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Online Steel Bar Straightness Evaluation using Non-Contact Laser-Based Method

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Straightness is an important quality factor for steel bars, but the current methods for straightness inspection of bars are time-consuming and still need to be performed offline. To overcome the challenges of straightness quality inspection, in this work, a laser-based straightness evaluation system is proposed. Line-laser displacement sensors are equipped to gather the cross-sectional contours of a bar at various positions, and the relative offsets of cross-sectional centers are computed. The straightness of a bar is evaluated by the maximum offset within segments of a specific length, in *mm/m* units. To measure the segmental curvatures of entire bars, the proposed system is built on the processing line and performs dynamic measurement while a bar is moving on the conveyor. The Fourier decomposition method is used to extract the frequency components reflecting the straightness. The experiment results show that the features of bars with the straightening process cluster closely in contrast to those without straightening, demonstrating that bars with qualified straightness perform consistent mechanics of material properties. Based on the clustering models built for individual sizes of steel bars, the experiments show that over 95% bars with unqualified straightness can be successfully identified.

Keywords: Steel bar, Straightness, Laser-displacement sensor

1. INTRODUCTION

In commercial metal markets, round steel bars are important products that are widely used to produce the parts of machines, vehicle components, and aerospace carriers. To assess the quality of round steel bars, straightness is an important evaluation factor for high-quality products, because in the downstream manufacturing process, unexpected bending of steel bars may cause obstruction of the processing line and result in manufacturing disruptions.

Straightness is determined by curvature as demonstrated in Figure 1, by measuring the longest distance from the bar to the baseline formed by the two side endpoints, in units (*mm*/*m*). In many international quality standards and specifications, the straightness of steel bars has been explicitly specified. According to Japanese Industrial Standard (JIS), for instance, the maximum curvature should not be more than 30 mm in any 1m length.

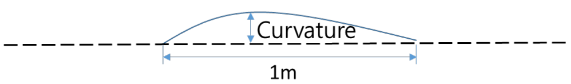

Fig.1. Straightness of a steel bar based on the curvature measured within a segment.

During the manufacturing process, the bending of round steel bars may happen at various stages, such as the rolling and cooling processes. Uneven rolling forces and poor cooling temperature control may cause non-uniform stress and consequently result in asymmetric deformation, leading to poor straightness. Therefore, bars are required to be inspected individually before they are shipped from the factory to customers to ensure quality.

In practice, feeler gauges are the most commonly used method to evaluate the straightness of steel bars. To perform the measurement, however, the round bars need to be placed on a platform with specific flatness, and the widest gap between the platform and the bar surface must be located to insert the feeler gauge and determine the straightness. The measurement process, however, is tedious and cannot be performed online, making it difficult to perform a full inspection of the steel bars produced in a lot.

Therefore, it is urgent to develop the techniques that can help the operator to evaluate the straightness directly on the processing lines to meet the requirements of quality standards and specifications. Although some automatic equipment vendors have provided solutions that can automatically inspect the straightness of rounded metal bars by means of non-contact sensor methods, only bars shorter than 2 m can be applied because the long bars may deform due to self-weight. There is still no reliable online measurement solution for measuring the straightness of the steel bars exceeding 3 m.

Therefore, in this work, we present a method for the online straightness measurement of round steel bars. In this paper, Section 2 explains the principle of non-contact laser displacement sensors and how the sensors are composed to perform curvature evaluation. Section 3 shows the online dynamic measurement, and the method to distinguish the bars of poor straightness is proposed in this section. In addition, the experiment results using bars of various dimensions are also presented. Finally, the experiment results are discussed, and a brief conclusion is made in Section 4.

2. NON-CONTACT CURVATURE MEASUREMENT

In order to improve the efficiency of measuring the straightness of steel bars on manufacturing lines, non-contact measurement methods are required. Optical-based methods are the most commonly used in non-contact sensing, and the laser displacement sensors of 10 μm precision are utilized to detect the cross-sectional shape of bars. By combining these sensors with geometric calculation techniques, the segmental curvature of steel bars can be obtained. The straightness of a steel bar can then be evaluated by the curvature data measured at different segments of the bar.

