Straightness measurement of a long guide way
A comparison of dual-beam laser technique and optical collimator

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Abstract

For large machines with long guide ways, it is important to align the guide ways both in the vertical direction and horizontal direction. Conventional methods are using a piano wire and collimator, using an electronic level, using an alignment laser and position-sensitive detector, and using an autocollimator. All of the above methods are either very time consuming or with limited resolution and accuracy.

Reported here is a technique to determine the guide way straightness by measuring the slopes at each point along the travel using a dual-beam Laser Doppler Displacement Meter (LDDM™). The straightness is obtained by integrating the local slopes at each measuring point over the total travel. The slope or the angular change of the dual-retroreflector is equal to the difference of the two linear displacement changes divided by the separation of the 2 retroreflectors. Since both displacement and angle can be measured simultaneously, the straightness can be measured in one continuous stroke without stopping. Hence it is more accurate and also saves time. The theoretical basis of the technique, the accuracy of the measurement, and a comparison with other techniques will be discussed.

To verify the performance, data were taken on a long guide way by both dual-beam laser system and by a wire collimator. Repeated measurements were performed for a length of 15 m, 10m, and 5 m. The test setup, data collection and analysis, and test results will be reported.

I. Introduction

For large machines with long guide ways, it is important to align the guide ways both in the vertical direction and horizontal direction. Conventional methods are: using a piano wire, using an autocollimator, using electronic level, using a laser beam and a quadratic detector and using a laser interferometer and Wollaston prism. For the piano wire method, the resolution is low and time consuming. For the electronic level method, the accuracy is not enough and also in the vertical direction only. For the autocollimator method, the resolution and accuracy is relatively low. For the laser interferometer and Wollaston prism method, the alignment and setup are very difficult due to the complex optics. For the laser beam and quadratic detector method, because of the air circulation or turbulence the accuracy is rather limited for long guide ways.

Described here is a technique to determine the straightness by measuring the slopes at each point along the travel using a dual-beam Laser Doppler Displacement Meter (LDDM™)[1]. The straightness is obtained by integrating the local slopes at each measuring point over the total travel [2]. The theoretical basis of the technique, the accuracy of the measurement, and a comparison with other techniques, is discussed.

II. Straightness definition and measurement methods

A straightness error is defined as the deviation perpendicular to the direction of travel as shown in Fig. 1. Assuming the ideal travel path is a straight line, any deviation from the straight line in the horizontal plane is called horizontal straightness and in the vertical plane is called vertical straightness.

The laser interferometer and Wollaston prism method is based on the optical path difference between two laser beams at a divergent angle and the target. The optical path difference is proportional to the vertical displacement of the target of the straightness. Hence it is a measure of the straightness in the direction perpendicular to the travel in the plane of the two beams. This method requires very complex and expensive optics, the alignment and operation are very difficult and time consuming.

The laser beam and quadratic detector method is based on the straightness of a laser beam. A laser beam is pointing in the direction of the travel and a quadratic detector is used to determine the centroid of the laser beam. Any displacement in the direction perpendicular to the travel is determined by the output of the quadratic detector. Hence it is a measure of the straightness in both vertical and horizontal directions. This method is relatively easy to setup and align. However, it is more sensitive to the air circulation or turbulence. Long time average is needed to minimize the turbulent fluctuations.

The piano wire and collimator method is based on the straightness of a piano wire. This is a very old method. The resolution and accuracy are rather limited. It is a manual operation and very time consuming. This is a direct measurement and is still commonly used.

III. Laser slope method

The laser slope method is based on the measurement of the slope to determine the straightness. Briefly, a dual-beam Laser Doppler Displacement Meter (LDDM™) and a dual-retroreflector are used to measure the slopes at each point along the travel. The straightness is obtained by integrating the local slopes at each measuring point over the total travel. The slope or the angular change of the dual-retroreflector is equal to the difference of the two linear displacement changes divided by the separation of the 2 retroreflectors. Since both displacement and angle can be measured simultaneously, the straightness can be measured in one continuous stroke without stopping. Hence it saves time.

