Laser Displacement Sensor in the Application of Aero-Engine Blade Measurement

Bin Sun and Bing Li

Abstract—This paper proposes a novel error-compensation model that can effectively reduce the impact of the incident angle error of a laser displacement sensor (LDS) that measures accuracy. The laser triangulation method is an effective method of measurement. It is characterized by non-contact, large measuring range and high measuring efficiency. However, the measurement accuracy is affected by the incidence angle. To improve the measurement accuracy, a practical measurement strategy is presented. The experiment was carried out using a standard hard alloy ball calibration LDS. By introducing the error model, the experimental data were improved. Finally, in the application of an aero-engine blade measurement, the crossed curves method was used to calculate incidence angle of the measuring point. By comparing the LDS with a high-precision coordinate measuring machine (CMM) in experiments, the LDS accuracy is significantly improved. The results show that the laser measuring system has the thinner structure and higher efficiency than the CMM, so this paper is worth promoting.

Index Terms—Laser displacement sensor, free-form surface, error compensation, non-contact measurement, aero-engine blade.

I. INTRODUCTION

At present, the non-contact and optoelectronic methods play an important role in machine vision, auto industries, die/mould manufacturing, reverse engineering and other industrial applications [1]–[3]. Laser Displacement Sensor (LDS) is based on the triangulation measurement principle that is a precise, non-contact and one-dimensional laser displacement measuring system. Due to its numerous advantages, such as good stability, large measurement range, high accuracy and high speed, LDS has become widely available in the domain of dimensional measurement of parts [4], product quality inspection [5], [6], three-dimensional shape measurement [7], [8] and so on. A pointed LDS is quite suitable for digitizing a freeform surface because of its small light spot and effortless data processing. It is characterized by non-contact and rapid measurements; especially in the case of a large-scale and non-uniform surface. Some traditional measuring systems, such as the well-known coordinate measuring machine (CMM), often fail for some large-scale and free form surfaces [9]. However, the geometrical and optical conditions of the measurement, such as the surface quality, surface color, measurement distance and surface orientation, are likely to have a significant impact on the measurement accuracy of the LDS. The measurement errors caused by the influential factors mentioned above have been widely investigated in the laboratory [10]–[13]. Some optimization methods can reduce the degree of the measurement errors of the model; however, many methods are used only to quantify analysis in theory. Thereby, research of a more precise and comprehensive measurement model of the LDS and of an appropriate calibration technique would have a significant impact on improving the accuracy of the LDS and expanding its application in engineering.

In this paper the main goals are as follows: (1) The traditional triangulation measurement model of the LDS is described, then, a quantifiable error-compensation model based on geometrical optics that accounts for the effect of the incident angle is presented. (2) The LDS calibration experiment is done using a standard hard alloy ball on a four-coordinate measuring system. (3) The experimental results of the aero-engine blade surface measurement model and compensation will prove its effectiveness and reliability.

II. INCLINATION ERROR MODEL OF LDS

A. The Factors Affecting the Measurement Precision of a LDS

The main factors affecting the measurement precision of a LDS are the error in depth of measurement field, inclination error, surface color, surface roughness, etc. The surface roughness, which influences the shape and intensity of distribution of scattered light will affect the measurement results. Jianfeng et al. [14], Kaichen and Guoxiong [15] and other scholars have carried out further research on the surface roughness of different materials. The research found that the parameters of LDS can be optimized by choosing the appropriate incident angle of the beam. If the surface roughness measured is in the range of 0.4~3μm, it has little effect on the measurement precision of the sensor, and no compensation is needed. Because the surface colors absorb the light from the semiconductor laser in the sensor differently at various stages, the surface color difference can also cause the difference in measurement results. Zexiao et al. [16] and Wang et al. [17] and other scholars have studied the different surface colors of the measured object. The studies show that the influence of

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red is minimal, and black is maximum when dealing with lasers in red wavelength area. So, the red or orange surface is recommended as the measured surface when using LDS to measure the displacement of an object. The inclination error is the most influential factors to the measurement precision of a LDS, studied by Vukašinović et al. [18] and Wang et al. [19] and other scholars. They carried out some experiments and got some results. But, these are all qualitative analyses with some reference value. However, in order to efficiently compensate the inclination error in engineering applications, it is necessary to study and establish the quantitative model of inclination error.

