

Research on non-contact scanning measurement of pressure vessel head

W J Ding, C H Jiang, X L Liao, S P Sheng, Y L Liu

Hangzhou Institute of Special Equipment Inspection, Hangzhou, China

Email: 2420673693@qq.com

Abstract. This paper gives firstly a brief analysis of the harm of the shape deviation of pressure vessel head and disadvantages of traditional head mechanical contact measurement. On the basis of these, a non-contact laser-scanning measurement is presented. And then this paper introduces its principle, and analyzes in detail existing errors in measuring the head contour. Finally, Simulated defect measurement results are presented in the paper.

1. Introduction

Head is one of the main components of the pressure vessel, which is to ensure the sealing of pressure vessel. Strength failure, instability can lead to the overall safety problems of pressure vessels. The influence of different shapes of head on large pressure vessels is obviously, especially for the strength and stability of large pressure vessels.

The stress concentration of the head is closely related to its shape, and the larger head shape deviation may cause more serious stress concentration. Sometimes, the stress intensity where the inner wall of the small head appeared transition to straight edge by round (R) can be nearly 4 times the normal stress, it is obviously that the geometric deviation of the shape of the head can not be ignored for the safety of pressure vessels^[1]. Check of the head parameters, especially the shape deviation, is an important work in the manufacture of pressure vessels^[2]. At present, the measurement of the inner surface shape and the important parameters of the head geometry are mainly based on the mechanical contact measurement, including the whole model test and head inspection coordinate measuring instrument^[3]. The former way was to detect the offset distance between the inner surface of the head to model; the latter way was to formula design of head curve theory coordinate detector, point contact head surface to obtain the measured data by using the detector, in order to determine the shape and quality of the inner surface of the head. These testing methods essentially use mechanical contact measurement, there are many problems in testing such as consumption, low measurement accuracy, low efficiency and poor operability, etc^[4].



Therefore, this paper proposes a laser non-contact scanning method for head parameter detection, detection of important parameters of head by laser non-contact measurement and scanning motor, in order to overcome the shortcomings of traditional detection methods.

2. The pressure vessel head non-contact laser-scanning measurement

The method proposed in this paper complete the inspection of the head parameters, by using the laser scanning detection device located in the head end fixing to the support rod, and distance detection and rotating scanning detection of the motor. Here, this paper selects the detection of inner surface profile curve of head as an example to introduce the method.

3. The positioning and the axis position of head scanning measurement

One of the key parts in the head scan detection is the localization and determination of the axis position. According to the standard, the deviation of the head of the pressure vessel is the deviation of the section profile curve and the standard curve of the axis of the head. So capturing the position of the axis of the head is also the key element of the measurement. And the positioning is to find the shape of the head detection or zero starting point. Figure 1 is the schematic diagram for overlooking the scanning detection mechanism to detect the head. As shown in Figure 1, the scan detection mechanism includes a support bar (2 in Figure 1a), a locking device (3 in Figure 1a) and a distance detection module and a multi dimension scanning module (4 in Figure 1a). During the detection, the supporting rod used in arbitrary head (1 in Figure 1a) on the end, the lower end of the support rod on both sides respectively is fixed on the edge of the arc concave head with the locking device. The distance detection module and multi dimension scanning module is arranged in the support bar below, and is located in the arc concave surface of head, as illustrated in Figure 1b. Figure 2 is the assembly sketch map of distance detection module and the multi dimension scanning module. There, distance detection module (8 in Figure 2) is used to realize the detection of the distance among the points of the head, and the multi dimension scanning module (5, 6, 7 in Figure 2) provides the distance detection module and the rotation of the two dimensions.