As shown in Fig. 1, let the actual travel path with perpendicular motion in the vertical plane be z(x), and define the reference as a straight line passing through the initial point and the end point. That is z(0) = z(L) = 0, where L is the length of the guide way. The local slope is:

$$\frac{\mathrm{dz}}{\mathrm{dx}} = \tan\theta \qquad (1)$$

Assuming the radius of curvature R is much larger than the measurement increment Δx. Tan θ is approximately equal to θ. Hence,

$$z(x) = \int_0^x \frac{dz}{dx}dx = \int_0^x \theta(x)dx \qquad (2)$$

The total number of point N is equal to L/Δx. Let x_n = nΔx, n = 0, 1,…N. then

$$z(x_n) = \sum_{i=0}^{n} \theta(x_{i-1})\Delta x + const \qquad (3)$$

Since z(0) = z(L) = O, Eqn (3) becomes

$$z(x_n) = \sum_{i=0}^{n} \theta(x_{i-1})\Delta x - \frac{n}{N}\sum_{i=0}^{N} \theta(x_{i-1})\Delta x \qquad (4)$$

Where z(x_n) is the straightness in the vertical plane, θ(x_n) is the measured pitch angle, Δx is the increment of the measurement, and N is the total number of points.

Similarly for the horizontal plane,

$$y(x_n) = \sum_{i=0}^{n} \phi(x_{i-1})\Delta x - \frac{n}{N}\sum_{i=0}^{N} \phi(x_{i-1})\Delta x \qquad (5)$$

Where y(x_n) is the straightness in the horizontal plane, ϕ(x_n) is the measured yaw angle, Δx is the increment of the measurement, and N is the total number of points.

IV. Test setup, data collection and analysis

To test the performances, the straightness of a long guide way was measured by the conventional piano wire and collimator method and the laser slope method. The piano wire method is very time consuming and require 2 persons to perform the measurement. The laser slope method is very fast and efficient. Once the laser is aligned, the data collection is on the fly in a few minutes.

First mount the LDDM dual-beam laser head at one end of the long guide way and mount the dual-retroreflector on a slide as shown in Fig. 2. Align the laser beam to be parallel to the guide way and position the dual-retroreflector such that the return laser beams enter the receiving apertures. Once the laser is aligned, start the data collection software and move the dual-retroreflector continuously along the guide way from the starting position to the ending position.

Using the LDDM Windows based software, the data collection is automatic and on the fly without stop. Hence it is very efficient and fast. After the data is collected, the result can be displayed as the slopes along the guide way or as the straightness along the guide way. The angular resolution is 0.2 arcsec and the straightness resolution is 0.001 mm.

V. Measurement results

Measurements were performed by both the laser slope method and by the piano wire and collimator method with 3 different lengths, 5 m, 10 m, and 15 m. For the 5 meter length, the measured result using the laser slop method is plotted in Fig. 3, and the measured result using the piano wire method is plotted in Fig. 4. Similarly the measured results of 10 meter length and 5 meter length are plotted in Figs. 5, 6, 7, and 8 respectively. The agreements between these two methods are very good, but the resolution of the piano method is relatively low.

VI. Summary and conclusion

The basic theory of the laser slope method has been described and its performance verified. As compare to other methods, the advantages of the laser slope method are: higher resolution, easier to setup and operation, automatic data collection, and time saving.

References

1, C.P. Wang, "Laser Doppler Displacement Meter" Lasers and Optronics, 6 (No.9), pp. 69-71, September 1987.

2, C.P. Wang, "Alignment of a Long Guide Way" Optodyne, Inc. Application Note #1102, 1998.

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Figure captions

1. Definition of straightness
2. The setup of a laser head and dual-retroreflector on a long guide way.
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4. Straightness measured by the Leiz piano wire and collimator method over 15 m. The vertical scale is in µm and the horizontal scale is in mm.
5. Straightness measured by the laser slope method over 10 m.
6. Straightness measured by the Leiz piano wire and collimator method over 10 m. The vertical scale is in µm and the horizontal scale is in mm.
7. Straightness measured by the laser slope method over 5 m.
8. Straightness measured by the Leiz piano wire and collimator method over 5 m. The vertical scale is in µm and the horizontal scale is in mm.

