following enables to determine each type of deformations separately, and that under ordinary operating circumstances while the kiln is rotating and heated.

GROUND CONTROL AND PHOTOGRAPHY

Ten photographs were taken of each of the sections of the kiln, including the two tires supporting it, with a TMK camera from Zeiss, at three stations located 16 meters from the kiln's axis of symmetry. The station in the middle was positioned opposite the center of the section and the extreme stations were positioned 8 meters on either side.

Four photographs were taken from the right- hand station with the camera maintaining a nearly constant orientation.

The time interval between two successive exposures was an integer number of rotation periods (one period = 50 seconds), plus 12.5 seconds, hence during each exposure a different quarter of the kiln's shell turned its face towards the camera.

A similar photography procedure was carried out at the left-hand station. The first photograph at that station was taken at a moment, at which the time interval between that moment and the moment of the first exposure at the right-hand station equalled an integer number of periods plus 6.25 seconds.

The two remaining photographs were taken from the middle station. The first photograph was taken after an integer number of periods from the moment at which the second photograph at the left-hand station was exposed. In such a manner, a stereoscopic pair, consisting of the first photograph from the center and the second from the left station was formed, from which coordinates of several points on the shell could be determined by a conventioal photogrammetic procedure. Another stereo-pair was formed in a similar way, from the second plate exposed at the station in the middle and the second plate taken at the right hand station.

Six control points were positioned along the section of the kiln being photographed, three equally spaced in front of the kiln and three in the rear, at a distance of about 5 meters from the axis of symmetry. The locations of the control points were established by surveying methods, the accuracy of the coordinates being characterized by a m.s.e. of one milimeter.

MEASURING THE DEVIATIONS OF THE "TIRES" CENTERS FROM THE STRAIGHT LINE

The tires may be regarded as true circles with centers not being influenced by the kiln's rotations, thus assuming fixed positions in space. Since the images of those centers do not appear on the photographs, their spatial position cannot be determined by conventional methods. But they can be derived from measured photocoordinates of points located on the circumference of the images of the tires. Although no conjugate points on the circumference can be found on all of the eight photographs taken at the extreme stations, mathematical relations between photo coordinates of those points and the six parameters determining the position, size and orientation of the tire, can be formulated. The parameters are:

X_c, Y_c, Z_c - Coordinates of the center of the tire.

R - The radius of the tire

A - The angle between the horizontal diameter of the "tire" and the Y axis.

V - The angle of inclination of the tire plane from the verticality.

The assumed reference system is described as follows:
X - axis - horizontal and nearly parallel to the kiln's axis of symetry.
Z - axis - is vertical
Y - axis - perpendicular to the XZ plane.

The equation of a cyrcle in space is obtained by combinating an equation of a sphere with equation of a plane:

$$(X-X_c)^2 + (Y-Y_c)^2 + (Z-Z_c)^2 = R^2 \qquad .1$$

$$(X-X_c)\cos(A)\cos(V)-(Y-Y_c)\sin(A)\cos(V)-(Z-Z_c)\sin(V)=0 \qquad .2$$

Equations (1) and (2) contain three additional unkowns the spacial coordinates X,Y,Z of a point located on the circumference of the circle (tire). Applying the colinearity condition to the measured image coordinates (x,y) and the object coordinates (X,Y,Z) of the point yield two additional equations.

$$\frac{X-X_0}{Y-Y_0} = \frac{a_{11}x + a_{12}y + a_{13}f}{a_{31}x + a_{32}y + a_{33}f} \qquad .3$$

$$\frac{Z-Z_0}{Y-Y_0} = \frac{a_{21}x + a_{22}y + a_{23}f}{a_{31}x + a_{32}y + a_{33}f} \qquad .4$$

where :

X_0, Y_0, Z_0 denote the coordinates of the nodal point.

f is the focal length of the camera.

