

Research on Tank Volume Metrology for Petroleum and Liquid Petroleum Products Based on 3D Laser Scanning Method

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Abstract: One course radius measurement method for vertical tank volume metrology based on 3D laser scan principle was researched. Method of distance measurement by phase and angular measurement by optical grating was applied to acquire coordinates of points in each course under the control of servo system, and the permitted error of point location is 2mm. Fitting algorithms base on direct iterative method (DIM) and least square method (LSM) were used to process measured data and deduce equivalent radius of each course. In comparison experiment, one 1000m³ vertical tank was used as test object. Compared to strapping method (international mandatory standard), the maximal deviation radius value of method discussed is 2.8mm, and the maximal difference of radius value calculated by DIM and LSM is 0.1mm. The experimental results verified the method discussed in this paper.

Keywords: Course radius, Measurement, Vertical tank, Volume metrology, Fitting algorithm, Comparison experiment

1. Introduction

Vertical cylindrical tank is one type of tanks in general use throughout the world for the storage of petroleum and petroleum products. Measurement of liquid levels and the use of the tank capacity table permit the assessment of volume of the liquid held in store or transferred. In order to be accepted for fiscal or custody transfer application, vertical cylindrical tanks shall be calibrated carefully to ensure the accuracy of volume measurement of liquid contained^{[1][2]}.

There are mainly three volume calibration methods used for vertical tank, which are strapping method, optical reference line method and optical triangulation method.

The strapping method involves measuring tank external circumference that is then converted into tank internal diameter at each course by subtract the course thicknesses^[3]. The method has been used for more than half a century and is still regarded as the referee method for evaluation of all existing and future emerging technologies. With the increase of tank diameter and height, determination of tank circumferences at higher elevation (other than the bottom course generally) tends to be more and more difficult and dangerous. Therefore, the strapping method is applied mostly as reference method.

For optical reference line method, one vertical reference line is established by using an optical device. A magnetic trolley with ruler intersecting the optical reference line moves along the tank shell^[4]. The circumference of bottom course is measured by strapping method, and the radial offsets of higher courses are measured optically. By using the reference circumference and the radial offsets, diameter at each course is computed mathematically. The main advantage of this method is the avoiding of work at height.

The optical triangulation method also known as OTM is an extension of the optical reference line method. With two theodolites at a known distance, the target points on tank shell are determined by triangulation^{[5][6]}. OTM is more easily adopted for internal application because the optical devices can be located in one single location for the entire calibration, and provides capability to carry out calibration from ground level without any manual strapping.

For the three calibration methods above, the core tasks is the radius measurement for each course. There is one hypothesis that the shape of vertical tank is strictly one cylinder. Although this simplification of geometrical characteristics could reduce the complexity of calibration, and only two position of each course are measured in situ, the sampled points are too few to describe the whole tank geometrical model correctly due to the deformation of tank. On the other hand, the automation of calibration should be researched to improve the efficiency of work. Especially with the upsizing of vertical tank volume (such as 100,000m³), the two problems become more and more important.

In this paper, one automated measuring system for vertical tank volume was researched based on 3D laser scan method. Method of distance measurement by phase and angular measurement by optical grating was applied to acquire coordinate values of points in each course. Two fitting algorithms based on direct iterative method (DIM) and least square method (LSM) were used to process measured data and deduce equivalent radius of each course. One comparison experiment was carried out to validate the method discussed.

2. Measurement System Based on 3D Laser Scanning Method

The measurement system for coordinates of points in tank shell is shown as Fig.1 and Fig.2. The 3D laser scan was installed firmly on the bottom of vertical tank, and adjusted to horizontal level.

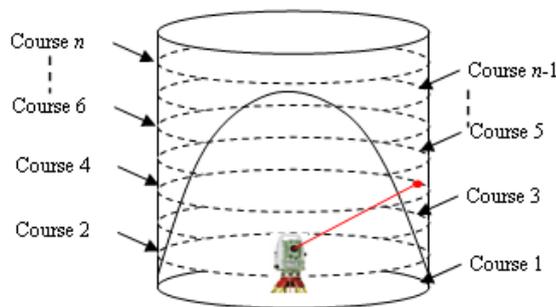


Fig.1 The measurement system for coordinated of points in tank shell

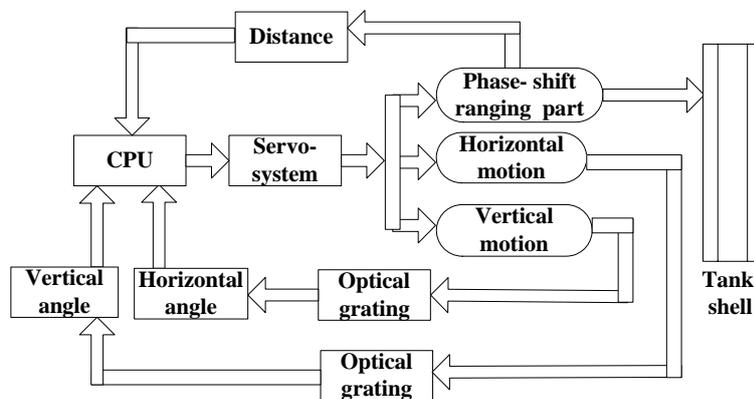


Fig.2 The schematic diagram of measurement for length and angular

During measurement, the laser is transmitted from the instrument to the surface of tank shell. According to the phase-shift principle, the distance r_p between point and instrument can be achieved by formula (1)

