

Dynamic Parallel Roll Alignment

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Abstract: A new method of checking the alignment of parallel rolls, while they are rotating, is described in this paper. The method utilizes the autoreflection technique, along with a strobe light and photoelectric trigger, to determine the orientation of the normal to a mirror fixed to the end of a roll. Three or more observations of the normal at different rotational positions of the roll allow for the computation of the roll's rotation-axis orientation. The method was applied to a small machine in both the dynamic (operating) and static (nonoperating) modes. From this application, it was determined that standard deviations of orientations can be expected to be in the order of 4 arcs for the dynamic mode and 2 arcs for the static mode.

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Introduction

Many industrial processes use systems of rolls that must be parallel to one another within certain operating specifications. For example, in the manufacture of paper, paper breakage can occur if the rolls which the paper passes over are not parallel. As the speed of manufacturing processes increase, tolerances in parallelism become more stringent, so a very accurate method of measuring the orientation of rolls is needed by industry.

As machine speeds increase, the downtime required to survey rolls becomes more expensive due to lost production. Thus, methods of orientation determination should be quick to implement.

It is well known that machines deform as they move from a shutdown mode into an operating state. Causes of deformation include thermal growth, vibration,

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addition of load, and mechanical properties of the rolls. Since these deformations can be quite significant and operating conditions are usually more relevant than shutdown conditions, a method of determining shaft orientation during operation is desired.

Sprent and Hudson (1996) describe a method that uses autocollimation to quickly and accurately measure the orientation of rolls in a machinery shutdown scenario. This paper extends the method introduced by these writers so that orientation of a roll while it is in operation can also be determined.

Existing Methods of Orientation Determination

Rolls are usually aligned vertically using a level that is fit with a parallel-plate micrometer and sights to scales set on the crown or invert of the roll. Horizontally, the rolls are aligned by surveying offsets from horizontal tangents to the machine roll using a jig transit. This method, however, suffers because a clear line of sight is required along each line offset from the machine roll.

Bayly and Teskey (1992) developed a system using a theodolite intersection to determine the position of targets fixed onto the rims of machine rolls. The position of the targets yields, through circle fitting, the orientation of the roll. The position of the target is referenced to a fixed datum and determined through network adjustment. Instrument locations themselves can be anywhere and are solved by resection to known datum points. Although this does not require long lines of sight, the method does require many observations to establish the location of stations and targets.

Sprent and Hudson (1996) introduced a method using autocollimation to determine the orientation of the normal of a mirror fixed to a roll. As the roll rotates, the normal of the mirror subtends a cone, and by observing the normal in at least three positions, the orientation of this cone can be solved.

All of the above methods can only be used to measure the static alignment of rolls. Teskey et al. (1993) developed a method using a theodolite intersection and a laser spot as a target on rolls. The method can be applied in the static (non operating) or dynamic (operating) mode. The method produces good results but is quite slow due to the large number of observations required.

In this paper, Sprent and Hudson's method is modified to use a strobe light and a photoelectric trigger to optically freeze the observed mirror, thus allowing the determination of dynamic alignment of parallel rolls. Sprent and Hudson's method is also modified in that autoreflexion is used instead of autocollimation.

Autoreflexion and Autocollimation

In autoreflexion, the condition which exists when a line of sight is normal to a reflecting surface (typically a mirror) is shown in Fig. 1. The procedure used to achieve this condition with a theodolite can be summarized as follows: focus on the mirror first, then focus on the reflection of the autoreflexion ring around the telescope (the reflected image will be at twice the distance to the mirror; Fig. 1), finally translate and rotate the theodolite to achieve the autoreflexion condition.

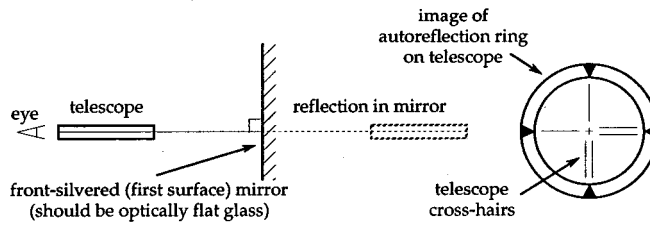


Fig. 1. Autoreflection

With a leveled theodolite having a line of sight normal to a mirror, vertical circle and horizontal circle readings on the theodolite give a direct measure of the orientation of the mirror and the orientation of the normal to the mirror.

Autocollimation is a technique very similar to autoreflection. Both techniques are described in detail in Kissam (1962). Autoreflection is usually used in industrial applications because autocollimation requires specialized equipment (an eyepiece), it cannot be achieved under normal to bright lighting conditions, and it is very sensitive to vibrations (the blurred image cannot be seen).