2.1 Laser Displacement Sensing

A laser displacement sensor is one of the most commonly used devices to measure distance deviation. The principle of laser displacement sensing is demonstrated in Figure 2. A laser beam is projected vertically onto a plane, and the height deviation Δz of the plane will proportionally result in the deviation of the position of the laser light focusing onto the image sensor ΔH. Therefore, by means of detecting the offset of the position where the laser spot focuses on the image sensor ΔH, Δz can be derived as shown in Equation (1).

$$k = \Delta Z \times \frac{\gamma \times sin(\alpha+\beta)}{p \times cos\beta} \quad (1)$$

$$\Delta H = p \times k \quad (2)$$

Where α and β are the tilt angles between the central axis of the image sensor, the laser beam axis, and the vertical line, respectively. In the vertical projecting case, $\beta = 0$. γ denotes the magnification factor of the camera lens system.

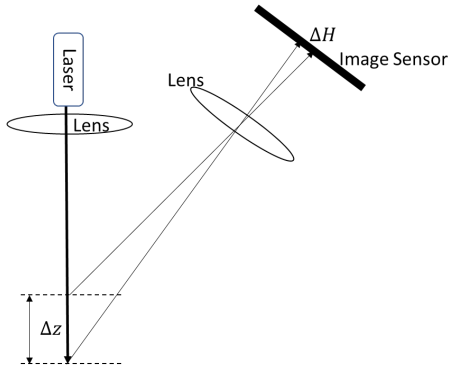

Fig.2. Optical geometry of the laser displacement measurement with the laser path vertical to the target plane.

Where p denotes the pixel size of the image sensor, and k is the number of pixels corresponding to the offset ΔH.[1]

With the progress of laser techniques, line lasers can also be adopted for displacement measurement sensors. Using line lasers with optical calibration, the height variation along the laser line can be determined continuously, so the cross-sectional shape of a bar can be depicted by projecting the laser line perpendicular to the central axis of the bar, as shown in Figure 3.

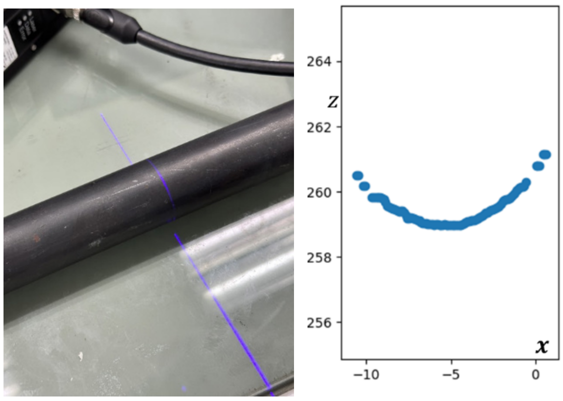

Fig.3. Measuring the cross-sectional shape of a steel bar (left), and the obtained value; the x-axis corresponds to the laser line, and z denotes the distance value (right).

2.2 Ellipse Fitting and Cross-Sectional Center Positioning

To measure the bending of a steel bar, the first step is to find the relative offsets of cross-sectional centers at different positions of the bar along the central axis. From the cross-sectional surface contours obtained by the line-laser displacement sensors, the optimal center of cross-sections can be inferred from the gathered contour data points by utilizing the geometrical properties of ellipses.

