RECENT DEVELOPMENT FOR SURFACE DISTORTION MEASUREMENT

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Abstract: Small distortions on the surface of sheet metal stamping parts may have significant impact on the optical appearance of the final product after finish treatment. Recently, there are considerable research activities in the development of optical methods for surface distortion measurement because of the full-field and nondestructive nature of these methods. Optical methods such as Lights and Mirrors, Defracto, 3D-Digitazition for contour measurement, 3D-Digitazition for surface distortion measurement etc. are emerging as strong candidates for industrial inspections of surface distortion. Because each technique has always its unique advantages and disadvantage for different applications, the selection of one technique depends on the particular objective as well as limitations of each technique. This paper will give a through review of the above optical methods for surface distortion measurement. In particular, the recent development "3D-Digitazition for surface distortion measurement" will be discussed in details. The fundamental and methodology are demonstrated by example of surface distortion measurement on door panel of a car body.

Introduction: The demands for greater quality on the surface sheet metal stamping parts has created a need for better techniques of nondestructive and not-contacting surface inspection. Nowadays, different technologies have been used for body surface inspection. They can be summarized as follows: Lights and mirrors, "D Sight" from Defracto and 3D digitization for measuring surface shape.

This method of Lights and Mirror has been widely used to inspect surface distortion by observing (through human eyes) the reflected light from mirror-like surface. If the surface to be inspected is not smooth enough, a thin oil film should be spread on the surface so that the applied light can be reflected from the surface. The measuring sensitive of this technique greatly depends on the observation direction, the bigger the angle is, the higher the sensitivity. The advantage of this method is its simplification. It is able to find a small surface distortion, such as a dent or a surface low. However, it is a qualitative method and impossible to indicate the depth of the lows, a success entirely depends on observing and illuminating direction and the experiences of the operator. Moreover, the method is suited only for a mirror-like surface, for the surfaces like aluminum and sheet-metal material, a surface pre-processing (e.g. applying a oil on the surface) are required.

The technique of Defracto technique has also been used for detecting a surface distortion by automotive industries. Although the measuring sensitivity of this technique is very high (it has a capability to find a surface distortion less than 25 microns in depth), the results obtained depend greatly on the experiences of the operator. Similar to Light and mirror method, the measuring sensitive greatly depends on the observing and illuminating direction, and it is a qualitative method and suited only for a mirror-like surface

Nowadays, the demands for greater quality on the surface sheet metal stamping parts has created a need for a technique of quantitative measurement of surface distortion. The mission of the measurement is not only to find the surface distortion on sheet metal stamping parts, but also to improve the manufacturing quality, e.g. to improve the quality of the die-sets. 3D digitization for measuring surface shape is a relatively new technique to deliver surface geometry quantitatively and has been applied for contour and 3D-shape measurement. In this paper, we have developed this technique for surface distortions measurement so that the surface low, highs and dents can be evaluated quantitatively.

Fundamental of 3D Digitization: 3D digitization is a technique for 3D shape (contour) measurement based on the optical triangulation. Fig. 1 shows the fundamental of spot of light triangulation. A relationship between a displacement Δx (usually called distortion) and the surface depth change Δz can be derived as following:

$$\Delta x = M \cdot \Delta a \quad (1)$$

where Δx is the distortion, M is the magnification of the camera used and Δa is a distance from observed point on the object surface to optical axis of the digital camera.

Because Δa is equal to $\Delta z \bullet \sin\theta$ from geometry, the relationship between the distortion Δx and the surface depth change Δz is given by:

$$\Delta x = M \cdot \sin\theta \cdot \Delta z = k \cdot \Delta z \quad (2)$$

where k is called the sensitivity factor.

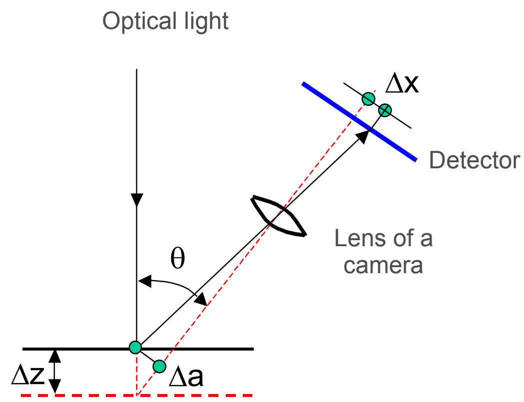


Fig. 1 Principle of Spot of light triangulation

The fundamental of 3D digitization is to get the contour information Δz by measuring the fringe distortion Δx. Fig. 1 shows only the spot of light triangulation. In order to measure the contour information on a whole surface, a fringe pattern created by a projector should be projected onto the object surface. Fig. 2 shows an example of 3D digitization for whole field 3D shape measurement. While a fringe pattern is projected onto a flat surface, the fringes are a pattern that looks like a group of parallel lines (cf. Fig. 2a). While the fringe pattern is projected onto a 3D-object surface, the fringe pattern is distorted and it looks like Fig. 2b. By measuring the magnitude and direction of the distortions at each position, the 3D-shape of object to be tested can be determined in full field.