B. Laser Triangulation Principle

The LDS is a designed precision optical instrument based on the principle of laser triangulation. It can transform displacement information of optical signals into electrical signals by laser triangulation method, which measures the triangle formed by the incident beam and the reflected laser beam. The measurement principle is described as follows: The laser transmitter axis, the optical axis of the lens acceptance and the Charge-Coupled Device (CCD) linear array are all in the same plane; the Laser emits a beam of parallel light, focusing on the object surface by the condenser lens; then, the laser beam is received by an imaging lens at another angle due to the diffuse reflection and a spot is formed on the sensitive surface of the CCD linear array sensor of the LDS; if the position of the laser point changes because of the displacement of the changing measured object, the position of the spot on the CCD linear array sensor of the LDS changes as well; the position of the laser point \( x \) on the surface of the measured object can be calculated according to the position of the spot \( x' \).

Fig. 1 shows a typical direct laser triangulation schematic; an optical system consists of a laser transmitter, convergent lens, receiving lens, the CCD linear array sensor and subsequent signal processing circuit, etc. The trigonometric sine theorem is shown below:

\[
\begin{align*}
x &= \frac{Lx' \sin \phi}{L' \sin \beta - x' \sin (\phi + \beta)}
\end{align*}
\]

In the above formula, \( x \) is the movement distance of the object and \( x' \) is the movement distance of corresponding image point; \( \omega \) is the angle between the two beams of reflection; \( \beta \) is the angle between the normal vector of the measurement surface and the axis of the receiving lens; \( \varphi \) is the angle between the surface of the photosensitive CCD receiving lens axis; \( L \) is the object distance of receiving lens, which is the distance between point A and receiver lens; \( L' \) is the image distance of receiving lens, which is the distance between receiver lens and the center of the imaging surface, as all should be seen in Fig. 1.

The parameter of the LDS design is based on the incident light being perpendicular to the surface. Once the incident light is inclined, it will produce an inclination error. This is because as the inclination of light scattering from the lens changes the spatial distribution of the reception, the position of the converged spot on the CCD light centroid is changed. If Eq.(1) is still used to calculate the amount of displacement, it will produce errors. This is the root cause when the object plane is inclined to produce a measurement error. Research shows that compensating the inclination angle error of the LDS can effectively improve the accuracy of the measurement surface.

To analyze the quantitative variation of the incident angle error, the relationship between the inclination angle and the convergence spot centroid position need to be inferred on CCD of the object surface. When the incident light beam does not coincide with the direction normal to the surface of the measured object light spot, considering that the object plane has tilted, the inclination angle is \( \alpha \) and \( \alpha \) is the angle between the normal vector and the incident beam, as shown in Figure 2.

The quantitative variation of the incident angle (or inclination angle) error is analyzed according to the relevant literature. By optical imaging principle shown in Fig. 2,
we can get quantitative model inclination error, which can be expressed as [9]:

$$E_\alpha = \frac{R^2 L'^2 x \cos \beta}{L^3} \left( 1 + 2 \frac{x}{L} \cos \beta \right) \left[ \tan \beta - \tan (\beta - \alpha) \right]$$  \hspace{1cm} (2)

In the equation above, the only two input variables are the incident angle $\alpha$ and displacement $x$ of the object. $\beta$, $L$ and $L'$ are design parameters of the LDS, and $R$ is the effective radius of the lens. These analysis lead to the following three conclusions:

1. When the object surface inclination $\alpha$ is constant, the measurement error $E_\alpha$ increases with increasing depth of field measurements;
2. When the displacement $x$ of the object is constant, the measurement error $E_\alpha$ increases with increasing body surface angle;
3. When $\alpha > 0$, direction of the error is the same with the direction of displacement;
4. When $\alpha < 0$, direction of the error is opposite to the direction of displacement.

In the model above, the only two input variables are the incident angle $\alpha$ and the displacement of the object. It provides a good prediction of the error tendency and allows a reasonable level of error compensation. In spite of certain assumptions mentioned above, from the perspective of engineering application, the quantitative models can improve the precision of measurement. Thence, it has a good sense of value and promotion.