An ellipse on a two-dimensional plane can be presented by Equation (3), shown below, which contains six parameters,[2]

$$F(x,z) = ax^2 + bxz + cy^2 + dx + ez + f = \mathbb{x} \cdot \mathbb{a} \quad (3)$$

Where $\mathbb{x} = [x^2,\ xz,\ z^2,\ x,\ z,\ 1]$, $\mathbb{a} = [a,\ b,\ c,\ d,\ e, f]^T$ and (x, z) represents a measured data point such that $F(x,\ z) = 0$. When n contour data points are captured, these data are composed into an $n \times 6$ design matrix, as shown in Equation (4) [2],

$$D = \begin{pmatrix} x_1^2 & z_1^2 & \cdots & x_1 & z_1 & 1 \\ x_2^2 & z_2^2 & & x_2 & z_2 & 1 \\ \vdots & & \ddots & \vdots & & \\ x_n^2 & z_n^2 & \cdots & x_n & z_n & 1 \end{pmatrix} \quad (4)$$

Two conditional terms can then be written as Equations (5) and (6), respectively.

$$min\|D\mathbb{a}\|^2, \quad (5)$$

$$\mathbb{a}^T C\mathbb{a} = 1,, \quad (6)$$

Where C is a constraint matrix of the size 6×6. By introducing a Lagrange multiplier λ, the two conditions can be combined as the Lagrange Equation (7)

$$L = \mathbb{a}^T D^T D\mathbb{a} - \lambda(\mathbb{a}^T C\mathbb{a} - 1), \quad (7)$$

Which yields:

$$\begin{cases} (D^T D)\mathbb{a} = \lambda C\mathbb{a} \\ \mathbb{a}^T C\mathbb{a} = 1 \end{cases} \quad (8)$$

Equation (8) implies that, with the eigen-decomposition method, we can obtain up to six solutions $(\lambda_i,\ \mathbb{a}_i)$. The smallest positive eigenvalue and the corresponding eigenvector represent the best-fit ellipse parameters. Ellipse geometric properties can be computed by the derived parameters, including the center point, major and minor axes, and the inclination angle. The center point represents the shape center of the cross-section, and the major and minor axes reflect the diameter of the bar.

Because there may be a tilt angle between the laser beam direction and the normal direction, the cross-section will appear elliptical, rather than circular. In geometry, the major axis of the fitting ellipse will vary with the tilt angle, but the minor axis will remain unchanged, as demonstrated in Figure 4.

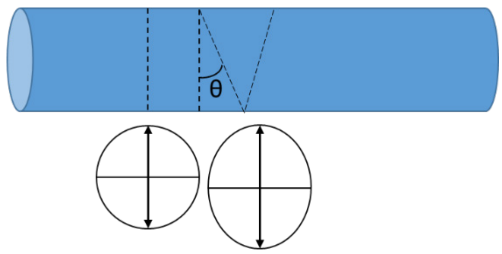

Fig.4. Tilt angle of the laser beam direction and the resulting elliptical cross-section.

2.3 Segment Curvature Estimation

A perfectly straight steel bar would have all of its cross-sectional center points lying on a single straight line. In other words, to evaluate the curvature of a bar, the relative displacement of the cross-sectional center points against the reference straight line can be used. Mathematically, by measuring more than three cross-sectional center points within a segment of a bar, the curvature of the segment can be computed. An equipment vendor, LAP, provides a straightness check equipment, utilizing three cross-sectional center points to measure the distance of the center point between the straight line established from the two end points in units of mm/m[3]. Although it is simple and efficient, if the largest offset, however, does not occur at the position where the center measuring point is located, the curvature will be underestimated. Clearly, using more cross-sectional center points can yield curvature with higher accuracy. In addition, because the deformation of metal material is often continuously curved, the bending can be approximated by fitting the cross-sectional center points into a continuous polynomial curve.

In this work, therefore, we propose a method utilizing four laser displacement sensors installed within a fixed length segment L. With four cross-sectional shape center points (x_i, y_i, z_i), $i = 1$–4, captured synchronically each time, the two endpoints build the base straight line, and all four points are used to fit a polynomial curve, as demonstrated in Figure 5.

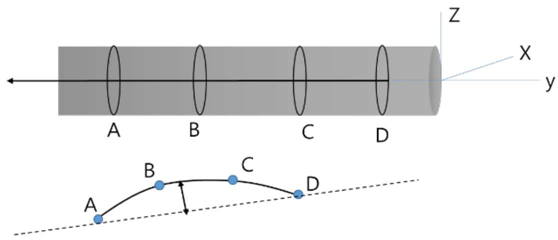

Fig.5. Schematic diagram of the segmental curvature measurement system architecture composed of four laser displacement sensors.