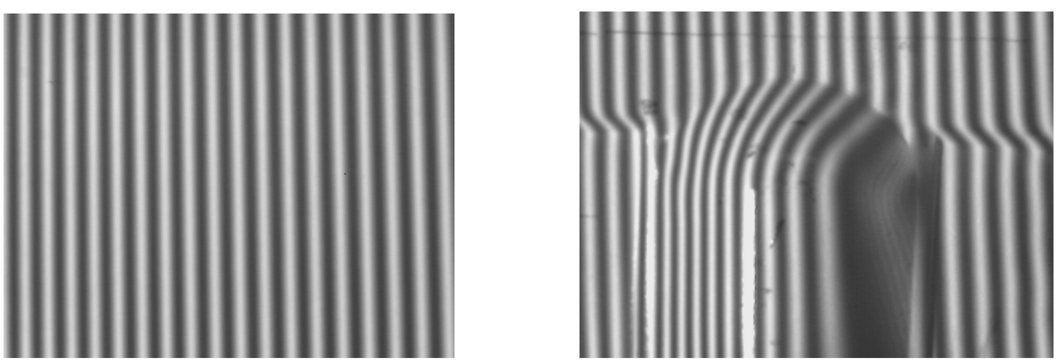

(a) (b)

Fig. 2 (a) a fringe pattern projected on a flat surface, (b) the fringe pattern projected on 3D-object

A key issue to determine the 3D-shape is how to determine the distortion Δx as showed in Fig. (2b). In the following part of the paper, we will discussed how to quantitatively determine the distortion Δx. An equation of the intensity expression for the fringe pattern on the flat object surface can be explained by [1-2]:

$$I = a(x,y) + b(x,y)\cos\left(\frac{2\pi}{P}x\right)$$

or $$I = a(x,y) + b(x,y)\cos\Delta_f \quad (3)$$

where $\Delta_f = \left(\frac{2\pi}{P}x\right)$ is called a phase distribution of a intensity equation, P is the pitch of the fringe pattern, i.e. the distance between two adjacent fringes, a(x,y) is the background of the fringe pattern and b(x,y) is related to the contrast of the pattern. While the fringe pattern is projected onto a 3D-object surface, the fringes are distorted and the intensity equation on the 3D-object surface becomes:

$$I' = a(x,y) + b(x,y) \cos \left[\frac{2\pi}{P}(x - \Delta x)\right]$$
$$= a(x,y) + b(x,y) \cos \left\{\frac{2\pi}{P} [x - k(x,y)\, \Delta z(x,y)]\right\}$$

or $$I' = a(x,y) + b(x,y) \cos \Delta_c \qquad (4)$$

where $\Delta_c = \frac{2\pi}{P} [x - k(x,y)\, \Delta z(x,y)]$ is called the phase distribution on 3D object, k(x,y) is the sensitivity factor at each point which has been explained in equation (2), $\Delta z(x,y)$ is the contour information which we want to measure. Assuming Δ_c and Δ_f is determinable, the subtraction between Δ_c and Δ_f produces:

$$\Delta_f - \Delta_c = \left\{\frac{2\pi}{P} x - \frac{2\pi}{P} [x - k(x,y)\, \Delta z(x,y)]\right\}$$
$$= \frac{2\pi}{P} k(x,y)\, \Delta z(x,y) \qquad (5)$$

Equation 5 can be rewritten by:

$$\Delta z(x,y) = (\Delta_f - \Delta_c)/\frac{2\pi}{P} k(x,y) = (\Delta_f - \Delta_c)/K(x,y) \qquad (6)$$

where $\Delta z(x,y)$ is the contour data, Δ_f and Δ_c are the phase distribution of the intensity equation shown in (3) and (4), respectively. The capital letter K(x,y) is the sensitivity factor for a whole-field measuring system, it is direct proportional to k(x,y) - the sensitivity factor for point measurement, but indirect proportional to the pitch P.

