IV Conferencia Panamericana de END
Buenos Aires – Octubre 2007

AAENDE
Asociación Argentina de Ensayos No Destructivos y Estructurales

Laser displacement sensor characterization for use in optical gauging of threaded pipes

Sebastián Berra, Javier Etcheverry, Nicolás Bonadeo
Center for Industrial Research, TenarisSiderca
Campana, Prov. Buenos Aires, CP 2804, Argentina
+54 (3489) 435089
nbonadeo@tenaris.com

Abstract

The accuracy to which the physical dimensions of steel pipe threads are machined is important to guarantee the performance of a connection. These dimensions are routinely measured manually with mechanical calipers and gauges specifically designed for that purpose. As the industry evolves to more demanding applications, the thread designs become more complex and manufacturing tolerances are narrowed down (0.001" in many parameters). To obtain this level of accuracy with manual gauges requires a very strict instrument calibration and a great effort from the inspectors. Here, the use of laser displacement sensors is proposed as an alternative method for thread inspection. The main advantages of this technique are the non-contact nature of the sensor, the fast automatic inspection, and high accuracy of the measurements. The major challenges to overcome are the effects of the high reflectivity of the machined surface, the spurious signals when inspecting edges and the hostile industrial environment.
Data is presented on the effects of surface condition on the performance of laser displacement sensors and the characterization of the real data rate. Results of the measurement on step height, taper, and pitch standards are shown and their accuracy is discussed.

1. Introduction

The quality of the pipe thread connection used by the oil and gas industry is important for the integrity of the pipe column; therefore, several parameters are measured routinely by the pipe manufacturers in their mills. These parameters include thread step height, pitch, taper, and thread length. The use of mechanical gauges to perform these measurements requires strict calibrations and great effort from inspectors to achieve the level of accuracy imposed by the low tolerances admitted in nowadays demanding applications.
An optical gauge based on laser triangulation displacement sensors could offer a non-contact, fast, automatic and accurate means to measure multiple thread parameters and provide a way to record those parameters automatically, ensuring the correct transfer of information to the data base. However, because of their working principle, these sensors have been specified to work and perform better with diffused surfaces. To the contrary, pipe threads exhibit a machined surface with high specular reflectivity and speckel

pattern formation. Therefore, manufacturer specifications cannot be used as a guideline for the performance, and sensors need to be tested for these specific conditions.

In addition, thread parameters such as pitch thread require a precise measurement of the edge location in the dimension perpendicular to the laser propagation. The precision of such measurement depends on the sensor type, laser spot and post processing of the data performed by the sensor head that are not specified in detail by manufacturers. Therefore, as a starting point for the development of an optical gauge, a thorough characterization of the basic properties of two commercially available laser displacement sensors based on different sensor technologies have been performed: the LK-031 manufactured by Keyence that has a CCD as a detector, and the LMI that is based on a position sensor device (PSD). As result of these tests the LMI sensor has been discarded for this application and limitations on the data rate and edge locations on the Keyence sensor have been clearly revealed.

2. Fundamentals of laser triangulation method

The laser displacement sensors are based on the ancient technique of using angles to measure distances via triangulation. Light scattered by the object surface at different distances arrives at the collecting lens at different angles; then the lens transforms the angle into position by imaging the spot onto the detector. Figure 1 shows a schematic view of the device. Light from a laser is focused on the sample by a set of optics. If the laser source is a diode laser, cylindrical lenses are necessary to correct for the beam ellipticity. The light scattered by the sample is captured and focused by collection lenses onto the detector. The spot position, which is proportional to the sensor-to-sample distance, shifts up and down as the measured surface moves downward and upward. Although according to geometrical optics the relationship between the surface-to-sensor distance and spot position is linear, aberration in the collection optics, non homogeneous spot intensity, spurious reflections and detector nonlinearities can make this relationship very complex. Whether these negative effects can be corrected or minimized depends on the choice of detector, controller algorithm and linearization.

