THREE DIMENSIONAL SURVEY FOR MAGNET ALIGNMENT

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A triangulation based only on the length measurements is widely used for an alignment of magnets of the synchrotron. But the recent development of the three dimensional survey using the precision theodolites allow the precise alignment of the magnets even where an extensive view of magnets is difficult. The method employs at least two theodolites, placed where all targets can be seen, to obtain the stereographic sight. The coordinates of the target points are derived from the horizontal and vertical angles measured on-line with two theodolites, so what is called the short chords and perpendiculars can be obtained immediately. The method is useful particularly at the place where an access is difficult.

Introduction

With an invention of the electronic surveying instruments such as an electronic theodolite and an opto-electronic tachymeter, an on-line measuring system becomes available in the field of the magnet alignment. Even with the new system the fundamental method is a triangulation based on the non-contact measurements. The accelerator magnets require the precise positional accuracy to retain the beam within a specified aperture, so measurements of the magnet position have to be highly accurate. The positional error has an effect on the closed orbit in a synchrotron by more than 10 times of the error. The measurement accuracy should be less than a few ten micrometers. Therefore the special surveying technique called an astral survey has been developed to give the accurate data analysis for the measurements even in the narrow and curved tunnel [1]. In this technique only the length measurements are adopted because they give the accurate data. The Distinvar instrument and offset measuring instrument using nylon string [2] or laser [3] are the products of this technique. We have adopted the Distometer as an alternative of the Distinvar for several years [4]. These are used as the standard instuments so far but require the calibration using a laser interferometer on the calibration bench long enough to accommodate the invar wires. The offset instrument can be also calibrated on the same bench.

If two electronic precision theodolites are used, the spatial coordinates of the target points on the subjects can be determined through on-line measurements by connecting them to a computer. The program computes the coordinates from angles measured with theodolites. Angles determine only the relative positional relations between the targets. A short scale bar with the known length, 1 m or so, is used to fix the physical coordinates relative to an assumed origin. They compose the three dimensional survey system including the program. If the scale bar is calibrated accurately, no other calibration is necessary.

We apply this system to the small scale magnet alignment in the TRISTAN synchrotron tunnels and have confirmed its validity. The systems used are the electronic coordinate determination system (ECDS2) of Kern & Ltd. [5,6] and the total system of Nikon Corp.

Three dimensional formulation and accuracy

In the formulation the provision is assumed to determine the relation between two theodolites. Fig. 1 shows the horizontal and vertical angular relations of theodolites.

The vertical angles do not depend on the place where the theodolites are placed, if the survey is resticted in an area so small that the curvature of the earth is negligible. The horizontal angle, however, depends on the initial direction of the theodolite. This difference of the horizontal angle is assumed as κ in the figure. Assuming the 3-D coordinate of one theodolite as (0,0,0) and the other as (bx, by, bz), the following relations are obtained for a target,

$$
\begin{aligned}
&R1\cos\beta_1\cos\alpha_1 - R2\cos\beta_2\cos\alpha_2 = bx \\
&R1\cos\beta_1\sin\alpha_1 - R2\cos\beta_2\sin\alpha_2 - by = 0 \\
&R1\sin\beta_1 - R2\sin\beta_2 - bz = 0
\end{aligned}
\qquad (1
$$

where R1 and R2 are the target distances from both theodolites. many targets are observed, the above equations can be expressed i the matrix form,

$$(M)\ X = B \qquad (2$$

where M is (3n) x (2n+2) matrix, n being the number of targets,

$$
M = \begin{pmatrix}
A_1 & 0 & 0 & 0 & \cdots\cdots & 0 & B \\
0 & A_2 & 0 & 0 & \cdots\cdots & 0 & B \\
\cdot & \cdot & \cdot & \cdot & \cdots & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdots & \cdot & \cdot \\
0 & 0 & 0 & 0 & \cdots\cdots & A_n & B
\end{pmatrix} \qquad (3
$$

$$
A_i = \begin{pmatrix}
\cos\beta_{i1}\cos\alpha_{i1} & -\cos\beta_{i2}\cos\alpha_{i2} \\
\cos\beta_{i1}\sin\alpha_{i1} & -\cos\beta_{i2}\sin\alpha_{i2} \\
\sin\beta_{i1} & -\sin\beta_{i2}
\end{pmatrix}, \qquad
B = \begin{pmatrix}
0 & 0 \\
-1 & 0 \\
0 & -1
\end{pmatrix}
$$

$$(i = 1, 2, \ldots\ldots, n)$$

X is the vector with (2n+2) elements,

$$X = (R11\ R12\ R21\ R22\ R31\ R32 \cdots\cdots Rn1\ Rn2\ by\ bz)^t \qquad (4)$$

and B is the vector with (3n) elements,

$$B = (bx\ \ 0\ \ 0\ \ bx\ \ 0\ \ 0 \cdots\cdots bx\ \ 0\ \ 0)^t \qquad (5)$$

The solution X is obtained by the least squares method assuming b: = 1. If two target points giving the absolute distance are included i measurements, a magnification factor can be calculated. Multiplyin this factor to the vector X, the absolute coordinates are obtained.