Now, the key for determine contour $\Delta z(x,y)$ becomes:

(1) To quantitatively measure Δ_f and Δ_c

(2) To determine K(x,y), also called "calibration".

In order to determine the phase distribution Δ_f or Δ_c from an intensity equation, the phase shift technique should be used. The Phase shift technique is method to quantitatively determine phase values of Δ_f or Δ_c from three or four intensity images (equations) [3]. The following shows briefly the fundamental for calculating phase distribution Δ_f by recording four intensity images:

$$\begin{aligned}
I_1(x,y) &= a(x,y) + b(x,y) \cos (\Delta_f) \\
I_2(x,y) &= a(x,y) + b(x,y) \cos (\Delta_f + 90°) = a(x,y) - b(x,y) \sin \Delta_f \\
I_3(x,y) &= a(x,y) + b(x,y) \cos (\Delta_f + 180°) = a(x,y) - b(x,y) \cos \Delta_f \\
I_4(x,y) &= a(x,y) + b(x,y) \cos (\Delta_f + 270°) = a(x,y) + b(x,y) \sin \Delta_f
\end{aligned} \qquad (7)$$

The phase shifting 90°, 180° and 270° can be obtained by moving the fringe pattern to small displacements P/4, P/2 and 3P/4, respectively. The phase distribution Δ_f can be determined now from the above equations as follows:

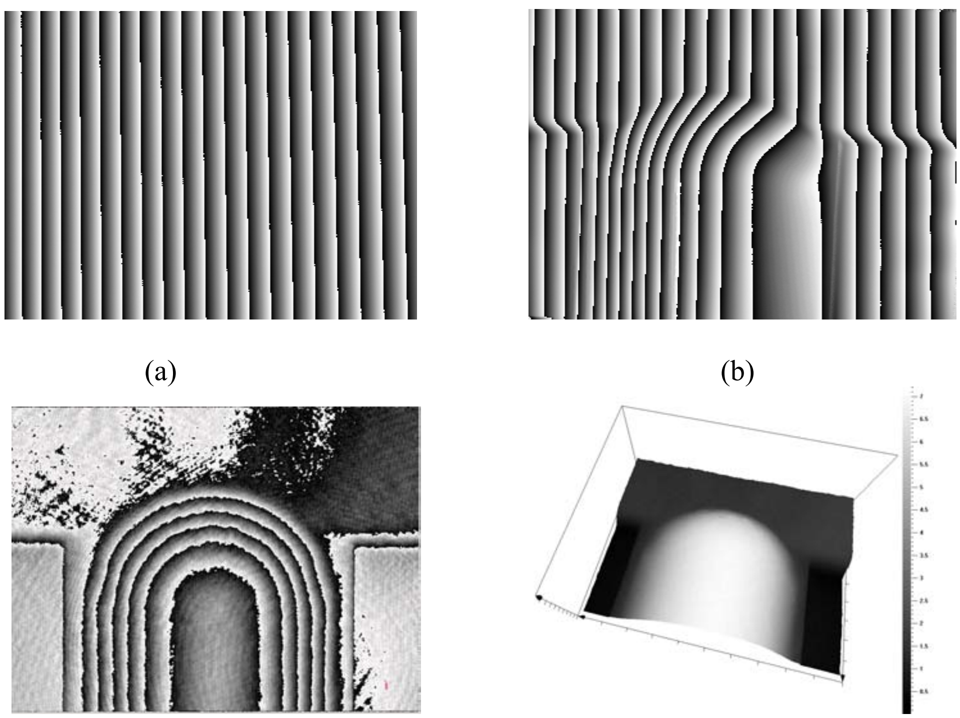
$$\Delta_f = arc \tan \left[\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right] \qquad (8)$$

In same way, the phase distribution Δ_c in the intensity equation I' can be determined too.

