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Straightness evaluation using inclinometers with a pair of offset bars

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ABSTRACT

To evaluate the straightness of large objects, the use of an inclinometer is advantageous because it requires neither straight shape references nor transferring mechanisms. Herein, we consider adopting it for precise (with greater accuracy than 1 mm) evaluation of the straightness of linear particle accelerators (linacs) that are several hundred meters long or longer. In this study, the straightness evaluation of a 206-m-long part of the KEK injector linac was demonstrated using inclinometers with a pair of cantilevers called offset bars. The offset bars were adopted to extend the evaluation length by avoiding obstacles that block the evaluation path. Errors caused by the offset bars can be eliminated by reversal measurement considering the slope angles of the offset bars. The derived straightness corresponded with those derived by an alignment telescope and a laser-based alignment system within several millimeters and partly within several hundred micrometers. The reproducibility of slope angles for an arbitrary measurement point was 15 μrad at standard deviation. This corresponds to a standard deviation of 0.47 mm for straightness, with a total evaluation length of 500 m and measurement intervals of 2 m. The results indicate that our newly devised method is applicable for evaluating the straightness.

1. Introduction

Straightness evaluation is usually performed by scanning a detector along an object. Because errors in the scanning locus directly affect this evaluation, several kinds of error separating techniques have been proposed and developed for eliminating these errors [1–3]. In principle, they require no straight shape references, which become difficult to accurately define and maintain for increased evaluation lengths. It follows that they are inherently advantageous for evaluating relatively large objects. Straightness evaluation detecting tangential angles or differential straightness [4–6] is a simple and classical technique. Above all, the method using an inclinometer is considered to be advantageous for large objects because it requires no transferring mechanism that scans the detector with sufficient accuracy that the error separating techniques can be adopted in practice. The transferring mechanism often requires unacceptably excessive space and costs for large objects (over 10 m). The method using an autocollimator does not require such mechanisms; however, the evaluation length is restricted by the effective range of the measurement beam, whereas the method using an inclinometer does not have such limitations of evaluation length.

We have considered adopting the method using an inclinometer for accurately (with greater accuracy than 1 mm) evaluating large (with lengths of several hundred meters or longer) linear particle accelerators (linacs). We evaluated the straightness of a 71-m-long part of the KEK injector linac by using a precise inclinometer and demonstrated that the reproducibility of the derived straightness was less than 49 μm at standard deviation and corresponded with those by two other methods, within submillimeters [7]. This showed that the evaluation was fairly reliable; however, the evaluation length was limited by obstacles that blocked the evaluation path, and the length could not be extended.

Here, we added a pair of cantilevers called offset bars at each measurement point for avoiding the obstacles and extended the evaluation length by shifting the evaluation path. Errors arising from the offset bars were eliminated by newly devised reversal measurement, which considers the slope angle of each offset bar.

2. Principle

2.1. Straightness evaluation using an inclinometer

Fig. 1(a) and (b) shows the principles of straightness evaluation using an inclinometer. The inclinometer sequentially detects the

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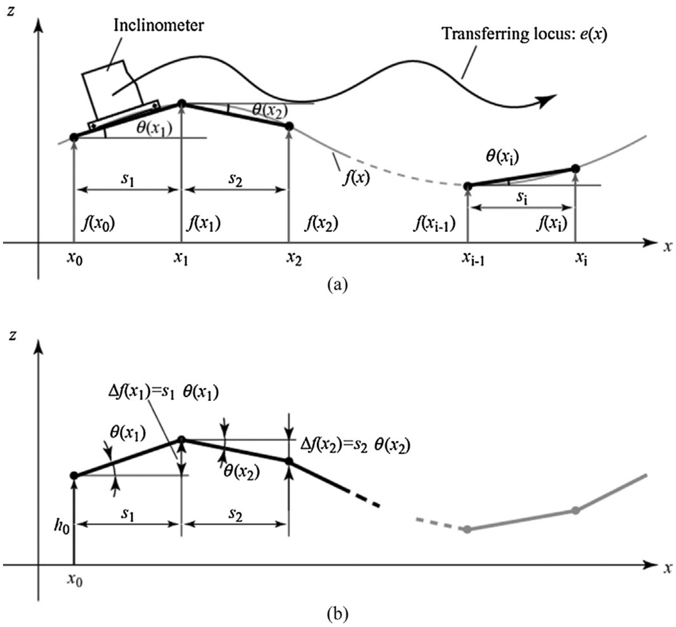

Fig. 1. (a) Straightness evaluation based on tangential angles, $\theta(x_i)$, of an object, $f(x)$, using an inclinometer. (b) Straightness derived by integrating the detected angles.

tangential angle, $\theta(x_i)$, of the profile shape, $f(x)$, for an object at each measurement point, x_i ($i = 0$–n), where the inclinometer is moved in the x-direction along which the measurement points are aligned (Fig. 1(a)). Straightness is evaluated by the shape, $f(x_n)$, which is derived by integrating the detected angles as

$$f(x_n) = h_0 + \sum_{i=1}^{n} s_i \cdot \theta(x_i), \tag{1}$$

where h_0 stands for the arbitrarily defined shape of the first measuring point and s_i stands for the distance between neighboring measuring points (Fig. 1(b)).