$$r_p = [\lambda(m + \varepsilon)]/2 \quad (1)$$

Where r_p is measured distance; $\lambda = \lambda_0/n$ is wavelength of laser and n is the refractive index; m is the integral order of interference fringes ; ε is the partial order of interference fringes. Vertical angle β_p and horizontal angle α_p for each point are acquired by optical grating^[7-9]. Therefore, with the center o of the instrument as original of coordinate and plumb-line as vertical axis, one rectangular coordinate was established as shown in Fig.3.

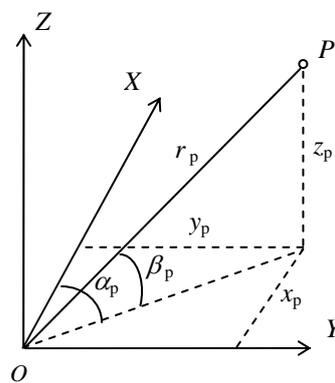


Fig.3 The coordinate system for measurement system

The coordinate value (x_p, y_p, z_p) of each point P in tank shell could be deduce based on the three parameters r_p, β_p and α_p

$$\left. \begin{aligned} x_p &= r_p \cos \beta_p \cos \alpha_p \\ y_p &= r_p \cos \beta_p \sin \alpha_p \\ z_p &= r_p \sin \beta_p \end{aligned} \right\} \quad (2)$$

The method can be automated to scan the tank both horizontally and vertically. It is obvious that the 3D laser scan method is more sophisticated and advanced compared to all others, and is primarily an internal calibration technology.

3. The Algorithm of Radius Fitting for Measured Points of Each Course

The algorithm of radius fitting for measured points of each course is very important for computation of vertical tank volume. According to technical requirement of OIML R71^[10], the vertical tank is regarded as ideal cylinder. Therefore, the core problem of data processing is the equation fitting of circle curve $(x - x_c)^2 + (y - y_c)^2 = R^2$, and deducing the equivalent radius R for each course at different height. The equivalent radius R is the most important parameter for volume computation, and two algorithms based on DIM and LSM were applied to carry out the research on fitting of R .

3.1 Algorithms based on DIM

The fitting of circle curve of data scanned from vertical tank is one problem of minimization of nonlinear objective function with multi variables in nature, to which calculation by iteration is one of the most effective solutions^{[11][12]}. For this algorithm, there is no requirement for derivation of function, and with merit of simple use, because it can be used whether the objective function is continuous and differentiable or not.

Firstly, the center of fitting curve (x_{c0}, y_{c0}) is initialized and set to $(0, 0)$ generally, and then the objective function f_{obj} is defined as equation (3)

$$f_{obj} = |R_m - R_{m-1}| \quad (3)$$

Where R_m is the estimated value of radius when iterative step is m . The iteration algorithm is

$$\left. \begin{aligned} x_{cm} &= \sum_{i=1}^n x_i / n - (R_m / n) \sum_{i=1}^n \frac{x_i - x_{c(m-1)}}{r_i} \\ y_{cm} &= \sum_{i=1}^n y_i / n - (R_m / n) \sum_{i=1}^n \frac{y_i - y_{c(m-1)}}{r_i} \\ r_i &= \sqrt{(x_i - x_{c(m-1)})^2 + (y_i - y_{c(m-1)})^2} \\ R_m &= \sum_{i=1}^n \sqrt{(x_i - x_{c(m-1)})^2 + (y_i - y_{c(m-1)})^2} / n \end{aligned} \right\} \quad (4)$$