III. ERROR EXPERIMENT FOR INCIDENT ANGLE

A. Laser Displacement Sensor and Coordinate Measuring System

The employed LDS, shown in Fig. 3(a) consists of a HML, a controller and a HL-C211BE LDS (Measuring range $\pm 15$mm, Linearity $\pm 0.03\%$ F.S., and Resolution $0.25\mu$m), which are all produced by Panasonic. The LDS uses a red semiconductor laser (658nm) as the light source. Its integrated circuit chip is a patented technology system. The LDS can obtain a high-density light receiving element and close to the limit of the processing speed, so that it can achieve a higher speed and resolution. The LDS’s controller has many functions. Compensation and parameters such as measurement methods, the color of objects, materials and roughness in the LDS have been optimized. When used according to the measured object characteristics through the operation of a panel dialogue menu, setting the appropriate parameters would reduce the error in order to improve the accuracy of detection of complex surfaces. In this paper, some experiments that were not performed by the manufacturer were made to compensate for inclination angle error.

Experiments were carried out on the blade surface measuring instrument, as shown in Fig. 3(b). The four-coordinate measuring body includes three vertical X-axis, Y-axis, Z-axis and a rotary platform. Each axis is operated by the servo motor control and movement along the Precision Ball Track. The precision of the movement encoder system is 0.001 mm by positioning a Renishaw Grating Ruler, which provides high movement accuracy. The LDS mounted on the X-axis, detects the blade profile when placed on the rotary platform.

B. LDS Status Adjustment

As shown in Fig. 4, it is necessary to carry out the calibration of the LDS beam to guarantee the accuracy. It only needs to ensure the direction of the beam and the axis in alignment to satisfy the Abel principle because the condition of X-axis, Y-axis, Z-axis has been determined by the mechanical structure. To display the location of the beam, the high precision CCD of scA780-54gm (Basler’s product, Germany) is selected. The calibration principle of the horizontal beam is the same as that of the vertical beam, the principle of which is shown in Fig. 4(b). Move the location of the LDS along the Y-axis and record the spots of CCD when it stands in the two endpoints. As showed in Fig. 4(c) and (d), the coordinates of the light beam are obtained by using the MATLAB to process the CCD images. The LDS fixture is slightly adjusted to refer to the departure position to make sure the location of the light spot does not move. Finally the direction of the beam and the measuring direction of the LDS are the same through repeatedly calibration.

C. Error Experiment for Incident Angle

To analyze the effects of the incident angle on the measuring precision. In the case of free-form surface measurement,
Fig. 4. LDS attitude adjustment. (a) CCD acquisition display. (b) Beam horizontal alignment. (c) The first light spot centroid coordinates. (d) The second light spot centroid coordinates;

A standard hard alloy ball was made by Taylor Hobson. Its main parameters are: diameter = 22.4965mm, form error < 0.003mm. The ball was used as a reference artifact to characterize the geometric properties of a free-form surface. The experimental set-up is shown in Fig. 5(a). Various points on the standard ball were measured to acquire various incident angles.

\[ \alpha = \sin^{-1} \left( \frac{CD}{CO} \right) = \sin^{-1} \left( \frac{AB}{RS} \right) \]  

According to the illustrated triangular relationship in Fig. 5(b), the error can be obtained by the following:

\[ E_r = BC - BC_L \]
\[ = DE + AE - BC_L \]
\[ = OE - OD + AE_L - BC_L \]
\[ = RS - \sqrt{RS^2 - (AB)^2} + AE_L - BC_L \]
\[ = RS - \sqrt{RS^2 - (AB)^2} - (BC_L - AE_L) \]  

The incident angle \( \alpha \) can be calculated using the Pythagorean theorem.