Because y_i, the positions where the laser sensors are installed along the bar axial axis, are already known, the points (x_i, y_i, z_i) can be decomposed into (y_i, x_i) and (y_i, z_i) lying on the y–x plane and y–z plane, respectively, as shown in Figure 6. The four points are fitted into two curves on both planes, represented by the following two-variable Equations (9) and (10).

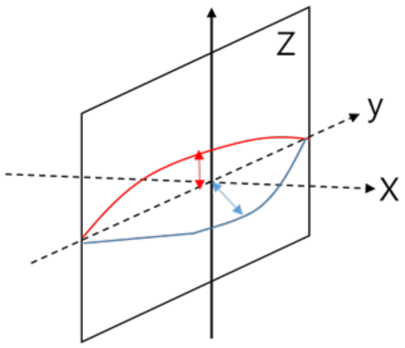

Fig.6. Curves fitted by cross-sectional center points at the y–x and y–z planes.

$$z = a_1 y^2 + b_1 y + c_1 \quad (9)$$

$$x = a_2 y^2 + b_2 y + c_2 \quad (10)$$

All the cross-sectional center points (y_i, x_i) can be expressed in matrix form, and Equation (9) becomes Equation (11).

$$\begin{bmatrix} y_1 & y_1^2 & 1 \\ y_2 & y_2^2 & 1 \\ y_3 & y_3^2 & 1 \\ y_4 & y_4^2 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{a_1} \\ \boldsymbol{b_1} \\ \boldsymbol{c_1} \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = Z \quad (11)$$

Let c_1 equal 0, then, a_1 and b_1 can be determined by solving the linear algebra equation. The same procedure applies to the cross-sectional center points (y_i, z_i), yielding a_2 and b_2 in equation (10). After these polynomial coefficients are obtained, the local maximum values of the curves, x_{center} and z_{center}, corresponding to the center of the segment on the y-axis at both planes can be derived, as shown in Figure 7.

Then the overall offset d representing the largest distance from the baseline can be computed by

$$\sqrt{(\boldsymbol{x_{center}^2} + \boldsymbol{z_{center}^2})}.$$

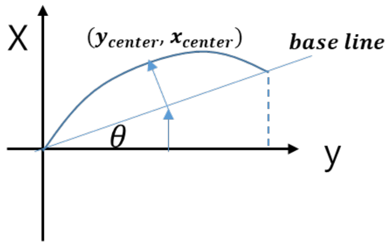

Fig. 7. The fitted curve at the y–x plane and the local extrema at (x_{center}, y_{center}).

2.4 Static Curvature Measurement

Figure 8 demonstrates the curvature measurement system built online, with four line-laser displacement sensors assembled within a fixed 1-meter-long segment. The bar on the conveyor roller is the calibration bar, with strict straightness less than 3 μm/1.2 m, and the system is calibrated by setting the four original measured cross-sectional centers of the calibration bar as reference zero points.

The static measurement result of a bar with straightness less than 2 mm/m is shown below, and the curvature measured by the proposed system is about 1.5 mm/m. In addition to the natural noise ranging within about ±0.01 mm, the vibration coming from the factory environment also increased the measurement value by about 0.03 mm. Based on experiments on 200 bars with diameters of 10 mm, 16 mm, and 21 mm, curvatures exceeding 2 mm/m can be reliably detected.

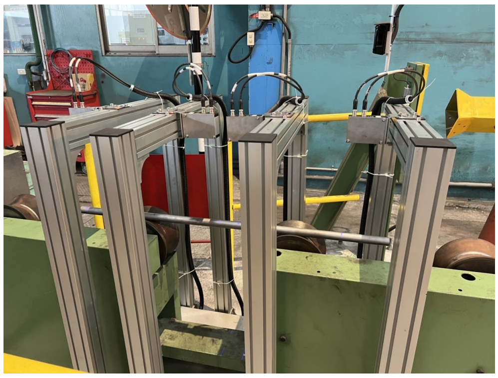

Fig.8. Segmental curvature measurement system constructed on the roller conveyor with the calibration bar.