To determine (calibrate) the system factor K(x,y), a plane surface is measured twice and between the two measurements, the plane is moved by a constant distance, e.g. 10 mm. Instead of phase measurements of a flat and a curved surface, e.g. Δ_f and Δ_c, the phase measurements on two flat surfaces on different position with a constant distance, i.e. Δ_{f1} and Δ_{f2}, are performed. Because of a constant movement, $\Delta z(x,y)$ is known, e.g. 10 mm. Obviously, K(x,y) can be determined from equation (6):

$$K(x,y) = (\Delta_{f1} - \Delta_{f2})/\Delta z(x,y) = (\Delta_{f1} - \Delta_{f2})/10 \quad (9)$$

According to the definition of K(x,y) [cf. equation (6) and (2)], K(x,y) is defined as $K(x,y) = (2\pi/P)\, k(x,y) = (2\pi/P)\, M \sin \theta(x,y)$. M is the magnification of the camera used. The M value will keep constant if the camera zoom setting does not change. It is also easy to keep a constant pitch P. Therefore, the calibration factor K(x,y) depends mainly on the angle $\theta(x,y)$. If the camera and the projector position keep constant and the distance from object surface to the measuring system doesn't change, the sensitivity factor K(x,y) will keep constant. A new calibration is required only if the position relationship among the camera, the projector and distance is changed. Of course, a new calibration is also required if any one of zoom and pitch P has been modified.



(a) (b) (c) (d)

Fig. 3 Principle of 3D-digitization for whole field 3D-shape measurement (a) Δ_f of a flat surface (reference plane), (b) Δ_c on 3D-object, (c) the phase difference $\Delta_f - \Delta_c$ and (d) display of 3D-shape [including an operation of $(\Delta_f - \Delta_c)/K(x,y)$]

Let us look at equation (6) again. So far, we have shown how to quantitatively measure Δ_f and Δ_c as well as how to determine the sensitivity factor K(x,y). Obviously, the contour data $\Delta z(x,y)$ can now be determined quantitatively. Fig. 3 shows an example of 3D-digitization for whole field 3D-shape measurement. Although a phase distribution Δ_f is displayed in Fig. 3, the phase distribution Δ_f of a flat surface doesn't change with different object. Therefore, this image can be saved in computer and utilized for other measurements. That means, K(x,y) and Δ_f are determinable before measurement, only Δ_c is required for the ***practical*** measurement. For determining Δ_c, four images need to be recorded due to utilization of the phase shift technique. The time for measurement of Δ_c is about 2-3 seconds.

Principle of 3D Digitization for surface distortion measurement: Surface distortion described here means a surface low, high and dent. Usually a quantitative value for such surface distortions lies between 25 to 250 microns in depth and a few millimeter in size for dents and from several decade to two hundred millimeters in size for surface lows and highs. If a surface distortion lies on a flat surface, such a distortion is relative easy to be localized by the current 3D-Digitization technique. However, most sheet metal stamping parts in automotive industries, such as door panel etc. is not a flat surface, they are usually a curved surface, a distortion on a curved surface becomes difficult to be identified by the current 3D-Digitization technique. This results from the fundamental of 3D-Digitization technique. As described above, 3D-Digitization technique measures contour information. If the object to be tested has a curved surface, both contour and surface distortion information will be measured. Usually, the contour value is much bigger that the surface distortion value, for instance, the shape value of an object is 10 mm in depth and a distortion is 40 microns. This distortion value occupied only 0.4% of the contour value. For a hardware resolution with 8 bit, there are 256 gray levels lie between the maximal and minimal value, 0.4% of the 256 gray levels is only 1 gray level. Obviously, such a surface distortion is impossible to be identified.

If the contour data can be removed, the information of the surface distortion becomes visible. This is just the basic idea of 3D Digitization for surface distortion measurement.

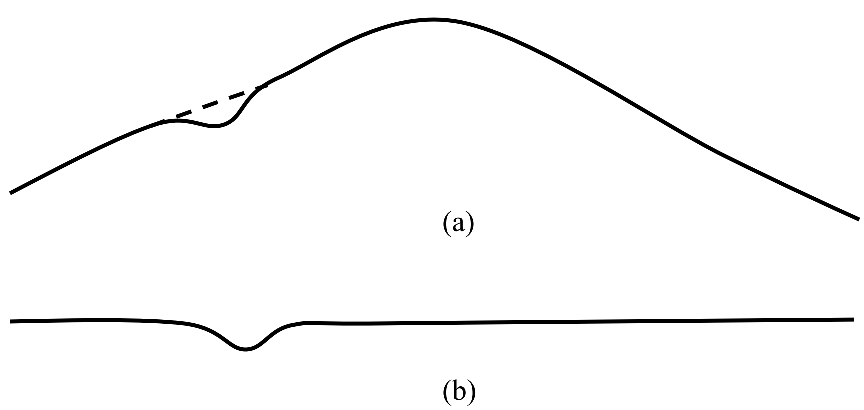


Fig. 4 Fundamental of 3D Digitization for surface distortion measurement (a) data containing both contour and distortion, (b) data after removing the contour information.