Before the start of the experiment, LDS scans standard ball along the X-axis and find out the highest point X1 in the X-axis. Next LDS scan along the Z-axis at X1 point, so the
peak E (as shown in Fig. 5(a)) must be on the scanning path. The distance AE represents the scan depth of LDS. When AE is taken for different values, LDS scans the standard ball along the Z-axis. The experimental data is collected and can be compensated by the quantifiable error model in Section 2. MATLAB processes and visually displays data in a two-dimensional pattern shown in Fig. 6. Influence of different scan depth on the measurement errors of LDS are shown in Fig. 6(a). In (b), (c) and (d), the red asterisk-dot curve represents the raw value error. The blue round-dot curve with circles is the compensated value error. It is clear that the error of the measurement data is effectively corrected, with error value within 10μm (−16° ~ 6° of incident angle). Accuracy has been improved significantly.

IV. THE BLADE SURFACE MEASUREMENT APPLICATIONS

A. The Incident Angle Calculation Method of the Blade

Before measuring the vane type blade, the inclination calculation method needs to be known. It is necessary to research the method to calculate the normal vector of the free surfaces measurement points. In this section, an improved cross-curve method [20], [21] based on five data points is developed to calculate the unit normal vector. As shown in Fig. 7, the LDS scans along two crossed curves at equal step size. One curve is longitudinal and the other is latitudinal. They intersect at the measurement point. One curve is longitudinal and the other is latitudinal. They intersect at the measurement point \(P_1(x_1, y_1)\). Four points \(P_0(x_0, y_0)\), \(P_1(x_1, y_1)\), \(P_2(x_2, y_2)\), \(P_3(x_3, y_3)\), \(P_4(x_4, y_4)\) on the two curves are chosen: Two on the latitudinal curve and the others on the longitudinal curve. \(P_u\) and \(P_v\) are tangent vectors, and \(n\) is the normal vector of \(P_1\). In addition, the five points are arranged such that one central point is surrounded by four peripheral points approximately 90 degrees apart.

A quadratic Bezier curve (degree 2/order 3) that passes through the three points \(P_0\), \(P_1\) and \(P_2\) can be expressed as [22]:

\[
P(u) = (1 - u)^2 B_0 + 2u(1 - u) B_1 + u^2 B_2 \quad (5)
\]

Where, \(B_0\), \(B_1\) and \(B_2\) are the control points, which are derived as \(B_0 = P_0\), \(B_1 = P_1\), \(B_2 = P_2\) and \(u = u_1\).

\[
B_1 = \frac{-(1 - u_1)^2 P_0 + P_1 - u_1^2 P_2}{2u_1 (1 - u_1)} \quad (6)
\]

For point \(P_1\), tangent vector \(P_u\) can be expressed as:

\[
P_u = P' = -2(1 - u_1) P_0 + 2(1 - 2u_1)\]

\[
\times \frac{-(1 - u_1)^2 P_0 + P_1 - u_1^2 P_2}{2u_1(1 - u_1)} + 2u_1 P_2 \quad (7)
\]

Where, the curve through three points \(P_0(x_0, y_0)\), \(P_1(x_1, y_1)\) and \(P_2(x_2, y_2)\), the parameter \(u_1\) can be expressed as the formula (8), shown at the bottom of the next page.

Similarly, the other tangent vector \(P_v\) at the central point of another curve can also be calculated as \(P_v = P'(v_1)\). Hence, the unit normal vector \(n\) at the central point \(P_1(x_1, y_1)\) is:

\[
n = \frac{P_u \times P_v}{|P_u \times P_v|} \quad (9)
\]

Fig. 6. Different depth of field inclination angle errors and compensation graph: (a) influence of different scan depth on the measurement errors; (b) error compensation curve of 0mm; (c) error compensation curve of 4mm; and (d) error compensation curve of 8mm.

Because blade surfaces are non-uniform, there must be some inclination in measuring the LDS measuring point and the incident beam. Only when the proper angle of the measuring point method for normal vector and the incident beam is found can
the achieved data be accurately compensated. Measurement errors caused by the inclination angle are eliminated, so the blade surface accuracy is improved. In order for the algorithm to be implemented in engineering applications, blades should be mounted upright in the four coordinate system combining features of blade surface structure. As shown in Fig. 7 the axial direction of blade profile should be kept parallel with Z-axis to coordinate measuring system approximately. The cross section direction of blade profile should be kept parallel with Z-axis to measure the constraint conditions. After the end of the data collection, inclination measurement points are calculated. The measuring point error can be calculated using inclination error quantitative model. Finally, after correcting the measured data, the actual measured value of the measuring point can be obtained.

\[ P_c = P_o - E_A \] (11)

Equation (8) and equation (10) are very important for calculating the angle of the measuring points, thus causing the error-compensation model to be realized in engineering applications.