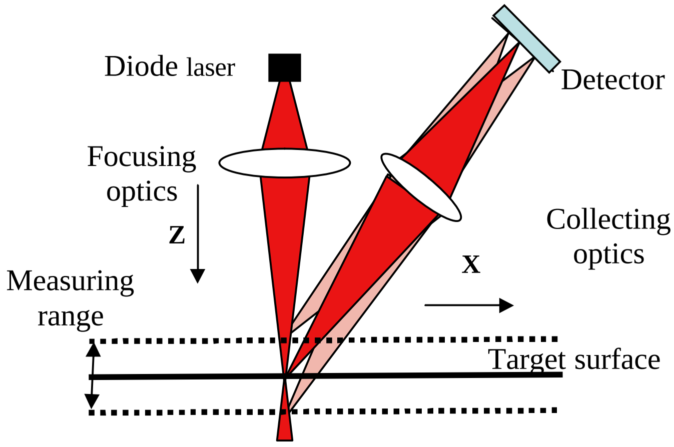

Figure 1: Diagram of a displacement sensor based on laser triangulation.

Although the device has spatial resolution on the X direction (see Figure 1), it is designed to measure distances in the Z direction. There is a clear compromise between the spot size (i.e. spatial resolution) and the sensor range given by the divergence of the laser spot.
Historically, the detector of choice was a position sensitive device (PSD). This device transforms a light spot into a voltage. However, because it integrates on the whole spot, it actually reports the position of the centroid of the spot, which may not be the best estimator of the "real" position of the reflected spot. If a spurious reflection creates a second spot onto the detector the reported distance will be the weighted average of the real and artificial position. In the presence of an edge that creates two spots on the detector, corresponding to the upper and lower surfaces of the edge, the device will also fail to give the right distance.
The incorporation of a linear CCD as an image element has opened new capabilities. Now, not only it is possible to measure the spot centroid position, but also the whole spot profile. Depending on the algorithm used in the controller and on the data acquisition speed, it is possible to differentiate spurious reflections and edges. The measurement is also less sensitive to changes in relative reflectivity.

3. Experimental set up

The experiments are designed to evaluate the performance of the sensor to measure thread step heights, taper and pitch on highly reflective steel surfaces. Each of these thread characteristics requires the measurement of a physical magnitude. Step height involves measuring vertical distances, taper requires measuring small angles, and pitch involves horizontal distance measurements and edge location. Each performance is evaluated individually using gauge standards of known and calibrated dimensions corresponding to step height, wedge angle and pitch.
A three axes manual translation stage (SIP 414M Society Genevase), with positioning accuracy better than one micron, is used to place the sensor. The sensor is assembled at the head of the translation stage, with the laser beam aiming downwards. The various samples and standards used in the sensor characterization are positioned directly below the sensor. The stage is moved along the Z axis to measure linearity and surface condition effects on the calibration curve, and moved in the direction orthogonal to the laser-detector plane (X axis) to perform edge detection measurements avoiding, in this way, multiple reflections originated at the step of the sample (see Figure 2).

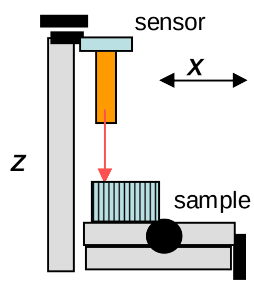

Figure 2: Side view of experimental set up

The position of the stage is read from the encoder via a serial RS232, and the sensor voltage output is measured using a National instrument PCI-6024E 12 bit data acquisition board. A LabView application automatically reads and plots the data in the computer. The stage is moved manually and each point is averaged 100 times at 10 KHz. An interval of one second is waited between points to ensure that the sensor output and stage position are synchronized.
The measurements are performed on standards with very high accuracy: standard pitch gauge, standard step height, and standard wedge angles. The use of these calibrated standards provides an excellent comparison for the sensor measurements.

4. Experimental results on the Keyence LK-031 sensor

4.1. Electronic noise measurement and sensor linearity

The electronic noise of the sensor and data acquisition board is evaluated under laboratory conditions by measuring a standard steel surface without moving the sensor or sample. The error is estimated to be less than 1 mV (1 μm) for ten averaged samples and 2-3 mV for a single measurement. The 12 bit DAC is the limitation in the latter case. In none of these conditions the electronic noise seemed to limit the performance of the sensor.
The sensor is calibrated by moving the Z axis of the translation stage and recording the position of the stage as read by the encoder and the displacement sensor output. The curves are obtained using cleaned machined steel surfaces and a sample threaded tube. The calibration curve on a threaded tube surface is shown in Figure 3, and the deviation from linear behavior for two consecutive scans in Figure 4. The calibration curve exhibits a maximum nonlinearity error of 6 μm in the 10 mm sensor range, and a standard deviation of 3 μm.