$a_{11} - a_{33}$ are the elements of the photograph's transformation matrix

Upon elimination of the object coordinates X,Y,Z from equations (1) to (4) a single equation is obtained which relates the two measured photo coordinates to twelve unknowns, six parameters describing the position and orientation of the circle in space and six orientation elements of the photograph. Photocoordinates of twenty five points were measured on each of the circumferences of the two tires recorded on the photograph. These provided fifty observation equations.

The ground coordinates of the six control points and the coordinates of their cunterparts measured on the photograph, having been inserted in the collinearity conditions (3) and (4), gave rise to additional twelve observation equations. The solution of the system of observation equations so obtained yielded the required twelve parameters. The accuracy of the determined center of the tire i.e. the coordinates X_c, Y_c, Z_c, has been estimated in two ways:

a. By analysing the variance-covariance matrix and the residuals of the photo coordinates resulting from the adjustment procedure.
b. by comparing the coordinates of the center of the same tire which have been derived from evaluating photographs of two consecutive sections of the kiln.

In the both cases the m.s.e. of the Y coordinate and the Z coordinate were 2 and 1 milimeter respecively.

DETERMINING THE DEFORMATIONS OF THE SHELL

As already stated two kinds of deformations, elastic and permanent have to be reckoned with. Determining these deformations is based on the following considerations. The image of the shell on the photograph is bounded by two lines (AB and CD on figure 1), referred to in the following as the upper and lower contours. Each of these is a locus of all points at which straight lines passing through the camera's nodal point are tangent to the shell. Having measured photo coordinates of a point on the contour, upper or lower, and utilizing the orientation of the camera which has already been solved, it is possible to form the equation of the corresponding tangent line by means of the collinearity conditions. The solved coordinates of the centers of the two tires supporting the section of the kiln provide another equation of a straight line in space, which can be regarded as the section's ideal axis of symmetry. The shortest distance between these lines is regarded to be the radial distance between the section's ideal axis of symmetry and the shell. When the cross section of the shell is not a perfect circle this distance is bigger then the real distance between the ideal axis of symmetry and the shell but considering the actual shape of the shell and the location of the nodal point, the difference between these two distances is about one milimeter, an half of the mean square error of measuring this distance.