Fig. 4 demonstrates the fundamental of this idea. For simplification only a section profile is discussed. In addition, for better understanding, the surface low has been amplified. Fig. 4a shows a measured curve contains both the contour information and a surface distortion. Our objective is to find a regression curve that represents the ideal curve of surface to be inspected. Because most surfaces of a car body can be expressed by a polynomial with order 2 as shown in equation 10, a regression surface can be created according to regression method of polynomial with order 2,

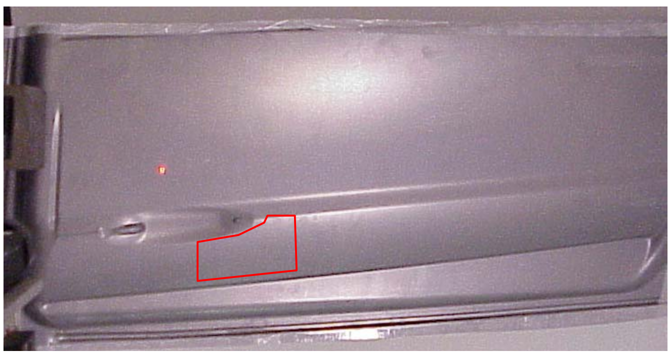
$$f(x, y) = a x^2 + b y^2 + c xy + d x + e y + f \quad (10)$$

Equation 10 represents a mathematic expression of the regression surface. By subtracting the data of the measured surface from that of the regression surface, the contour data are removed and the invisible information of distortion become visible.

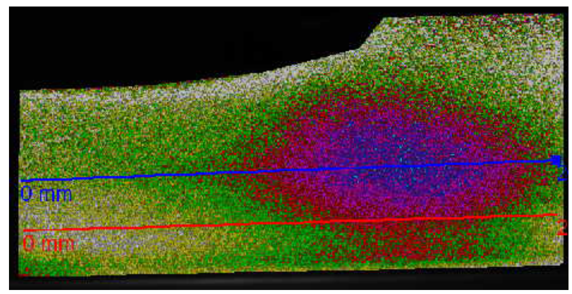
In practical applications, the measured data contain a lot of high-frequency noises. Therefore, before doing regression method, the original measured data should be smoothed by a specially developed smoothing algorithm [4-5].

Applications: A commercial measuring system based on the above theory, called ABIS, has been developed by the company of Steinbichler GmbH, Germany. The following measuring results were obtained by utilization of ABIS.

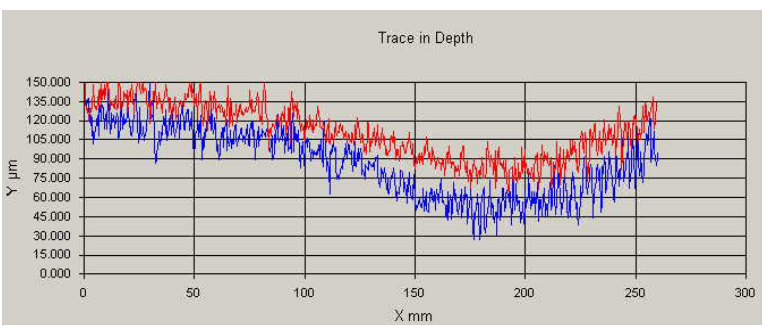
Fig. 5a shows a live image of a door panel. The area marked by red line shows the measuring area. Fig. 5c presents the measuring result that clearly shows a surface low. A section profile is demonstrated in Fig. 5c. The section profile indicated the surface low is about 40 microns in depth. The size of the surface low is about 150 mm in horizontal direction and 100 mm in vertical direction. After the measurement of the panel, it is stoned at the measuring area. The result obtained by stoning shows that a surface low is located at the exactly same position as 3D-digitazation indicated.



(a)



(b)



(c)

(c)

Fig. 5 An example for surface distortion measurement on a door panel, (a) live image, the area indicated by red line is the measuring area, (b) measured result, (c) a section display, and (d) the stoned area after measurement of 3D-digitazation.

Conclusions: A new technique for surface distortion has been explained and demonstrated. Because the contour data are removed, the very small information of surface low or high can be displayed very clearly. The measuring sensitivity of 3D-digitazation for surface distortion measurement is almost same as for 3D contour measurement. It can be down to 25 microns for a measuring are of 300x300 mm^2. The measuring result is well repeatable. It is expected that a wide range of applications of the technique will be seen in the near future.

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