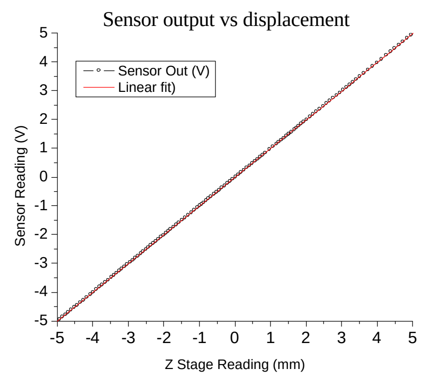

Figure 3: Sensor output vs Z-axis displacement

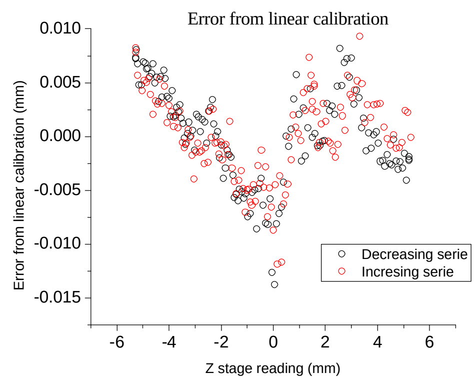

Figure 4: Error from linear fit measured for two consecutive series of data points.

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When linear fit coefficients obtained at different spots on the threaded tube are compared, deviations of the main value around 0.3% of the range are found. In a step of 1 mm the accuracy error due to this source would be only of 3 μm.

4.2. Standard step height gauge

A measurement of a standard height gauge of 1575 µm ± 3 µm is performed to evaluate the precision of the sensor in the thread step height determination. The top and bottom heights are calculated performing an average of the top and bottom points, discarding the data obtained at 300 µm from edge of the step. A typical data set is displayed in Figure 5 and a comparison of various measurements done at different places of the same standard is shown in Figure 6. As clearly seen in the graph, all the data points are within the standard accuracy.

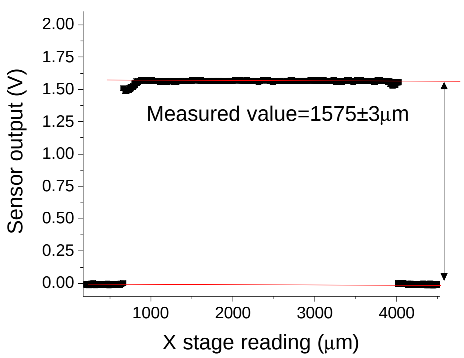

Figure 5: Measurement of standard height

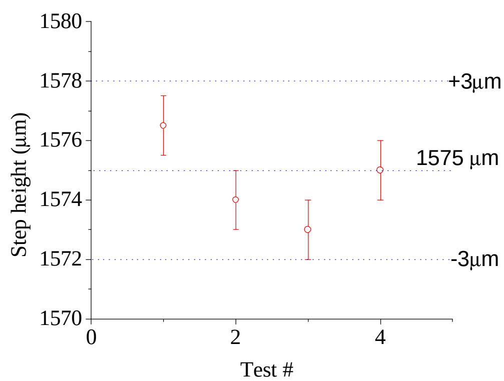

Figure 6: Comparison of various height measurements.

4.3. Standard wedge angle

Standard wedges with angle accuracies of 6” arcseconds are used to evaluate the performance of the sensor in measuring tapers and angle profiles. Measurements on several wedges with small angles in the range of typical taper values are shown Figure 7. The graph demonstrates that the sensor can measure small angles accurately.

Measurements on a standard wedge with a large angle are shown in Figure 8. Despite the small amount of light that goes toward the detector, the sensor is capable of measuring gauge angles of 30° and 45° quite accurately. A deviation is expected due to aberration in the optics, the deformation of the spot on the surface and poor signal-to-noise ratio. For angles larger than 45° degrees it was not possible to obtain measurements because for those angles the sensor is at more than 90° with respect to the reflected light, and no light reaches the detector at all. These measurements confirm the intuition that a unique sensor would not be able to measure taper, and load and stud angles.

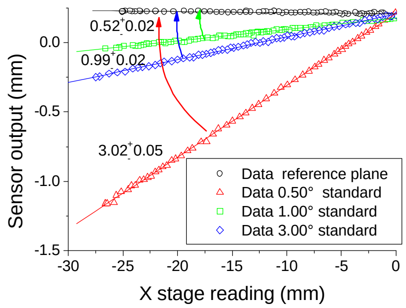	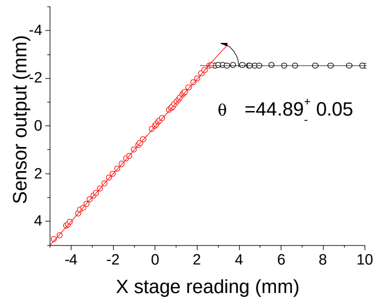
Figure 7: Measurements of Standard wedges with small angles	Figure 8: Angle measurements of a 45 degree standard wedge.