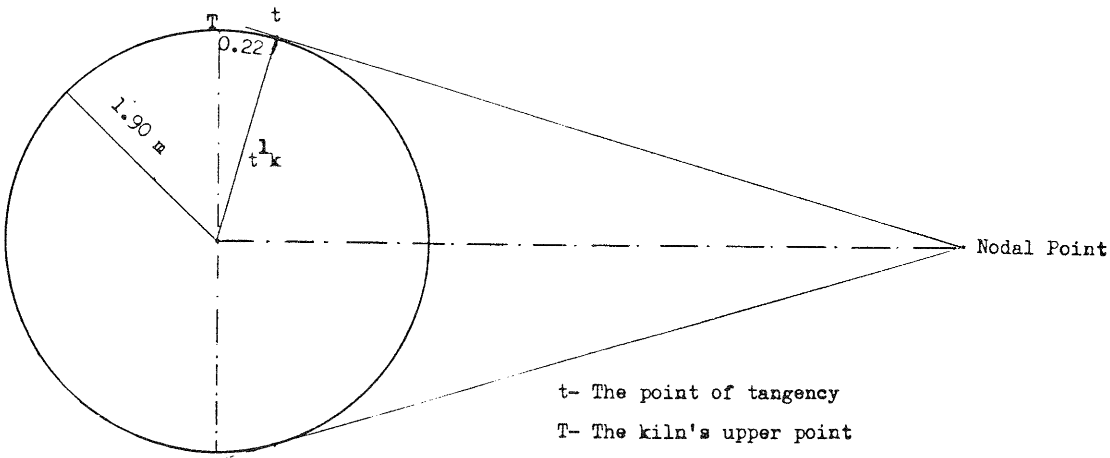

Fig. 3. A cross section of the cylinder

Two tangent points appertained to one cross section, measured on the upper and lower contours of the shell's image, are not on the same diameter. They are however very close to the diameter which is perpendicular to the plane defined by the center line and the nodal point and therefore the two radial distances to the tangent points are regarded as equal to the two radial distances to the points at the two edges of the diameter. (see figure 3)
Hence radial distances of a number of tangent points chosen randomly on the contours of the shell can be determined and by interpolation, such distances can be defined for any cross section of the shell. At a fixed point on the upper contour, eight radial distances can be computed from the eight photographs. If we recall that the time interval between two exposures equalled an integer number of periods plus 1/8 of a period, it is seen that the eight photographs can be regarded as having been taken one after another at equal intervals (1/8 of a period) and thus representing one complete cycle of the kiln's rotation. The difference between the above mentioned distances represent the differences between the parmanent deformations of the shell having been observed at its top at the eight moments of exposure. For the photograph no. k, taken at a moment equivalent to k/8 of the rotation period it is obtained:

$$ {}_{t}l_{k} = r_{t} + d_{k} \qquad .5 $$

where: ${}_{t}l_{k}$ -is the radial distance at the upper point of the kiln's cross section when the k-th photograph was taken.

r_t -is the pipe radius plus its elastic deformation at the top of the cross section.

d_k -is the permanent deformation of the kiln's shell at the top of this cross section in the moment in which the k-th photograph was taken.

Similarly, eight additional equations are obtained for a point at the bottom of the same cross section.

$$ {}_{b}l_{k} = r_{b} + d_{k+4} \qquad .6 $$

Although sixteen observation equations containing only ten unknowns are available, they can not be solved unless the following condition is imposed:

$$ \sum_{k=1}^{8} d_{k} = 0 \qquad .7 $$

From the above equations follows:

$$ r_{t} = 1/8 \sum_{k=1}^{8} {}_{t}l_{k} \qquad .8 $$

$$ r_{b} = 1/8 \sum_{k=1}^{8} {}_{b}l_{k} \qquad .9 $$

$$d_k = \frac{{}_t l_k + l_{k-4} - r_t - r_b}{2} \quad .10$$

The difference $\frac{r_b - r_t}{2}$ is the elastical deformation of the center of gravity of the considered cross section,

The distance of a point not located on one of the lines AB and CD (figure 1.) from the axis of symmetry of the kiln's section can be determined only if that point is positioned on a cross section premarked on the cylindrical shell (see lines PQ and UV on figure 1). Two points on each of these cross sections are marked by two small perpendicular lines. (see figure 1.) Their spacial coordinates are determined by the conventional photogrammetric procedures using the two stereoscopic pairs, consisting of one photograph from the middle station and one photograph from an extreme station.
The equation of the plane corresponding to the marked cross section is derived from the following conditions; it is perpendicular to the axis of symmetry and the sum of squares of the distances from that plane towards the points on the cross section is a minimum. The spacial coordinates of any other point on that cross section are determined from its photo coordinates on a single photograph, using the equation of the plane and the two equations of the collinearity condition. These coordinates are used to determine the radial distances between the point and the section's ideal axis of symmetry. Eight different radial distances are obtained for each point of the cross section, from the eight photographs taken from the two extreme stations. Each of them is a sum of the constant radius plus the elastic deformation and the varying permanent deformation at that point at the moment of exposure.

RESULTS AND CONCLUSIONS

The results of the measurments show that the shape of the shell remains almost an ideal circle. The elastic deformations are less than 2 milimeters,which is commensurable with the m.s.e. of determining a radial distance from the axis of symmetry. The sag of the axis of symmetry at the middle of the kiln's segment was found to be 23 milimeters, while the sag at a 7.50 meters distance from the tire was 20 milimeters. The difference between these two corresponds to the theoretical line of the elastic deformation of the axis, which is a fourth order parabola.
The measurements have detected permanent deformations of the shell of varying magnitudes at different poins, the largest deformation was 50 milimeter.