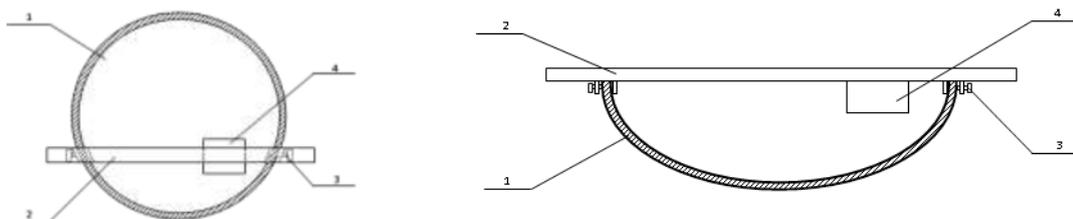


Figure 1. Schematic diagram of scanning detection mechanism

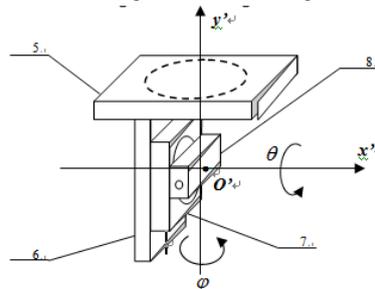


Figure 2. Schematic diagram of distance detection and multi-dimension scanning module

The method determination of the axis position is shown in Figure 3. O' is distance detection module (3 in Figure 7) for the measurement reference point of the device itself. When measuring, the first multi dimension scanning module direction is rotated to the zero position. Here is the definition of the zero distance detection module detects the direction (emergent light) parallel to the head m (contact surface supporting bar and head end). The direction angle of the multi dimension scanning module is arbitrary. In the distance detection module, The measure distance from the reference point to the end face of the head is $O'A$. Similarly, the scanning module drives the distance detection module to rotate 90 degrees for two times in the same direction, and the distance between the detection module and the end face of the head is detected, the distance $O'A'$ and the distance $O'B'$ were measured respectively. At the moment, the position of the center of the end face O'' to the reference point of the distance detection module O' can be determined. The angle between the $O'O''$ direction and the initial direction of the distance detection module, $O'A$ direction, is φ_o , this angle is determined by the following formula:

$$\varphi_o = \arctan \frac{O'B - O'B'}{O'A - O'A'} = \arctan \frac{b_1 - b_2}{a_1 - a_2} \quad (1)$$

In the formula, the distance values of $O'A$, $O'A'$, $O'B$, were a_1 , a_2 , b_1 and b_2 . Here, the O'' which is the center of the end face of the head, which is the real center of the surface profile of the head, but also the origin of the head inspection.

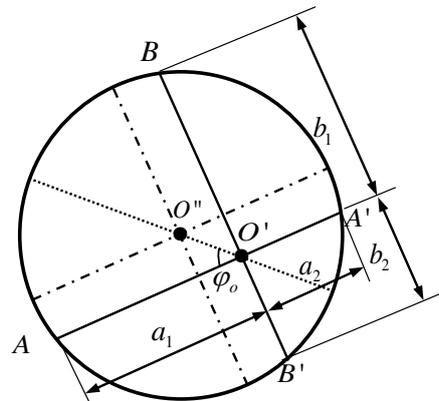


Figure 3. Determination of end face scanning direction of head

We can through the multi dimension scanning module rotate angle φ_o along the direction to complete positioning. When the direction of rotation is in place, the distance detection module is in position zero, that is, the distance detection module detects the direction is parallel to the end face of the head, At the same time, the direction is also through the O'' , which is the center point of the inner surface profile curve of the head. At the moment, a point on the head which is detected by the distance detection module is the starting point of the head detection. Thus, the positioning of the head detection is completed.

4. Detection of the deviation of the inner surface of the head

The positioning and the determination of the central axis make the distance detection module be detected in the initial state. As shown in Figure 4, the shape error of the surface profile of the head is detected. Multi dimension scanning module direction at position zero. Direction scanning direction center of the end head face of O'' . At the moment, the multi-dimensional scanning module rotates along the direction (the scanning surface), the distance detection module can detect the actual shape of the contour curve of the inner surface of the head.