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4.4. Edge location

To make an accurate measurement of the thread pitch, the sensor needs to be able to determine the location of the edge of a step. Various characteristics are important in that measurement; the repeatability of the determination, whether the result depends on the direction in which the measurement is performed, the influence of the sensor distance to the threaded tube, and the exact orientation of the sensor. Each case is analyzed separately in the following subsections.

4.4.1 Repeatability

A series of measurements of the step edge location are performed by scanning the sensor slowly several times. The small variation on the edge location for consecutive scans indicates that the edge determination is highly repeatable with uncertainties of the order of only few microns (Figure 9). Therefore, the controller is able to distinguish the edge with much higher repeatability than the laser beam spot diameter (up to 200 um on the limit of the working range). Never an intermediate value between the top and bottom values is given and in occasions an out-of-range value is set when the sensor cannot determine which spot is the real one, but that condition occurs over a very small region.

When the direction of the movement is reverted, the measurement of the location of the edge does vary, showing clear signs of hysteresis (Figure 10). The reason for this behavior originates in the way data is processed by the sensor controller. As the laser spot scans the surface, the CCD gets an image of the spot. On a flat surface there are only one strong spot and some minor spots coming from spurious reflections which are filtered out by the controller. However, at an edge, there are two intense spots, one coming from the top and the other one from the bottom of the edge. The controller disregards the second spot as a spurious reflection until the spot becomes much larger than the initial one. When this occurs, the real edge has already been left behind.

Because this process depends on which of the spots is first imaged in the CCD (the bottom one if the movement comes from the right in Figure 10 and the top one if the movement comes from the left), the location where the edge appears changes depending on the direction of movement.

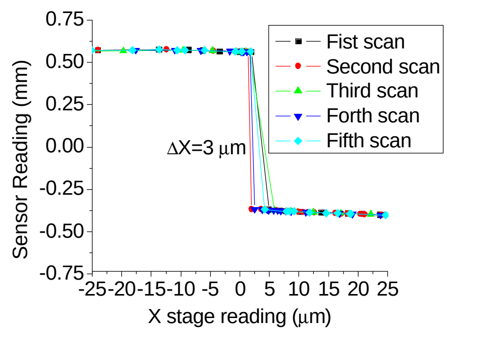

Figure 9: Edge location measurement for different sensor heights

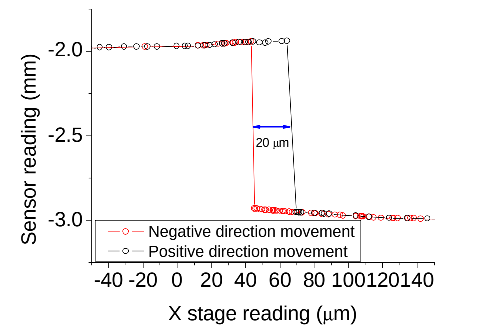

Figure 10: Edge location measurement for the positive and negative direction.

Fortunately, the controller criterion is robust, so that the edge location, although wrong in absolute value, is very consistent (see Figure 9). Therefore, if measurements are done in only one direction, all the edges are displaced by the same amount, bearing no major consequences on the pitch measurement.

4.1.2 Measurement of edge location at various sensor heights

As seen in previous sections, the way the location of the edge is chosen by the controller is quite arbitrary, so it is important to know what happens when the laser spot size becomes larger on the surface (i.e. the sample is not placed at the center of the measuring range).

In Figures11 and 12, edge profiles and edge location for various sensor heights are shown. Here, the surface of the step is scanned moving the X axis of the stage for various fixed Z-stage positions (sensor heights). The data demonstrate that the edge location is artificially changed by the sensor in a reasonably linear way within the positive and negative range. A linear fit to the positive range gives an error as large as 15µm per mm height change. This error will impact directly on a pitch measurement if the data are not taken at constant sensor-to-sample distance. For example, if a pitch is measured on thread with a 1/8 taper angle moving the sensor parallel to the axis of the tube, the pitch will appear 24 µm per inch shorter than what it really is.