3. DYNAMIC MEASUREMENT ANALYSIS

To meet the requirements for online evaluation of straightness, dynamic measurement is necessary. For bars longer than 6 meters, static measurement is impractical in an online setting, so bars need to be measured segment by segment. To implement straightness quality control online, both self-weight deformation and dynamic strain of the bar moving on the conveyor rollers affect curvature. Analyzing the continuously measured curvature data is a crucial step in recognizing bars with qualified straightness.

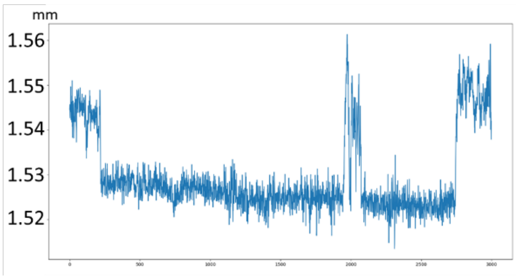

Fig.9. Static curvature measurement result of a bar.

3.1 Dynamic Segmental Curvature Measurement

Figure 10 plots the continuous segmental curvature values of a bar with qualified straightness (<3 mm/m) being dynamically measured by the proposed system online, and Figure 11 demonstrates the result of a bar of poor straightness. Both signals show obvious periodic waveforms coming from the support structure changing while the bars are moving. This occurs because self-weight produces a uniformly distributed force, and bars naturally deform on the conveyor at the support positions.

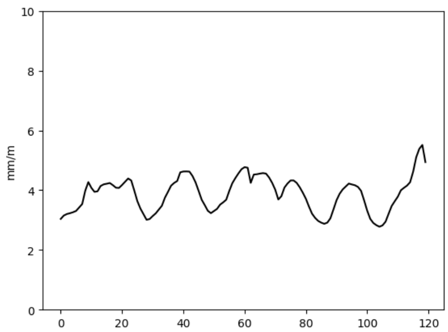

Fig.10. Dynamic segmental curvature measurement of a round bar of satisfactory straightness.

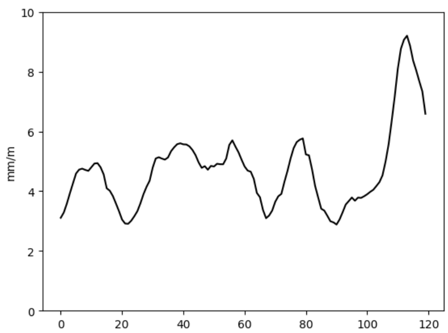

Fig.11. Dynamic segmental curvature measurement of a round bar of poor straightness.

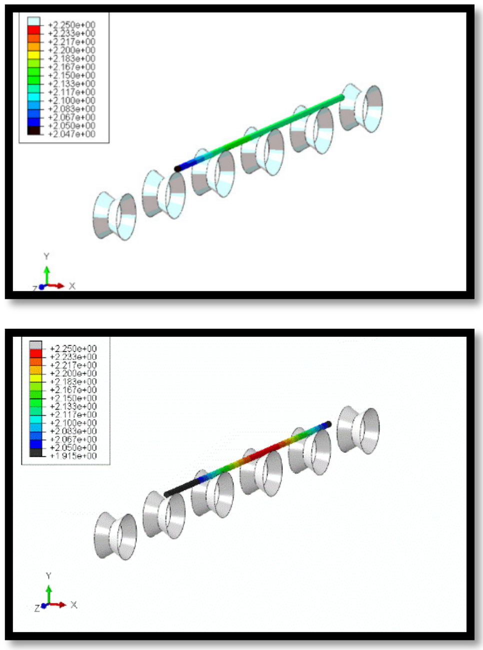

Fig.12. Segmental displacement of the round bar on the roller conveyor.

