Non-contact Measurement of Damaged External Tapered Thread Based on Linear Array CCD

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Abstract. The non-contact measurement of external tapered thread based on linear array CCD is presented to decrease the measuring error caused by local damage area contrast to the measurement with mechanical gauges. The thread is scanned by linear array CCD and the signal is processed by first order difference to obtain thread contour. For the thread with damage on tooth flank and deformation on generating line, the Hough transform and weighted least squares are adopted to reduce the local defects and to set up fitted thread contour equations that can reflect the real dimension. Then the dimensions can be calculated based on these equations according to the definition. The paper also presents the method to evaluate the local damage. Experiment shows that the method is suitable for the measurement of damaged thread.

1. Introduction

The tapered thread is used in large quantity on oil tube connection and casing connection in oil field. The tubing string needs to be screwed on and screwed out several times for reasons such as bump inspection, which will deform or damage the thread to some extents, therefore the tubing threads need to be detected to ensure they are in a relative safe state for working again. The measurement of tapered thread is performed mainly by mechanical thread gauges now, in which the contact of probe with thread teeth is necessary. When the thread has deformed or damaged in local area, the defect of thread may prevent the probe from going to the right place, which will induce a certain measuring error. The non-contact measurement is a good alternative to avoid such influence by measuring the thread image. Although some researches have be done on the non-contact measurement of tapered thread based on planar and linear array CCD [1-3], they are mainly focused on the inspection of normal thread for the dimension computing methods are based on the normal structure of thread, and will result in measuring error when apply on deformed thread. Therefore new methods suit for damaged thread are required to consider the influence of defects.

A linear array CCD containing 5400 pixels with the pixel size of 5µm is applied in the paper to obtain full-scale images of tapered thread with high resolution. The first order difference is applied on the signals to extract fringe points of thread teeth. The thread contour data is further processed to decrease the influence of defects and to obtain accurate fitted contour equations for measurement. The measuring principle is presented according to the definition of each dimension and the evaluation of local damage is also given.
2. Measuring system
The study of the paper is based on the measuring system in [3], which is shown in figure 1. The image of a tapered thread in parallel optical field is projected on linear CCD, which is dragged by a step motor to scan the whole thread image. The points on thread teeth can be recognized by first order difference method at the same time of scanning [4]. The thread contour data should be fitted by least squares method to reduce recognition error and to obtain generating line and flank line equations [5], on the base of which the dimensions can be calculated according to their definition. But for the damaged thread, the contour should be further processed to decrease the effect of defects on measuring.

![Image of tapered thread measuring system based on linear array CCD.](image)

3. Damage of thread and its processing
There are mainly two types of damage on thread. One is the damage on thread teeth, such as scratch and groove, which appear on the flank, as shown in figure 2. The up part and root part of the thread tooth flank is easy to be worn away as a deep notch, but the size is small. When the thread is abraded for many times or screwed with large torque, there will be large damage area on the flank. The other one is the deformation of generating line, which is caused by the making up an external thread of smaller taper into internal thread. Different processing method are needed for each damage to decrease their effect on measurement.

3.1. Modification of thread contour with local damage
The modification of thread contour means to derive reasonable equations that can reflect the integral shape of tooth flank. When the length of damage area on projecting tooth image is less than 1/2 of the flank, the undamaged part of the flank should be taken as the measuring basis. The Hough transform is adopted to detect the points on flank line [6]. Since the contour points have been acquired, the Hough transform can be applied directly.

The line equation in Hough transform is in the form of equation (1), where \( \rho \) and \( \theta \) are the variables in parameter space.

\[
\rho = x \cos \theta + y \sin \theta
\]  

When the tapered thread is placed horizontally the flank angle of thread tooth is 60° and 120° also, therefore \( \theta \) can be limited in a narrow scope to improve detecting speed. The detecting steps of \( \rho \) and \( \theta \) are set to 0.5° and 1 respectively to effectively remove defect points. Since the points that are detected on a line are actually distributed along the line in a scope, they need to be fitted as a line by least squares to obtain more accurate contour for measurement, as shown in figure 3. The contour of a tooth with defect in figure 3(a) is obtained directly by first order difference, and in figure 3(b) the points on right flank are extracted by Hough transform and be fitted to a line by least squares, the least squares fitted line of original contour with defect is also shown. There is a certain difference between these two fitted lines in angle and position, and the line removed defect points can reflect the total shape of flank more accurately. The display scale in the two figures is different for observation convenience, so the flank angle shown in the two figures looks different.
3.2. Modification of thread contour with large area damage

It is will be impossible to obtain the points belong to original contour on the tooth flank with large area defect, so a reasonable choice is to fit the damage flank into a line with a right way that will reflect the original flank as correctly as possible. Since the damage occurs along the normal direction of the flank, the total least squares method (TLS) that considering the deviation both on $x$ direction and $y$ direction will be more suitable for acquiring accurate flank line [7]. Suppose the line equation is in the form:

$$a(x - x_0) + y = 0$$

The simplified sum of squares of distance from contour points to fitting line is:

$$d(a, x_0) = \sum_{i=1}^{n} [a(x_i - x_0) + y_i]^2$$

Then the fitting parameters of $a$ and $x_0$ can be derived by the following two equations:

$$\frac{\partial d(a, x_0)}{\partial a} = 2\sum_{i=1}^{n} [a(x_i - x_0) + y_i](x_i - x_0) = 0$$

$$\frac{\partial d(a, x_0)}{\partial x_0} = -2a\sum_{i=1}^{n} [a(x_i - x_0) + y_i] = 0$$

The fitted contour of damaged thread is shown in figure 4. The fitted contour can reflect the actual shape of flank, and the fitting confidence is 95%.