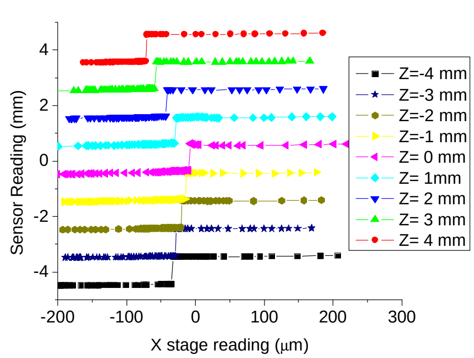

Figure 11: Edge profiles for various sensor heights

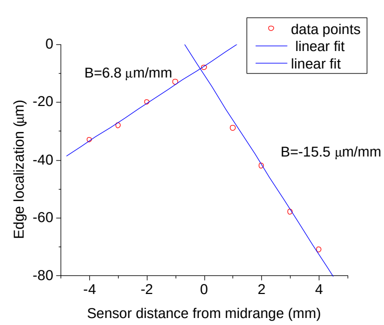

Figure 12: Edge measurement locations for various sensor heights.

This corresponds to an error of one part in a thousand, and is close to the tolerance of some premium connections. This error could be corrected in principle; however the error slopes shown in Figure 12 also depend on the exact orientation of the sensor with respect to the movement, making the implementation quite difficult. The origin of this error probably is in the large spot variations, the asymmetric nature of the beam spot and a certain degree of coma in the optics used that cannot be corrected by the controller logic.

4.2 ***Standard pitch gauge***

A Buttress standard with 5 threads per inch is used to gauge the pitch measurements. The standard has five steps corresponding to the 1st thread, 3rd thread, 8th thread, 13th thread and 18th thread. The measured average value of 5083±1.5 μm is very close to the nominal pitch of 5082.5 μm, although the individual point dispersion can be as large as 8 μm. In this measurement the type of errors discussed in section 4.1.2 due to changes in the sensor height are not expected because the measurement is done parallel to the gauge plane.

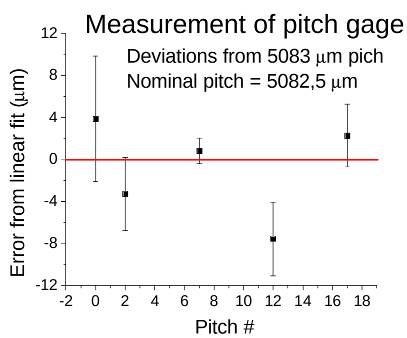

Figure B.14: Linear fit to the edge location (left) and deviation of average distance between edges (right).

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4.3 Data throughput

Although the sampling rate of the sensor is specified by the manufacturer to be around 2 KHz(1), this does not guarantee that the sensor puts a valid value at that rate. In fact the controller may decide (rightly or not) to discard a measurement because it deems it as invalid. In that case the last valid value is posted again at the output of the controller digital to analog converter. This cannot be controlled by any setting on the hardware and may occur even if the out of range alarm is set off. Because the user has no control on the criterion that the controller uses to discard a value, nor is he or she informed by any alarms, it is extremely important to understand how this limitation may distort the results. A series of measurements are performed using a rotating blade with equally spaced apertures (optical chopper shown in Figure 13). The distance detected by the sensor should be periodically modulated with amplitude Δz at the blade rotating frequency, alternating blade and support height distance values. By changing the modulation frequency an effective measurement of the ability of the sensor to adapt to height changes is obtained. The optical chopper has its own fast sensor that gives a high when the blade is in the path and a low when is blocking it, providing an accurate measurement of the real position of the blade.

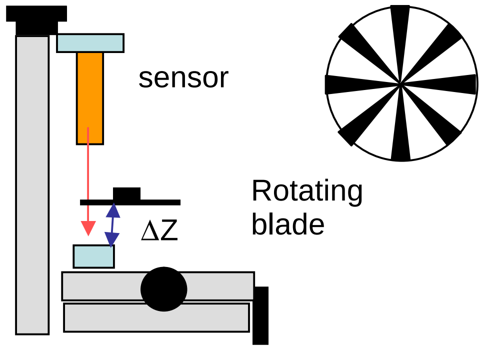

Figure 13: Set up used to estimate real data refresh rate.

Data of the sensor output (proportional to the distance measured) and the chopper output for different modulation frequencies are shown in Figure 14. As expected, for low modulated frequency both outputs coincide in time, with the edges aligned. However, as we increase the modulated frequency it is observed that the sensor output starts to lag behind the real position and misses some edges. At even higher frequency the sensor cannot keep up with the rate of change and gives a constant value.