The dynamic mechanical influences mentioned above lead to an additive effect on curvature values during dynamic measurements of steel bars. Based on the simulation results, the displacement may be up to 2.25 mm when a 3-meter-long bar with ideal straightness is moved on the roller conveyor. According to the mechanics of materials theorem, the deformation of a steel bar moving on the conveyor depends not only on the material properties but also on the structural mechanism of the conveyor rollers, which influences the displacement of each bar segment.

3.2 Dynamic Signal Analysis

To extract characteristics that sufficiently reflect the straightness of a bar from the dynamically measured signal, the background effects must be removed from the raw signal data. However, because the background factors are complex, it is difficult to accurately obtain the true curvature values directly from the measured signal.

In this work, the Functional Data Analysis (FDA) method is proposed to extract straightness features of steel bars from the continuous numerical signals. By projecting signals onto orthogonal bases through integral calculations, a signal is transformed into a set of coefficients corresponding to each basis function. The coefficients reveal the properties of the signals depending on the chosen basis.

Due to the periodicity of the straightness measurement signals, the Fourier basis is applied in this work to remove the signal components caused by periodically changing mechanical states. The low-frequency components of the signal, which are closer to the true straightness of the bars, can thus be extracted.

The Fourier basis is composed of cosine and sine functions. A signal $s_N(x)$ can be expressed as Equation (12)[5]

$$s_N(x) = a_0 + \sum_{n=1}^{N} \left(a_n \cos\left(2\pi \frac{n}{P} x\right) + b_n \sin\left(2\pi \frac{n}{P} x\right)\right) \quad \text{.......... (12)}$$

Where a_n, b_n are the coefficients corresponding to each trigonometric basis function. n is the number of cycles within a signal interval P.

The coefficients are computed by the following terms (13), (14), (15).

$$a_0 = \int_P s(x)\,dx, \quad \text{.......... (13)}$$

$$a_n = \int_P s(x) \cos\left(2\pi \tfrac{n}{P} x\right) dx, \quad \text{.......... (14)}$$

$$b_n = \int_P s(x) \sin\left(2\pi \tfrac{n}{P} x\right) dx. \quad \text{.......... (15)}$$

Here, a_0 obviously is the direct current (DC) offset of the signal, representing the average volume of the signal. A_n, b_n, $n=1$–N, are the coefficients corresponding to various frequency components.

To determine the straightness quality of a bar, only the coefficients for $n<3$ are considered, as shown in Figure 13. In other words, the signal feature can be described with the coefficients a_0, a_1, b_1, a_2, and b_2. Furthermore, only the magnitudes of the selected frequency components are considered, so the feature is expressed

as $[a_0, \sqrt{a_1^2 + b_1^2}, \sqrt{a_2^2 + b_2^2}]$.

With the proposed dynamic measurement method, and by comparing the signal features of 50 steel bars without a straightening process and 30 straightened bars (diameter = 32 mm), the feature points of the straightened bars cluster more closely, and the direct current component is significantly lower than that of the unstraightened bars, as shown in Figure 14. Furthermore, the 1st and 2nd order frequency components of the straightened bars are also much more consistent than those of the unstraightened bars.

This demonstrates that the dynamic responses obtained from the proposed measuring system can accurately reflect the straightness condition of bars. Although

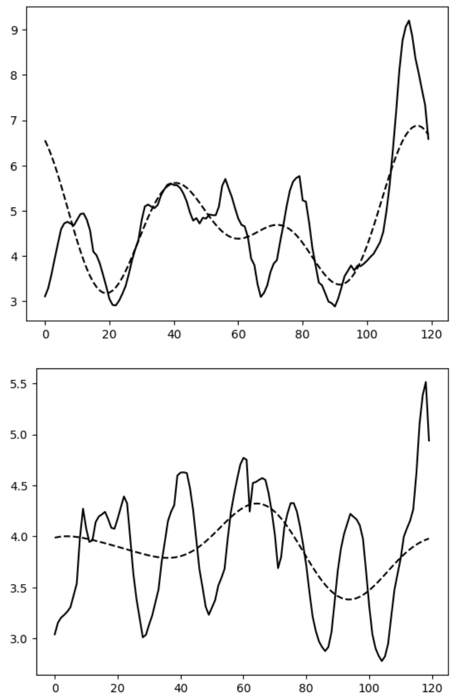

Fig.13. Dynamically measured segmental curvature of a bar with qualified straightness (left) and a bar with straightness out of tolerance (right). Dotted lines indicate the extracted low-frequency components.