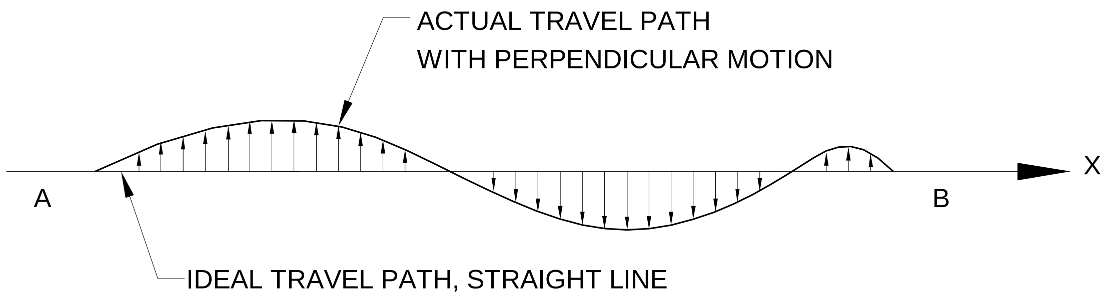

FIG 1, DEFINITION OF STRAIGHTNESS

Fig. 2, Setup of a laser head and dual-retroreflector on a long guide way.

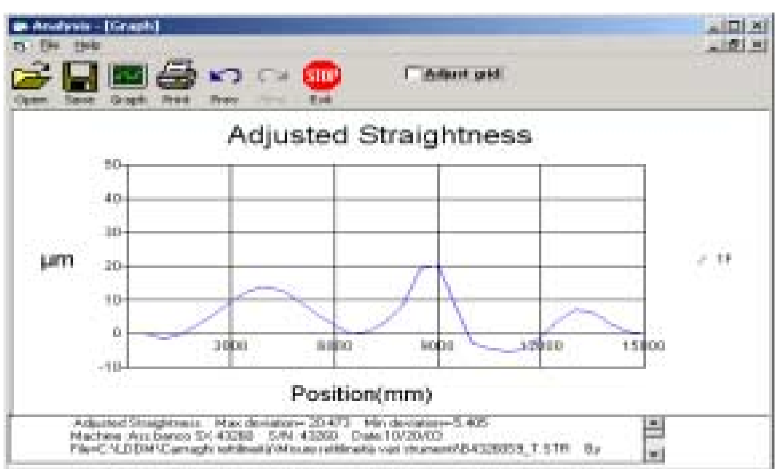

Fig. 3, Straightness measured by the laser slope method over 15 m.

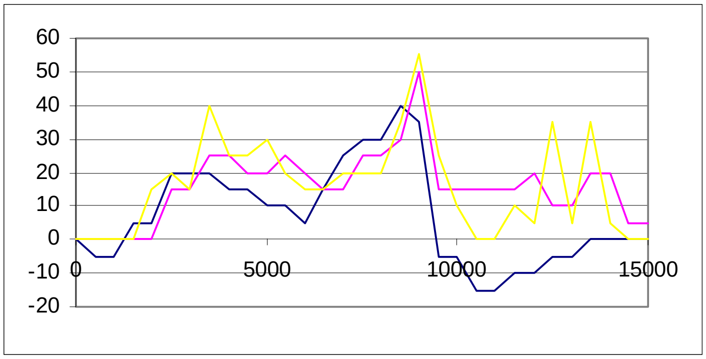

Fig. 4, Straightness measured by the Leiz piano wire and collimator method over 15 m. The vertical scale is in μm and the horizontal scale is in mm.