At the time of detection, distance detection module detects along the starting point from the head start scanning head detection to another relative face. In this paper, the measurement of the shape error of the inner surface profile is based on the vertex of the head as the reference point of the error calculation. The point is that the vertical head end line intersection with the inner surface contour line of the head which go through the center point of the head end O'' . It is also the point O in the graph. The vertical is the vertical axis. Let's make a coordinate system with the reference point O as the center, the detection of the coordinates of the surface of the head in the Figure 4 scanning process can be determined by the formula:

$$\begin{cases} x_c = \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2} - d \cos \theta_c \\ y_c = h_H - d \sin \theta_c \end{cases} \quad (2)$$

In the formula, d is the distance to the point C of the surface head Inner surface which is detected by the distance detection module. a_1 , a_2 , b_1 and b_2 respectively in the detection is the distance value of $O'A$, $O'A'$, $O'B$, $O'B'$. θ_c is the angle when the distance detection module is transferred to the point C in the direction of the multi dimension scanning module. Its positive or negative lies on the right hand rule in the coordinate system of Figure 2. Its angle size is equal to the angle $\angle O'O'C$. Its range meets the following formula:

$$\begin{aligned} \arctan \left[\frac{(h_H - p_b) / (p_a + \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2})}{\pi - (h_H - p_b) / (p_a - \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2})} \right] \leq \theta_c \leq \\ \arctan \left[\frac{(h_H - p_b) / (p_a + \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2})}{\pi - (h_H - p_b) / (p_a - \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2})} \right] \end{aligned} \quad (3)$$

The variables p_a and p_b are the long half axis and short half axis of the head. h_H is the actual distance between point O' of the test module reference to the point O of the head vertex along the y direction, or the actual distance between the center point O'' of the head face and point O of the head vertex in the formula (2) and formula (3).

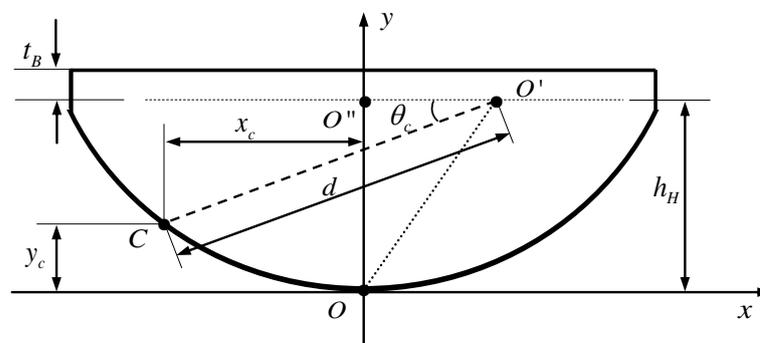


Figure 4. Scanning of inner surface profile of head

The actual distance between the center point O'' of the head face and point O of the head vertex is determined as shown in Figure 6. In the figure, the curve A is the theoretical outline of the head, and the curve B is the actual contour line of the head. The distance detection module is driven by the multi dimension scanning module to start from the detection start point, and after turning the angle θ_H along the direction, the outgoing light of the distance detection module just passes through the point O_A of the head vertex. Angle θ_H to meet the next type:

$$\theta_H = \arctan \left[(H - t_B) / \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2} \right] \quad (4)$$

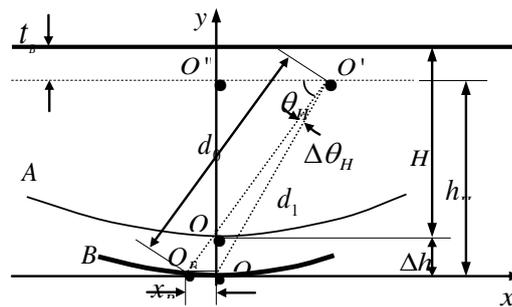


Figure 5. The determination of the actual distance between the head end face center and the head vertex