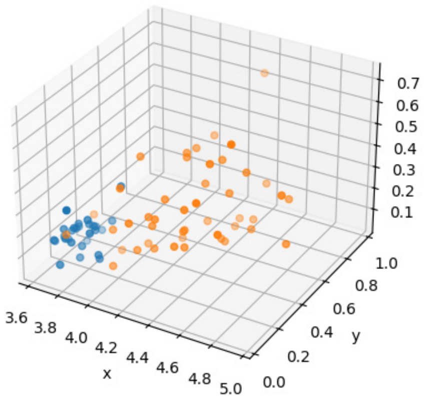

Fig.14. Dynamic straightness features of 32 mm diameter bars with (blue) and without (orange) straightening process.

the background effects come from the self-weight deformation of the materials and the conveyor structure mechanics, the experiment results show that bars with qualified straightness demonstrate consistent features in the measurement signals. Therefore, statistical outlier features can be regarded as risky products with high confidence.

According to the historical data, about 2% of straightened bars are still unqualified. By the multivariate z-test method with a statistical model built from mass-produced bars (such as straightened bars shown in Figure 14), these risky bars can be effectively recognized.

4. DISCUSSION AND CONCLUSION

4.1 Experiment Results and Discussion

Figure 15, shows the straightness features of three lots of bars of different diameters, 26 mm, 32 mm, and 40 mm, without a straightening process, and the features can be seen gathering into three distinct groups. Therefore, models for different diameters of bars are established individually, and the threshold to recognize the outliers can also be assigned independently, depending on the material properties. From the experiment results of 200 bars with three diameter sizes (26 mm, 32 mm, and 40 mm), 95% of the bars with unqualified straightness were successfully identified.

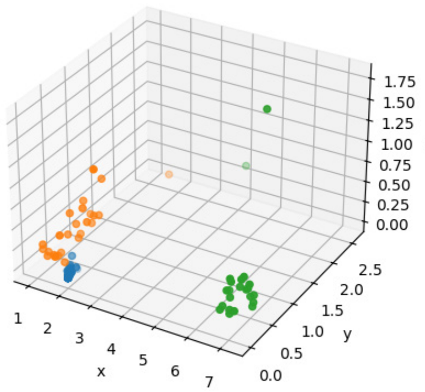

Fig.15. Dynamic straightness measurement features of bars with diameters of 26 mm (blue), 32 mm (orange), and 40 mm (green).

The result indicates that the self-weight corresponding to the diameters of the bars is the main factor affecting the response signal features, resulting in the background offset values. In conclusion, the bars with qualified straightness exhibit uniform mechanical properties, while the underqualified bars are bent irregularly. The proposed system is proven useful for mass-produced steel bars, as bars from the same lot of bars are expected to exhibit consistent material properties. The bars in the experiments with poor straightness but not identified were mainly characterized by large-scale bending. The proposed system is mainly used for segmental curvature measurement, detecting large-scale bending would require more sensors to extend the measurement range.

4.2 Conclusion and Future Works

In this work, we proposed a non-contact measurement system that can evaluate the straightness of bars online, under the combined effects of material deformation due to self-weight and supporting structure mechanics. This work integrated the optical techniques, geometry computation techniques, and functional data analysis, which play an important role in extracting the dominant features reflecting the straightness of a bar.

In the future, models for all diameter sizes of bars need to be developed, not only to identify bars with poor straightness, but also to avoid unnecessary straightening processes. The measurement process is important to meet the requirements of high-quality specifications, so guaranteeing the minimum straightness based on the dynamic measurement results is another important task.

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