The angle ambiguity κ in the horizontal angle (α_{i2}) is found b obtaining the zero crossing point of the following function which a summed up for all points, incrementing the dummy angle by 10 de in every repeated calculation,

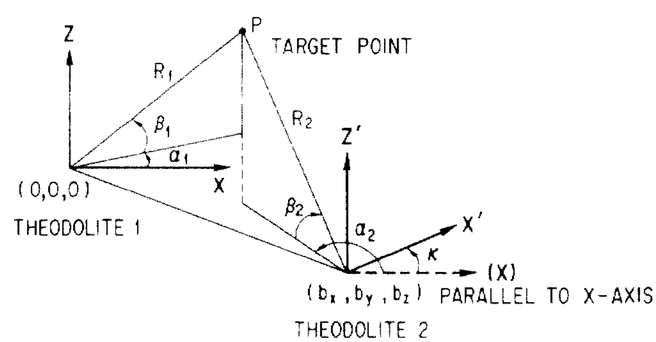

Fig. 1 Angular relations of theodolites.

$$S = \tan^{-1}(Z1/\sqrt{X1^2 + Y1^2}) - \tan^{-1}(Z2/\sqrt{(X2^2 + Y2^2)})$$
$$+ \tan^{-1}(Y1/X1) - \tan^{-1}(Y2/X2) \quad , \qquad (6)$$

where (X1, Y1, Z1) is the coordinate observed with the theodolite at the origin and (X2, Y2, Z2) the one observed with another theodolite whose horizontal ambiguity should be determined. Once the zero crossing angle is found within 10 deg, κ is gained by interpolation. Three examples are shown in Fig. 2 for the cases of κ = 88, 126.4 and 257 deg.

Due to the convergence criterion imposed on κ, errors apear in the final coordinates. For the criterion of 0.3 sec the error of the coordinates is ± 0.03 mm. If the measurement error of 0.3 sec (rms) is included, the coordinate error will be ± 0.05 mm under the same criterion. Imposing more strict criterion, further imporvement will be expected depending on the magnitude of the measurement error.

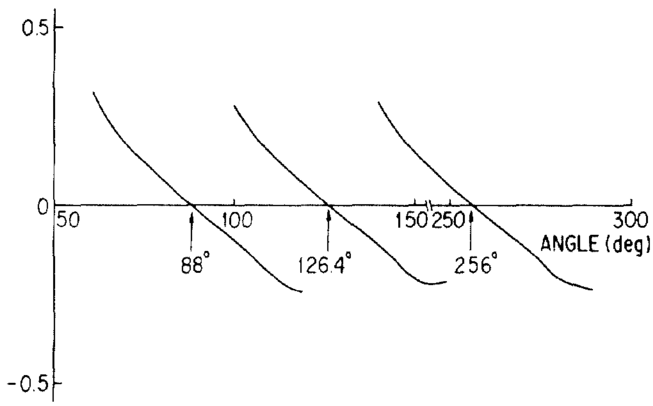

Fig. 2 Behavior of function S around the correct κ values.

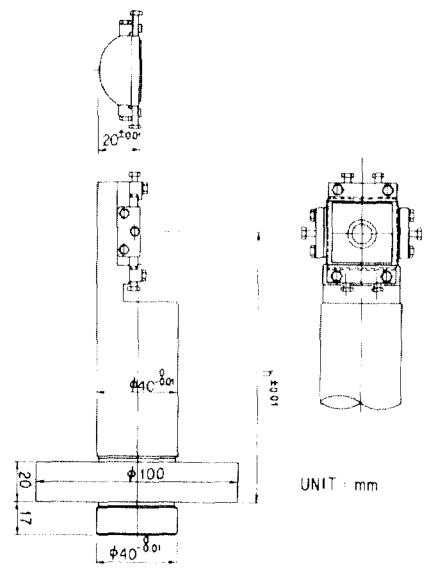

Fig. 3 Special target for the 3-D survey.

Fig. 4 Survey in the MR tunnel.

Target point

Every magnet has its own machined sockets at both ends centered accurately just on the beam line. Prior to the 3-D survey the target of Fig. 3 are set on magnets. The targeting point is printed on the adhesive nylon sheet and stuck on the adjustable plate which is fixed under a microscope so that the sighting point is on the pivotal axis within an accuracy of ± 0.01 mm. The diameter of the point is 0.2 mm for the present sticker which is convenient for the survey in a small area within 10 m. For a large area extending more than 10 m, it is preferable to use a larger point mark which is visible clearly far-off in space and fits well to a cross inside the theodolite. An accuracy sighting a point depends greatly on the structure of the target and affects the coordinate error of the point.