In the formula, the variable H is the distance from the head end to the head end of the head. The distance is also the total depth of the head. t_B is the distance from the detection module to the point O' of the end face. It is not consistent between the actual contour line of the head and the theoretical outline of the line A, assuming that both deviate Δh from the diagram in the curve B. At the moment, the light to reach the end face of the head is not the point O of the head vertex, but a point O_B near the top of the head, after the distance detection module rotation angle θ_H . Thus, it still need an angle $\Delta\theta_H$ to revise, after the distance detection module rotates angle θ_H . This angle $\Delta\theta_H$ satisfies the following formula:

$$\Delta\theta_H \approx (d_0 \cos \theta_H - \frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}) / d_0 \quad (5)$$

In the formula, d_0 is the actual detection after distance the distance detection module rotation angle θ_H from its reference point O' to the head vertex. Range detection module from the detection of the initial point began to rotate angle $\theta_H + \Delta\theta_H$, its emergent light reach the point O of the head vertex. Set the detected distance as d_0 , it can be obtained:

$$h_H = d_1 \cos(\theta_H + \Delta\theta_H) \quad (6)$$

By the formula (2), the distance detection module can detect the actual contour curve of the inner surface of the head. Finally, the shape error of the inner surface of the head can be determined by comparing with the theoretical curve of the inner surface of the head.

The definition of shape error is shown in Figure 7 (a). The curve B in the figure is the actual contour of the head. Making a theoretical contour curve of the head with the actual head contour vertex O as a reference point, which is curve A in the diagram, the center point of theoretical contour is point $O^\#$. Here, the shape error of the internal contour of the head is defined as the distance d -value from the point to the theoretical contour curve to the

theoretical profile curve of the head in the normal direction. In the figure, the shape error of a point C_B (θ_c) on the contour curve is the difference between $C_B O_f$ and $C_A O_f$, which is ε . Among them, $C_B O_f$ is the normal direction of point C_A on the theoretical contour curve, the shape error value is obtained by the following formula:

$$\begin{cases} \varepsilon(\theta_c) = \left\{ \left(\frac{1}{2} \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2} - d \cos \theta_c - x_{C_A} \right)^2 + (h_H - d \sin \theta_c - y_{C_A})^2 \right\}^{1/2} \\ x_{C_A} = a \cdot b / \sqrt{b^2 + a^2 \tan^2 \alpha} \\ y_{C_A} = a \cdot b \cdot \tan \alpha / \sqrt{b^2 + a^2 \tan^2 \alpha} \end{cases} \quad (7)$$