Where (x_i, y_i) , $i=1, 2, \dots, n$ are the n points obtained from measurement. Calculate x_{cm} , y_{cm} , r_i and R_m until the new value of R_m differs from old one by less than δ , as shown in equation (5)

$$f_{obj} < \delta \quad (5)$$

Where δ is the calculation threshold, and usually set to 0.1mm. If the iterative computation is finished, the latest values of (x_{cm}, y_{cm}) and R_m are regarded as the best fits of center and radius for sampled points on tank shell. Considering the 3D laser scan is installed near the center of tank bottom, the initialized value of (x_{c0}, y_{c0}) can be set by the equation (6) to accelerate the computation

$$x_{c0} = \sum_{i=1}^n x_i / n, y_{c0} = \sum_{i=1}^n y_i / n \quad (6)$$

3.2 Algorithm based on LSM

Algorithm based on LSM corresponds to the maximum likelihood criterion if the experimental errors have a normal distribution and can also be derived as a method of moments estimator^[13]^[14]. LSM is used for linear regression with still most frequency, which is the problem of finding a curve that best fits a set of data, and assumes that the best-fit curve of a given type is the curve that has the minimal sum of the deviations squared from a given set of data. To the fitting of vertical tank, the deviations squared ε can be defined as

$$\varepsilon = \left(\sum_{i=1}^n [(x_i - x_c)^2 + (y_i - y_c)^2] / n - R^2 \right)^2 \quad (7)$$

This equation involves three free parameters. Taking the derivative of ε with respect to x_c , y_c) and R and setting them to zero gives the following equations

$$\frac{\partial \varepsilon}{\partial x_c} = \frac{\partial \varepsilon}{\partial y_c} = \frac{\partial \varepsilon}{\partial R} = 0 \quad (8)$$

Solving these three equations gives the least square estimates of x_c , y_c and R as the following expressions

$$x_c = \frac{(\sum_{i=1}^n x_i^2 \sum_{i=1}^n x_i + \sum_{i=1}^n x_i \sum_{i=1}^n y_i^2 - \sum_{i=1}^n y_i^3 - \sum_{i=1}^n x_i y_i^2)(\sum_{i=1}^n y_i)^2 - \sum_{i=1}^n y_i^2 [1 - (\sum_{i=1}^n x_i^2 \sum_{i=1}^n y_i + \sum_{i=1}^n y_i \sum_{i=1}^n y_i^2 - \sum_{i=1}^n x_i^2 y_i - \sum_{i=1}^n y_i^3)](\sum_{i=1}^n x_i \sum_{i=1}^n y_i - \sum_{i=1}^n x_i y_i)}{2n[(\sum_{i=1}^n x_i)^2 - \sum_{i=1}^n x_i^2][(\sum_{i=1}^n y_i)^2 - \sum_{i=1}^n y_i^2] - 2n(\sum_{i=1}^n x_i \sum_{i=1}^n y_i - \sum_{i=1}^n x_i y_i)^2}$$

$$y_c = \frac{(\sum_{i=1}^n x_i^2 \sum_{i=1}^n x_i + \sum_{i=1}^n y_i \sum_{i=1}^n y_i^2 - \sum_{i=1}^n y_i^3 - \sum_{i=1}^n x_i^2 y_i)(\sum_{i=1}^n x_i)^2 - \sum_{i=1}^n x_i^2 [1 - (\sum_{i=1}^n x_i^2 \sum_{i=1}^n x_i + \sum_{i=1}^n x_i \sum_{i=1}^n y_i^2 - \sum_{i=1}^n x_i y_i^2 - \sum_{i=1}^n x_i^3)](\sum_{i=1}^n x_i \sum_{i=1}^n y_i - \sum_{i=1}^n x_i y_i)}{2n[(\sum_{i=1}^n x_i)^2 - \sum_{i=1}^n x_i^2][(\sum_{i=1}^n y_i)^2 - \sum_{i=1}^n y_i^2] - 2n(\sum_{i=1}^n x_i \sum_{i=1}^n y_i - \sum_{i=1}^n x_i y_i)^2}$$

$$R = \sqrt{x_c^2 - 2 \frac{\sum_{i=1}^n x_i}{n} + y_c^2 - 2 \frac{\sum_{i=1}^n y_i}{n} + \frac{\sum_{i=1}^n x_i^2}{n} + \frac{\sum_{i=1}^n y_i^2}{n}}$$

Where (x_i, y_i) , $i=1, 2, \dots, n$ are the n points obtained from measurement.

4. Comparison Experiment And Data Analysis

To verify the measuring method discussed above, comparison experiment system was designed, in which one 1000m³ vertical tank with top roof and 8 courses was used as test object. The height and diameter of this tank is 8.9m and 12.0m respectively. Two series of radius in each course at different height (about 1/4 and 3/4 of course height) were measured by strapping method complying with the requirement of OIML R71. It took about 10 days to complete the strapping work. The calculated radius value obtained from strapping method is named as R_{st} , which is regarded as the reference value. The laser measurement system was installed near the middle of tank bottom, and the configuration parameters were list in table 1.