Application to synchrotron magnets

The 3-D survey is applied to magnets of TRISTAN AR (accumulation ring) and MR (main ring). It includes two typical areas, small and large areas. The former is the narrow synchrotron tunnel and the latter the large experimental hall of MR. In the tunnel the triangle of survery is greatly obtuse-angled because of the small bending angle of a bending magnet as seen from Fig. 4. Whereas in the case of the experimental hall, the surveying triangles are nearly ideal, except that a big detector placed at an interaction region interferes the thorough sights. In this case the survey should be done twice to connect the geometries of both sides of the detector. The geometry of one side is fixed and that of the other side is connected by the rotation of the coordinate axis.

Alignment at small area

Errors estimated from the 3-D coordinates are less than ± 0.1 mm for the offset distance, less than ± 0.2 mm for the short chord and less than ± 0.03 mm vertically. Comparison is made between the conventional and 3-D survey methods in Table 1.

Table 1 Comparison of two methods at small area (unit; mm)

	3-D method	Conv. method	Difference
Short chord distance			
QD6(u) - QF6(u)	8059.496	8059.829	-0.333
QF6(u) - QD5(u)	8061.058	8060.992	0.066
Offset distance			
QF6(u)	98.575	98.634	-0.059
QF6(d)	98.263	98.225	0.038
Height (relative to QD6)			
QF6(u)	-0.55	-0.48	-0.07
QF6(d)	-0.61	-0.48	-0.13
QD5(u)	-0.53	-0.31	-0.22

(u) = upstream side, (d) = downstream side

Table 2 Comparison of two methods at large area (unit; mm)

	3-D method	Conv. method	Difference
Short chord distance			
QC2NL(u) - QC1NL(u)	3500.092	3500.343	-0.251
QC1NL(u) - QC1NR(u)	12000.910	12001.033	-0.123
QC1NR(u) - QC2NR(u)	4000.024	4000.317	-0.293
Offset distance			
QC2NL(d)	0.132	0.214	-0.082
QC1NL(u)	0.900	0.872	0.028
QC1NL(d)	0.844	0.567	0.277
QC1NR(u)	0.684	0.259	0.425
QC1NR(d)	0.924	0.715	0.209
QC2NR(u)	-0.126	-0.157	0.031
Height (relative to QC2NR(d))			
QC2NL(d)	-1.04	-0.91	-0.13
QC1NL(u)	-1.04	-0.88	-0.16
QC1NL(d)	-0.76	-0.76	0.00
QC1NR(u)	-0.63	-0.70	0.07
QC1NR(d)	0.38	0.05	0.03
QC2NR(u)	-0.30	-0.18	-0.12

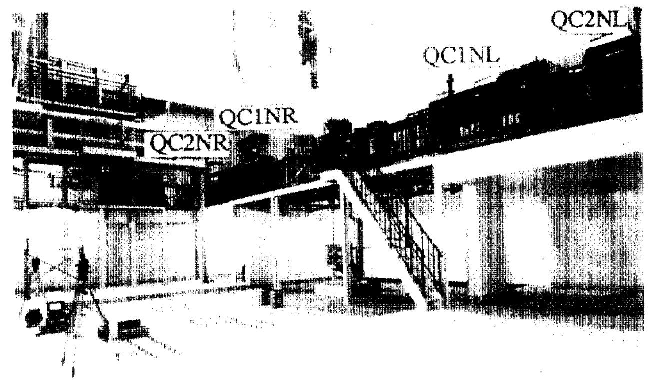

Fig. 5 Survey at the MR experimental hall.

Alignment at large area

Compared to the case of the small area, an accuracy is poor in the offset distance. Errors in the offset distance and short chord estimated from the 3-D coordinates are ± 0.4 mm and ± 0.3 mm, respectively. Main error is due to an inaccuracy in sighting the target points. Comparison of both methods is made in Table 2 which is the results obtained at one of the TRISTAN experimental halls where no big detector exists (Fig. 5).

Summary

The 3-D offset distance at small area gives good results, despite that both sightings of two theodolites are hard to intersect correctly on the target points at both ends. Though the coordinate error in the direction of the sight is as large as ± 0.15 mm, the offset error of the central magnet is less than ± 0.06 mm because its projection on the axis of the radial direction is small.

For the case of large area the survey should be repeated many times to increase an accuracy statistically. If the target is improved to be sighted clearly at a long distance, the 3-D coordinates will become more accurate.

The 3-D survey method offers an elegant method in an alignment of the accelerator magnet even at the place where it is difficult to access with the conventional instruments, since measurements are made externally. The angles measured with two theodolites are stored in the computer as an angle file and processed to give the 3-D coordinates with the same computer. Using a lap-top computer the portability of the system is well improved and the data can be recorded and processed by a person who manipulates the theodolite at any place. The 3-D coordinates are also converted to the required quantities such as the short chord distance and the offset distance which are useful for the precise alignment of the synchrotron magnets.

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