B. Experiment and Data Comparison

According to the characteristics of non-contact measurement, this paper presents a rapid method for establishing the blade measurement path planning which is suitable for engineering applications. In the two-dimensional plane of the blade features section, it will not consider inclination error first. The contour of one side is scanned by equal intervals to measure the constraint conditions. After the end of the data collection, inclination measurement points are calculated. The measuring point error can be calculated using inclination error quantitative model. Finally, after correcting the measured data, the actual measured value of the measuring point can be obtained. Similarly, the blade is rotated at 180° to acquire data along another edge. The blade section profile curve can be obtained after the data correction, as can be seen from Fig. 9 and the measurement data processing are shown in TABLE I.

In order to verify the reliability of the measurement results, the blade data was measured by the high-precision Coordinate Measuring Machine (CMM). This CMM comes from AEH (Xi’an, China). Its measuring system uses a Renishaw automatic indexing probe head with overall measurement accuracy ≤3μm. The data measured of the same cross-section of the blade with CMM and LDS is required to verify the correctness of the method. Before the measurement, a unified coordinate system is established for the blade to compare the test data because the blade surface is a complex surface, and parallel to Z-axis, then \( P_y(x, y) = 0 \). The inclination of the measuring point \( P_1 \) only has a relationship with the tangent vector \( P_y(x, y) \), so inclination \( \alpha \) can be expressed as:

\[
\alpha = \tan^{-1} \left( \frac{P_y}{\sqrt{(P_{x1})^2 + (P_{y1})^2}} \right) \\
= \tan^{-1} \left( \frac{\sqrt{(x_1-x_0)^2 + (y_1-y_0)^2}}{\sqrt{(x_1-x_0)^2 + (y_1-y_0)^2} + \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2}} \right) 
\] (10)
the coordinate values are also a complex issue. As shown in Fig. 10, according to the characteristics of the blade fixture, the three surfaces of the outermost of the standard gauge block are regarded as three coordinates of the reference plane to establish the coordinate system. The edge of the blade end is very thin with thickness of less than 40 μm. Due to the restrictions of the structural features, CMM and LDS cannot achieve accurate detection of blade edges. Therefore only the area within 1mm from the edge can be measure, and in this region, CMM and LDS are uniformly sampled along each edge by 40 data points.

By using CMM to measure blade, there are still many issues to be further discussed due to the complexity of establishing spatial coordinates and surface measurements. In this study, the use of standard gauge block on the blade fixture simplifies coordinate model, making the data comparison of CMM and LDS possible. When measuring the same amount of data, LDS takes about half the time of CMM. Although there are still some problems such as poor graphical display, it still has certain reference value as a way to study.

Finally, when a graph is plotted by MATLAB from the measurement data, and zoomed in the windows as shown in Fig. 11, it can be seen that the curve compensated is close to CMM.

V. Conclusion

The blade is one of the most critical parts of aero-engine. Because of its complex surface and difficult process, its surface quality plays a decisive influence on the performance of the aero-engine. This paper presents a method for rapid detection of the aviation blade surface, which enables quick and accurate collection of the blade surface measurement.

First, inclination error of the LDS is analyzed in the paper. From the principle of laser triangulation measurement, the geometry of the laser light path system is carried out by detailed analysis and research. According to the mechanism in view of the inclination error, a quantified mathematical model is deduced. By using a special blade fixture and standard gauge block, a quick measurement path was planned out. After correcting the raw data with the inclination error model,
the measurement precision of the laser displacement sensor is less than 10μm between −16° and 16° of the incident angle. Finally, by the experiment of comparing the LDS with a High-precision CMM, the LDS accuracy is significantly improved; measurement results have been significantly improved and enhanced.

The experimental results show that, this paper presents a new error compensation strategy. It does not only improve the measurement accuracy of the LDS, but can also greatly improve the efficiency of the blade surface detection. There is application value whether in protecting the quality of the blade in production, or in controlling the quality of the blade during repairing service.

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