Dynamic Orientation Determination of Parallel Rolls

The principle of Sprent and Hudson's method, in the case of a mirror attached to the end of a rotating shaft, is that the normal at a fixed point on the mirror subtends a cone in one revolution. Furthermore, the axis of this cone is parallel to the axis of rotation of the roll regardless of how the mirror is fixed to the roll (Fig. 2). Thus, by measuring the orientation of the normal in at least three phases of the roll's rotation, a cone can be fitted and the rotation axis of the roll determined. The orientation of the normals is determined using the autoreflection technique.

Also note that all normals to a flat mirror have the same direction. Thus, the actual point on the mirror sighted is irrelevant, as long as the autoreflection condition is fulfilled. This means that an observer has some freedom in where the theodolite is set up. In addition, the actual theodolite position does not have to be determined since only the orientations of the normals are required.

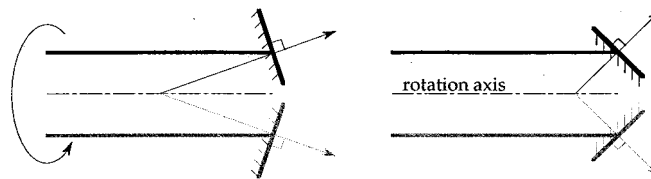


Fig. 2. Axis detection via autoreflection

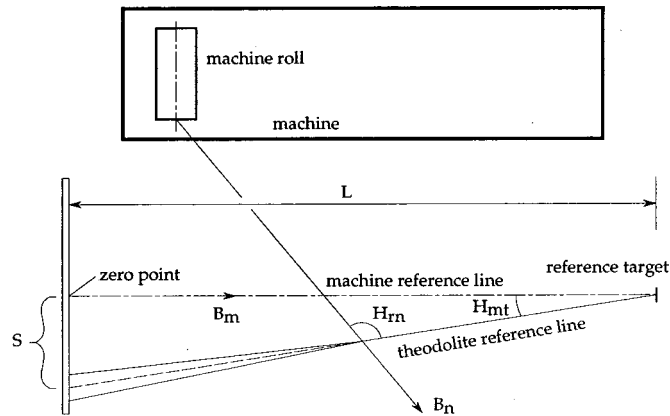


Fig. 3. Reduction to machine reference line

The orientation of the mirror normals in the horizontal plane must be referred to a machine reference line. This was done by setting up a horizontal scale bar at one end of the room and placing a reference target on the opposite wall (Fig. 3). The machine reference line was defined as the line passing through the reference target and a particular point on the scale bar. When making an observation, the theodolite is first set up so that the autoreflection condition is satisfied. The reference target, theodolite, and scale bar must also be in a vertical plane as shown in Fig. 3. Horizontal and vertical circle readings for the mirror normal are then read in both positions of the telescope.

The procedure used to convert the horizontal circle readings to a bearing relative to the machine reference line is summarized in the steps below:

1. Observe mirror normal and read horizontal circle reading H_n .
2. Point telescope at reference target and read horizontal circle reading H_r . The horizontal angle H_{rn} between the reference target and the mirror normal is then

$$H_{rn} = H_r - H_n \quad (1)$$

3. Transit the telescope and read scale bar reading S . The horizontal angle H_{mt} between the machine reference line and the theodolite reference line is then

$$H_{mt} = \text{atan}(S/L) \quad (2)$$

where L = horizontal distance from the reference point to the zero point on the scale bar.

4. Calculate the bearing B_n of the mirror normal as

$$B_n = B_m + 180^\circ - (H_{rn} + H_{mt}) \quad (3)$$

where B_m = bearing of the machine reference line from the zero point on the scale bar to the reference target.

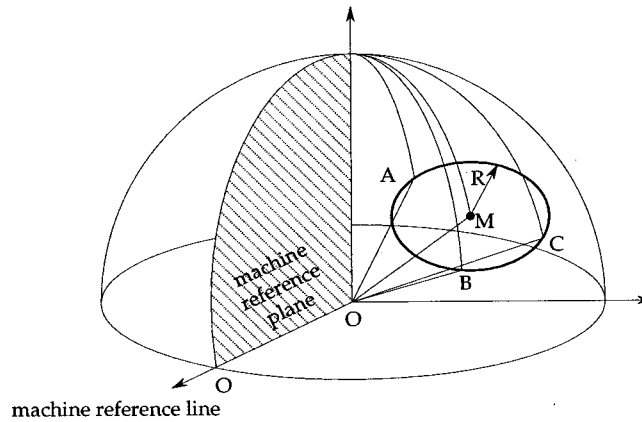


Fig. 4. Geometry of alignment technique

5. Repeat Steps 1 through 4 in the other position of the telescope. By meaning the two determinations of B_n , the horizontal collimation error of the theodolite will be eliminated.

When the roll is rotated into at least three positions and observations are made, the cone that defines the rotation of the mirror normal about the rotation axis of the roll can be calculated. As shown in Fig. 4, define a machine reference plane. The machine reference line is the vector \mathbf{OO} , the intersection of the machine reference plane with the horizontal. Next, let vector \mathbf{OM} represent the orientation of the rotation axis of the roll, and let vectors \mathbf{OA} , \mathbf{OB} , and \mathbf{OC} represent the orientations of the observed mirror normals.