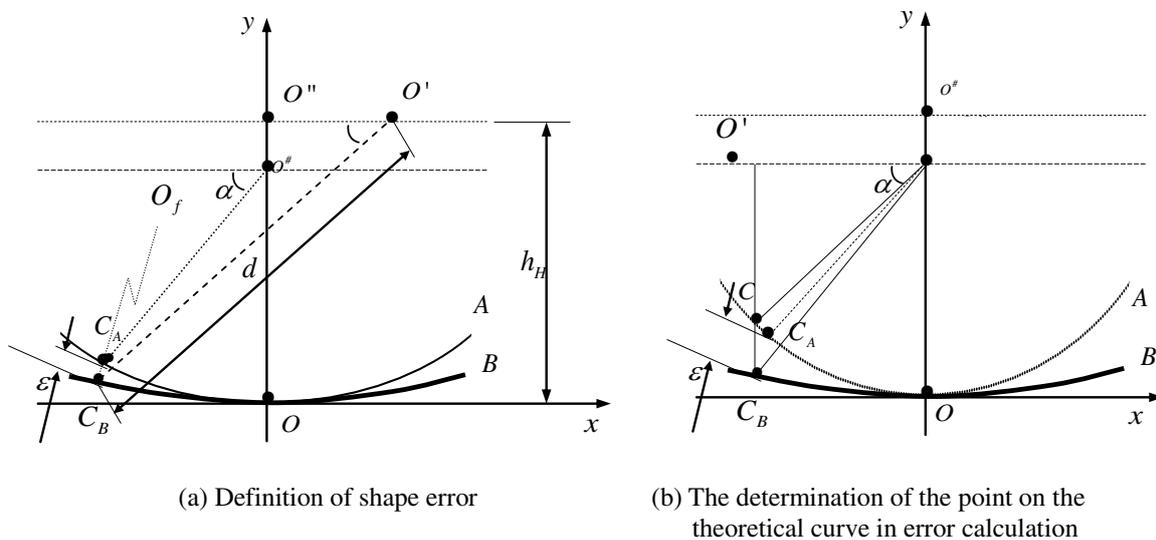


Figure 6. The Definition and calculation of shape error

In the formula, d is the detection module rotation to the angle θ_c , the detection module reference point O' to the head of the actual contour line corresponding to point C_B detection distance. The parameters α or C_A on the approximate theoretical curve are determined as shown in Figure 7 (b) shows. Through the actual contour curve point C_B to do the y axis parallel line and with the theoretical contour curve intersection point C , the parameter α for the half of the sum of angle $O'O'C$ and $O'O'C_B$ ($\alpha = (\angle O'O'C + \angle O'O'C_B) / 2$).

5. Actual measurement of head shape deviation based on non-contact laser scanning

In order to realize the non-contact laser scanning measurement and error analysis, this paper has carried out a field test on two different types of head equipment company in Hangzhou.

1) Elliptical head. Nominal parameter:

Shape: ellipse; diameter: 2800mm; total depth: 750mm; straight edge: 50mm.

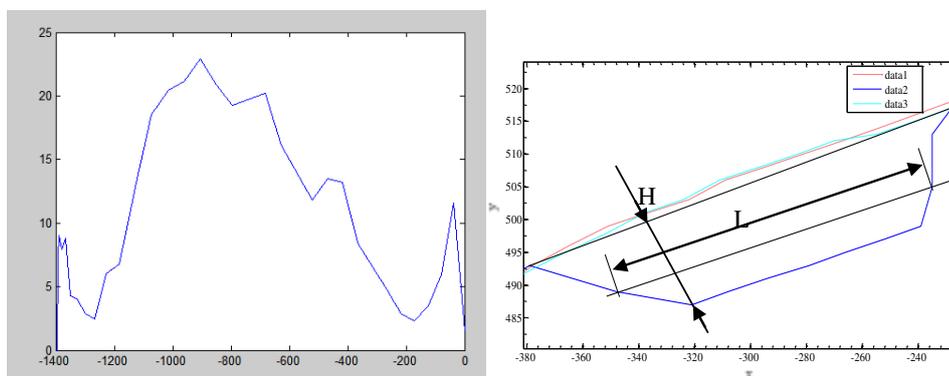
First of all, we used the principle of this paper to test the parameters of the header 3 times.

Secondly, we carried out point by point actual measurement of the head with a ruler, and compared the instrument test data with the measured data. The test data are shown in table 1.

Table 1. Comparison of instrument test and ruler measurement in head shape errors

	measure	1st	2nd	3rd	σ
Maximum internal deviation (mm)	8	10.3	9.2	9.8	0.551
Maximum external deviation(mm)	-1	-2.3	-1.2	-2.5	0.7

From Table 1, three measurement data by Instrument and measurement data contrast. The shape of the uncertainty of the maximum degree of 0.7mm in repetitive aspect; in accuracy aspect, the maximum deviation of the maximum deviation of 2.3mm; maximum deviation of the maximum 1.5mm.



(a) Local amplification test curve

(b) Selection of measurement direction

Figure 7. The test of block shaped objects placed on the inner surface of the head

We placed an iron round cake shaped object at the surface of the head at random, block shaped objects are tested, and tested the block shaped objects, local test curves are shown in Figure 7 (a). The block shaped objects in actual size are as follows: Length: 111.5mm; thickness: 15.5mm.