Table. 1 Parameters of laser measurement system

Parameters	Interval between sampled points	Maximal error Ranging	Maximal of ranging scope	Angle measurement scope	Sampling Rate	Time-consuming
Value	2mm	± 2mm 25m	at 80m	360°×320°	120,000points/s	2min

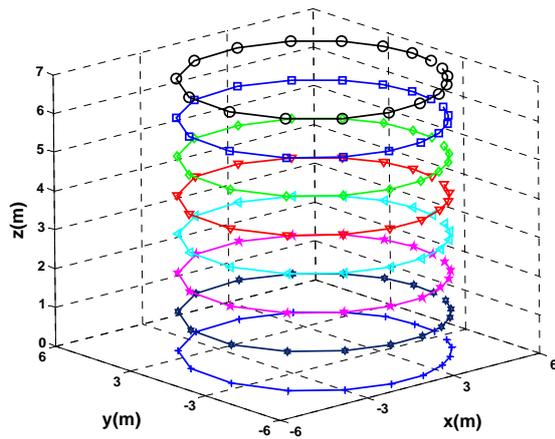


Fig.4 the space distributions of measured points from strapping method

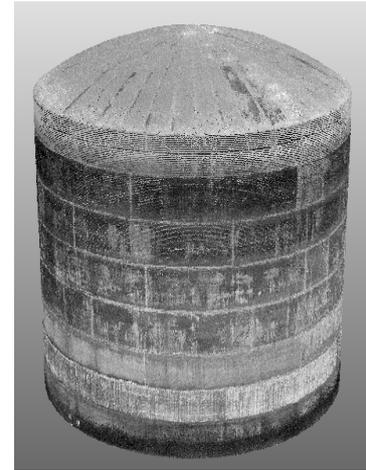


Fig.5 the space distributions of measured points from 3D laser scan method

The space distributions of measured points by two methods above were shown in Fig.4 and Fig.5 respectively. The geometric model obtained from 3D laser scan method consists of about 6,600,000 points, which is more accurate to describe the characteristics of vertical tank compared to data from the traditional strapping method including about 200 points. The data of scanned points were preceded by using two algorithms discussed to achieve the fitting value of radius at each course, which are expressed as R_{DIM} and R_{LSM} . The computation results between strapping method and laser scan method were shown in table 2.

Table.2 The computation results between strapping method and laser scan method

Course ID	Location	Computation Result Of Fitting Radius				
		R_{st}/mm	R_{DIM}/mm	$ R_{DIM}-R_{st} /mm$	R_{LSM}/mm	$ R_{LSM}-R_{st} /mm$
1	3/4 of course height	5980.2	5979.8	0.4	5979.8	0.4
2	1/4 of course height	5973.7	5974.2	0.5	5974.3	0.6
2	3/4 of course height	5972.6	5971.9	0.7	5971.9	0.7
3	1/4 of course height	5967.7	5965.6	2.1	5965.6	2.1
3	3/4 of course height	5967.2	5966.8	0.4	5966.9	0.3
4	1/4 of course height	5962.2	5962.1	0.1	5962.1	0.1
4	3/4 of course height	5961.3	5960.7	0.6	5960.7	0.6
5	1/4 of course height	5957.2	5956.2	1.0	5956.2	1.0
5	3/4 of course height	5957.5	5956.5	1.0	5956.5	1.0
6	1/4 of course height	5954.7	5954.5	0.2	5954.5	0.2
6	3/4 of course height	5955.0	5953.9	1.1	5954.0	1.0
7	1/4 of course height	5951.0	5950.5	0.5	5950.6	0.4
7	3/4 of course height	5952.7	5953.0	0.3	5953.0	0.3
8	1/4 of course height	5951.7	5952.5	0.8	5952.5	0.8
8	3/4 of course height	5951.3	5948.5	2.8	5948.5	2.8

Based on the comparison experiment, it can be concluded that the radius value obtained from 3D laser scan method is well consistent with reference value achieved by manual strapping method, and the maximal deviation is 2.8mm. It took less than one hour for the whole calibration in situ, so the work efficiency can be improved greatly by the new method.

On the other hand, the radius values calculated by DIM and LSM algorithms are so insignificant that the maximal difference is 0.1mm, thus the two algorithms can all be used to data process for vertical tank volume metrology. Algorithm based on DIM has the advantages of a simple use, but weakness of slow computation due to iterative procedure. On the contrary, algorithm based on LSM is with the merit of fast computation, but complexity.

5. Conclusions

(1) According to the technical requirements of international legal metrology recommendations, one course radius measurement method for vertical petroleum tank volume metrology was presented, based on 3D laser scan principle. The radius value obtained from 3D laser scan method is well consistent with reference value achieved by manual strapping method, and the maximal deviation is 2.8mm;

(2) Two algorithms based on DIM and LSM were studied for the computation of course radius from the scanned data, and were all verified by comparison experiment that the maximal difference of radius value from two algorithms is 0.1mm;

(3) By using the method discussed, the calibration efficiency of vertical tank volume can be improved greatly.

Acknowledgements

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