Here, the detected angle, $\theta(x_i)$, and consequently, the derived shape, $f(x_n)$, are not affected by the transferring locus, $e(x)$. The locus is predominantly used for reference in conventional straightness evaluations that directly detect the shape; however, it is difficult to maintain a sufficiently straight or accurate locus as the evaluation length increases. It follows that straightness evaluation using an inclinometer is advantageous for evaluating relatively large objects because it is not affected by the transferring locus.

2.2. Obstacle avoidance using a pair of offset bars

We previously evaluated the alignment of base plates in the KEK injector linac by using an inclinometer with a straight bar, as shown in Fig. 2(a) [7]. However, the evaluation length was limited by obstacles that blocked the evaluation path, as shown in Fig. 2(b). Here, we extended the evaluation length by using a pair of cantilevers called offset bars on each base plate to avoid obstacles by shifting the evaluation path. Slope angles for lines connecting each end of the offset bars were determined in place of those connecting each of their roots, which were the original targets of evaluation. Errors arising from the offset bars can be eliminated by reversal measurement, which considers the slope angles of the offset bars.

2.3. Reversal measurement considering slope angles of the offset bars

Fig. 3(a) and (b) shows reversal measurement [8] considering the slope angles of the offset bars before and after reversal. The measurement setup consists of a pair of offset bars, a and b; a straight bar, c; and three inclinometers, A, B, and C, which form a U-shape. Here, we aim to determine an angle, θ_t, which is the slope angle of a line connecting two measurement points, p and q, from measurements, θ_{ma}, θ_{mb}, θ_{mc}, θ_{na}, θ_{nb}, and θ_{nc}, made by the three inclinometers before and after reversal.

Before reversal (Fig. 3(a)), each root, a_r and b_r, of offset bars, a and b, is located on points, p and q; and two ends, c_1 and c_2, of the

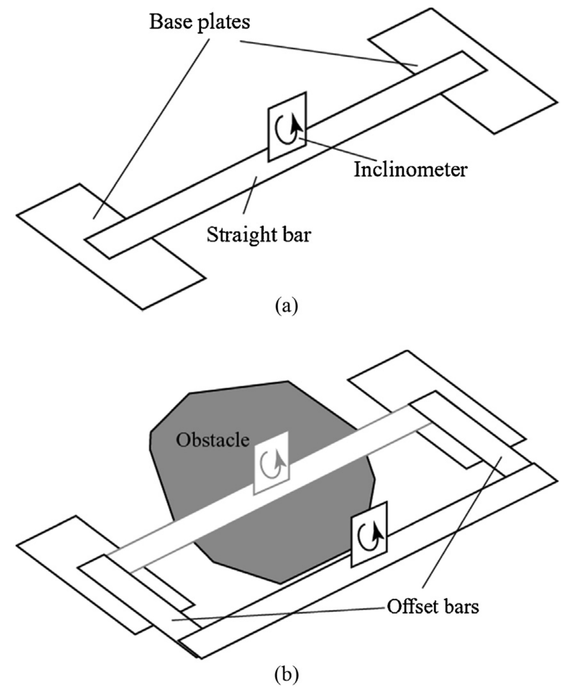

Fig. 2. (a) Straightness evaluation for the alignment of base plates using a straight bar and an inclinometer. (b) Pair of offset bars for avoiding obstacles that block the evaluation path.

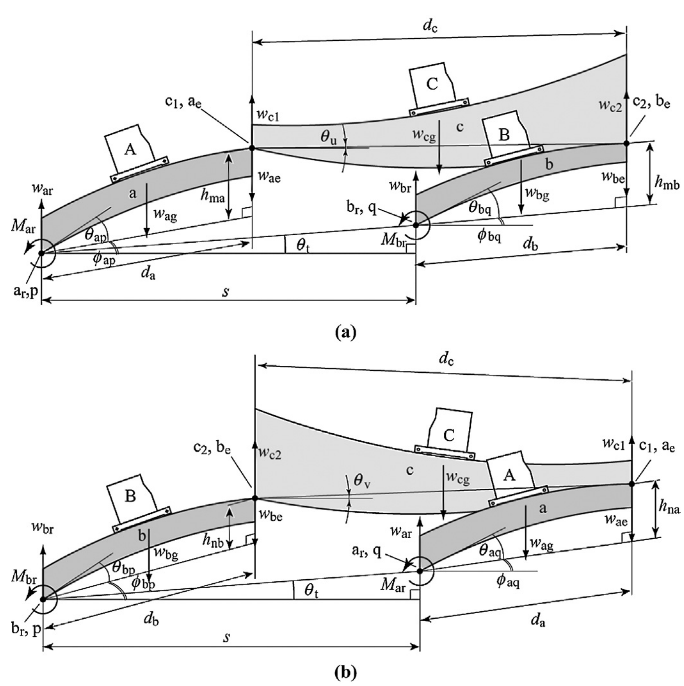

Fig. 3. Reversal measurement for angle measurement (a) before and (b) after reversal using a pair of offset bars, a and b; a straight bar, c; and three inclinometers, A, B, and C.