In Figure 7 (b), the direction of the thickness of H is taken as the direction of the radial direction (the direction of the measurement is directed toward the end of the end face center). The length of the L measuring point from block shaped object points on both sides and the actual laser scanning test are shown in Figure 7 (b). The measured actual dimensions are:

Length: 114.1mm; deviation: -2.6mm;

Thickness: 16.44mm; deviation: -0.94mm.

According to the actual test, this method of non-contact laser scanning measurement can be used to measure the shape of the head and the correct the parameters of measurement, and it is in accordance with the theoretical deviation analysis. In addition, from the theoretical analysis and the actual test, in order to increase the accuracy of the non-contact laser scanning device scanning, reduce the deviation, it have the following measures:

- 1) Using high precision laser distance measuring equipment. The accuracy of the equipment directly determines the follow-up scanning accuracy;
- 2) Before testing, it is needed to accurately determine the central axis, that is, the distance between the laser range finder and the center of the end face of the end face of the head. This deviation, which is mainly the deviation between the two centers of the end face of the vertical head, will affect the accuracy of the subsequent scanning. This deviation,

which is mainly the deviation between the two centers of the end face of the vertical head, will affect the accuracy of the subsequent scanning.

- 3) Mechanical assembly stability. Due to the influence of the precision of the mechanical device or part in the production, the actual size and design size will be biased. There will be some deviation in the coordination of the mechanical structure, and the cumulative effect of the mechanical assembly errors will affect the detection accuracy of the whole device^[5].

6. Conclusion

The transitional zone between the straight side section and the semi ellipsoid of the head is a sensitive area, the slight decrease of the corner radius will lead to the rapid increase of the numerical value of the shape system, and the maximum stress and the circumferential compressive stress on the outer surface of the transition region also increase rapidly. For internal pressure forming head, it means that the possibility of damage to both strength and stability will rapidly increase. So, it is very necessary to detect the deviation of the header of the pressure vessel^[6]. Comparing with the traditional contact measurement, the non-contact laser scanning measurement in this paper has the following advantages:

- 1) Eliminates the links of making and using the model. The test is simple and convenient, also the deviation caused by the test is reduced.
- 2) It can automatically find header center section to achieve data collection and processing of data, as well as the visual display of data;
- 3) In addition to the detection of the shape of the inner surface of the head, it is also easy to detect other parameters of the head, including roundness, depth, diameter, etc. At the same time, the head of various shapes can be detected, which can increase the convenience of detection, which is of great significance for the prevention of the failure of the container.

References

- [1] Xinlin Teng. Discussion about the Safety Inspection and Quality Supervision of Pressure Vessels[J]. China New Technologies and Products, 2011, (14): 41-43.
- [2] MA Li MIAO Cunjian ZHU Xiaobo. Research on Prediction Method of Plastic Deformation for Cold Stamping Formed Standard Elliptical Head Made of Austenitic Stainless Steel. JOURNAL OF MECHANICAL ENGINEERING, 2015, 51(6): 19-25.
- [3] Mingzhi Liu. The Coordinate Measuring Machine for Head Test [J]. Petro-chemical Equipment, 1991, 20(1): 37-38.
- [4] Zhang Jiangyu. Measurement of Shape Tolerance for Elliptical Head. CPVT. 1994, 1,11(1): 83-85.
- [5] LIN Jinghuan, DAI Yong, SHENG Shuiping, CHEN Haiyun. New universal laser scanning head detector[J]. Laser Technology. 2014, 9, 38(5): 651-654.
- [6] XIAN Chaozuo, Yuexin, HE Jianhua. Discussion on the allowable deviation of the shape of the head [J]. CHINA PETROLEUM MACHINERY. 2004, 32(4): 43-45.