3.3. Modification of thread generating line

The measurement of thread taper and pitch depends on generating line, and because of the strict size allowance of the two dimensions the generating line obtained for measurement should has enough accuracy. The generating line can be acquired by fitting the all the peaks of thread tooth root into a line. Since the wall of end part of tapered thread is thinner and easy to deform, when screwed into an internal thread the generating line of the end part will deflect toward axis, seen in figure 5. The other part of the thread generating line will keep their original shape because of the thicker wall, so when used for thread pitch measurement the generating line should take its original shape and the fitted line of deformed shape can be used for actual thread taper measuring. When the least squares are used to
fit generating line, the deviation of end part will induce larger fitting error. The weighted least squares method (WLS) [8] is adopted to consider the different effect of each data point on generating line fitting and to decrease the larger influence of end part on fitting result.

Figure 4. Contour of thread with large damage area and its fitted contour.

Suppose the fitted line equation is:

\[ y = kx + b \]  

The sum of squares of distance from contour points to fitted line is:

\[ d(k, b) = \sum_{i} w_i (kx_i + b - y_i)^2 \]  

Where \( w_i \) is the weight of deviation, through observation the weight is chosen as 2 constants corresponding to the end 1/3 part of generating line and other part to simplify working process. The parameters \( k \) and \( b \) can be obtained by partial derivative of equation (7) to \( k \) and \( b \) respectively and let the two equations equal zero. The fitting lines of a deformed generating line with normal least squares (LS) and weighted least squares are shown in figure 5. The normalized weight of end 1/3 part is 0.1 and the other part is 0.9 in the figure. It can be seen in figure 5, the weighted fitting line is more in accordance with the original generating line and can ensure the measurement of thread pitch, yet the normal fitting line can reflect the change in thread taper.

Figure 5. Deformation of generating line and its fitted lines.

4. Thread dimensions measurement

The dimensions need to be measured are thread taper, thread pitch, thread height and thread angle. The measurement of these dimensions on normal tapered thread can be seen in [3], and the measurement of damaged thread can still adopt these methods but the contour equations that the measurement refer to are replaced by the ones obtained in this paper, the measurement should also follow a certain sequence to decrease the effect of error transfer.

The generating line should be fitted first by WLS to measure the thread taper before deformation, which will be referred to in subsequent measurement. The normal LS fitting generating line can be used to compute the actual thread taper after deformation. The thread angle can be derived from the included angle of two fitted flank lines of a thread tooth. The thread height refers to the distance between the peaks of tooth top and tooth root along the direction vertical to axis. The WLS is used to
fit the generating line on teeth top and teeth root, such the direction of axis can be determined by
generating line and the measuring direction of thread height is derived consequently. With the fitted
flank line and generating line the thread pitch can be computed according to its definition.

Three damage evaluation criterions are presented to reflect the level of local damage and
deformation. The first criterion is the width of defects on tooth flank. The second one is the depth of
defect, which is the deepest distance of defect measured along the normal direction of flank. The third
one is the fluctuation of defect, which is expressed as the mean deviation of all the defect point to the
fitted flank line. All three criterions can be calculated after the damage area being recognized.

5. Experiment

An 2.5" oil tube thread that has been screwed for 8 times and obvious scratch can be seen on the
surface of tooth is measured with both mechanical gauges and non-contact system in this paper. The
measuring result is shown in table 1, in which the dimensions measured by mechanical gauges have
larger size deviation with their nominal value, and the thread pitch even exceeds its tolerance. Yet the
dimensions measured by non-contact system show better size stability. In fact when observed through
tool microscope, the larger groove marks can be seen on the teeth of both thread end and thread tail,
and the damage of thread end is much larger, which means the thread end has born large extrusion
force and the generating line of this part will deform. From the result in table 1, the probe of
mechanical has been interfered by the two kinds of damage and thus caused larger measuring error.

|                  | Thread taper (m/m) | Thread angle (°) | Thread height (mm) | Thread pitch (mm) |
|------------------|--------------------|------------------|--------------------|-------------------|
| Normal value     | 0.0625             | 60.0             | 1.412              | 2.540             |
| Mechanical gauge | 0.0678             | 60.5             | 1.391              | 2.622             |
| Non-contact system| 0.0611             | 59.5             | 1.405              | 2.581             |

6. Conclusion

The non-contact measurement of damaged thread can ensure the dimension accuracy on the whole by
decreasing the influence of damage area on measurement, and the local damage scale can also been
reflect by three evaluation criterion. The experiment shows non-contact measurement can not only
remove the measuring error accompanied with mechanical gauges but also improve the measuring
efficiency. Since several processing methods are needed for different damage, the measurement still
needs the participation of person. Further study should be carried out to realize measuring automation.

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