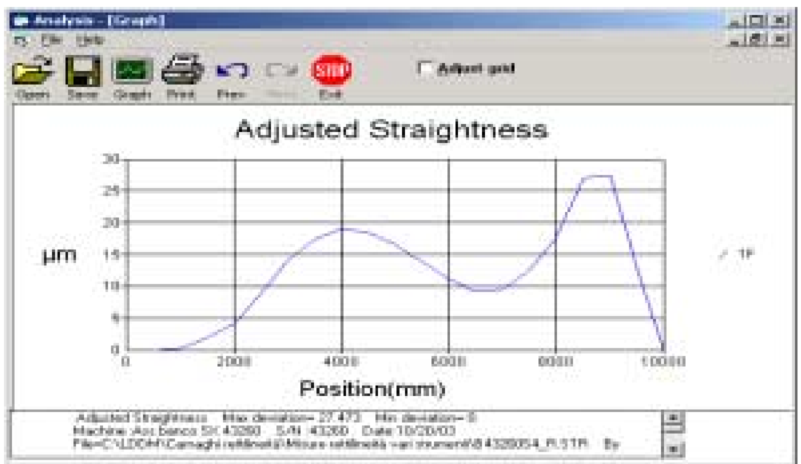

Fig. 5, Straightness measured by the laser slope method over 10 m.

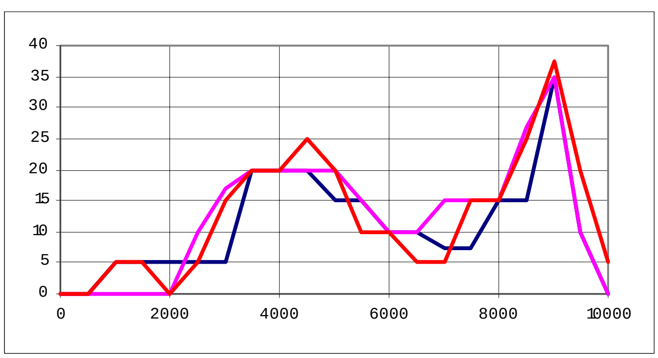

Fig. 6, Straightness measured by the Leiz piano wire and collimator method over 10 m. The vertical scale is in μm and the horizontal scale is in mm.

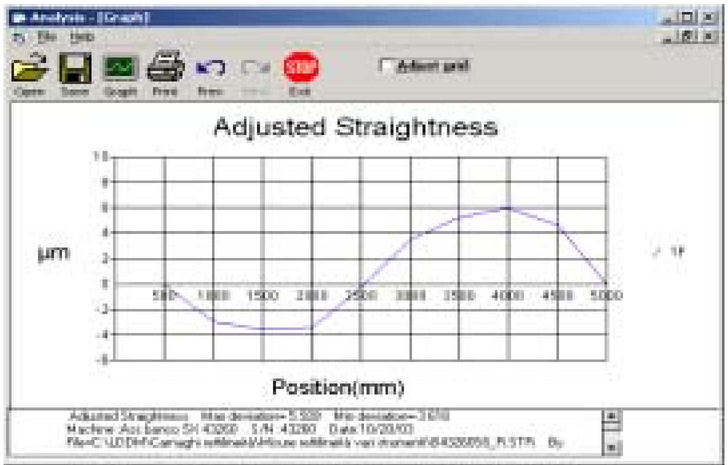

Fig. 7, Straightness measured by the laser slope method over 5 m.

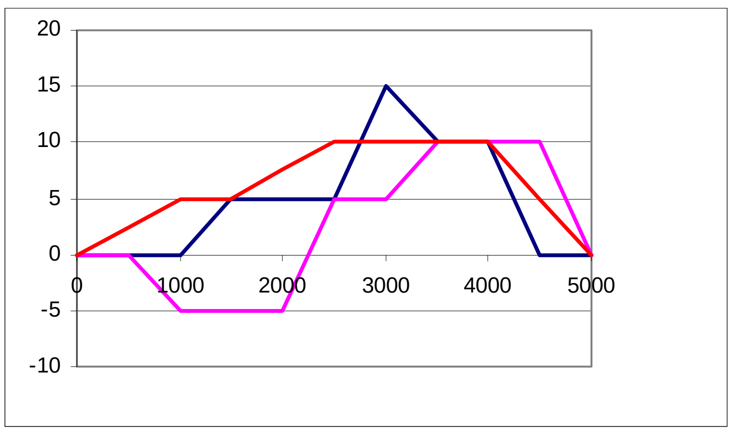

Fig. 8, Straightness measured by the Leiz piano wire and collimator method over 5 m. The vertical scale is in µm and the horizontal scale is in mm.