From the spherical trigonometry cosine law for sides (Beyer 1976) for each vector \mathbf{O}_i ($i = A, B, C$, etc.)

$$\cos R = \cos Z_i \cos Z_m + \sin Z_i \sin Z_m \cos(B_m - B_i) \quad (4)$$

with R = spherical radius of cone subtended by revolving normal; Z_i = zenith angle of observed normal; Z_m = zenith angle of rotation axis of roll; B_i = bearing of observed normal; and B_m = bearing of rotation axis of roll.

The set of equations generated can be solved as an implicit nonlinear least squares adjustment to obtain the desired parameters B_m and Z_m . One problem that arises is how to observe mirror normals at different phases of the roll rotation. If the machine is shutdown, this is not an issue since the rolls are at rest and can be manually rotated into different positions. This was the case in the survey done by Sprent and Hudson.

However, if the machine is running, the image formed by the mirror blurs. To solve this problem, the writers used a stroboscope to optically freeze the motion of the shaft. The strobe was triggered by a photoelectric pickup which sensed a timing mark on the roll. With the strobe positioned near the instrument, the observer only saw the image form once a revolution at a particular point in the

Table 1. Residuals (Shutdown Mode)

Horizontal circle and vertical circle observation number	Horizontal circle residual (arc seconds)	Vertical circle residual (arc seconds)
1	-0.6	-4.4
2	-4.1	+2.3
3	-2.7	+0.8
4	-0.3	+0.5
5	+2.0	+2.1
6	+5.8	-1.7

Note: Input standard deviations for all horizontal circle and vertical circle observations are ± 5 arc seconds. The variance factor is equal to 1.3.

rotation of the roll. This “apparent roll” could be rotated into several different rotation states by adjusting a phase delay on the strobe. The method worked extremely well even in bright-lighting conditions. Advantages of this method over other methods include the following:

1. The actual alignment of rolls while operating can be determined;
2. The instrumentation required is commonly available and easily used. In addition, the system can be easily automated throughout the use of interactive electronic-data collection;
3. There is no need to attach or remove targets once a mirror has been attached to the end of a roll. Future surveys can therefore be quickly completed;
4. The method is flexible in that any three or more positions of the roll rotation can be observed; and
5. It is not necessary to set up the theodolite over any particular point. Centering errors are eliminated, and the survey can also proceed more quickly.

Application of Method

The method was applied to determine changes in roll alignment, between shutdown and operating conditions, of one roll in a small machine. An optically flat mirror was epoxied at an exposed location on one end of the roll, and a reference target and scale bar were positioned as shown in Fig. 3. The distance L was approximately 8 m.

A Leica T2002 theodolite, fitted with an autoreflection ring (Fig. 1), was used to make all the observations. In both the shutdown and operating modes, six rotational positions of the roll were observed and adjusted. Each of the two sets of six rotational positions were distributed about equally around the rotation axis. About one-half hour was required to observe each set of rotational positions.

Residuals of the observations, computed in each adjustment, are listed in Tables 1 and 2. Also given with these tables are input standard deviations for all horizontal circle and vertical circle observations along with the variance factor computed in each adjustment. The variance factor in both cases is equal to the weighted sum squares of residuals divided by the redundancy, with the redun-

Table 2. Residuals (Operating Mode)

Horizontal circle and vertical circle observation number	Horizontal circle residual (arc seconds)	Vertical circle residual (arc seconds)
1	+2.8	-3.0
2	+3.2	+7.9
3	+5.7	-5.1
4	-4.8	+6.6
5	-9.4	-3.5
6	+2.3	-2.7

Note: Input standard deviations for all horizontal circle and vertical circle observations are ± 10 arc seconds. The variance factor is equal to 1.1.

dancy equal to 3 [6 equations less 3 unknowns (R, Z_m, B_m)]. This analysis of the residuals clearly indicates a good fit of the observations to the mathematical model of Eq. (4).

Standard deviations of roll orientations, computed from each adjustment, were 2 arc seconds for the shutdown mode (the same result achieved by Sprent and Hudson) and 4 arc seconds for the operating mode. The difference in roll orientation between shutdown mode and operating mode was 15 arc seconds. As noted previously, a shutdown mode/operating mode difference should be expected. In this case, the difference was probably caused by the operating force exerted on the roll by the drive motor.

The machine on which the method was applied had only one roll, but the method could obviously be extended to any number of rolls in a machine with a system of rolls. The time required to complete a set of observations on each roll would normally be expected to be about one-half hour, i.e., the same amount of time required in the application described above.

Conclusion

The autoreflexion method described in this paper can be applied in situations where it is necessary to check on the parallelity condition in systems of rolls. If the method is applied in the static (nonoperating) mode, standard deviations of orientations can be expected to be in the order of 2 arc seconds; if the method is applied in the dynamic (operating) mode, standard deviations of orientations can be expected to be in the order of 4 arc seconds.

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