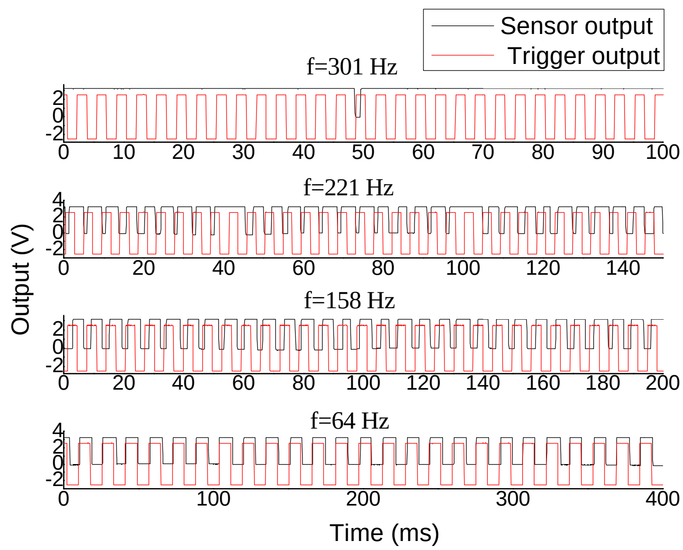

Figure 14: Sensor and trigger output for 301 Hz, 221Hz, 158 Hz and 64 Hz modulation frequencies.

These observations have serious consequences on the pitch measurements. The delay between the real and posted position can be handled as long as the scanning speed is constant; however, the invalid data points affect directly the ability to measure the edge at frequencies higher than 250 Hz. In Figure 14 the fact that at that frequency some edges are detected while others are not, originating an error on the edge determination is

clearly demonstrated. The estimated error is V/f where V is the speed of the scan and f is the maximum sensor operating modulation frequency (100 Hz).
A direct measurement of the delay can also be seen in Figure 15. Here a fast photodiode detector is placed beneath the rotating blade such that when the spot does not impact the blade, it is sensed by the photodiode.

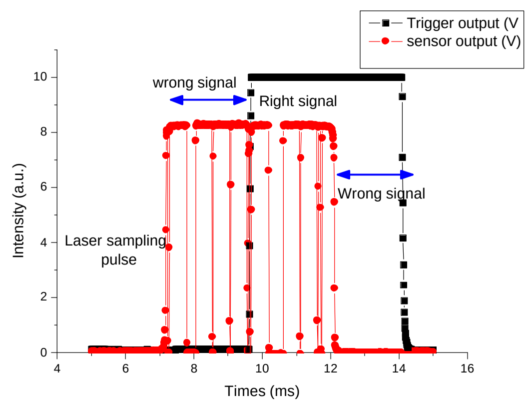

Figure 15: Comparison of the detected laser signal and sensor output.

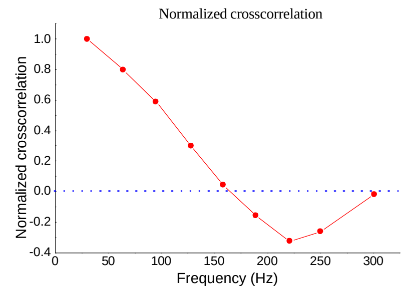

Figure 16: Normalized cross-correlation of sensor output and real blade position

The red curve has a pulse sequence at 0.5 ms intervals corresponding to the sensor sampling time. It takes many samples for the sensor to acknowledge that the surface height has in fact changed.
Using the data posted on Figure 14, the cross-correlation between the real (chopper output) and the posted position (sensor output) can be found multiplying both data. The results of that analysis, shown Figure 16, have an oscillation due to a phase lag and a damping due to missing points. To be safe it would be a reasonable criterion not to expect real data to be posted at higher data rate than 100Hz.

5. Experimental results on LMI 2401 sensor

This sensor is also based on the triangulation principle, but a position sensitive device is used for detecting the reflected light. In these detectors the signal is integrated and only the position of the centroid is given. Therefore, there is no discrimination against spurious reflections or beam deformations. For this reason the amount of data processing that the controller can do is limited to a linearization and gain equalization. However, this linearization is very sensitive to the sample surface, angle of incidence, etc. On the next section the basic characterization done for the Keyence LK-031 is followed.

5.1. Linearity

Using the set up described previously in section 2, the sensor response is measured. Deviations from a linear fit are shown not to follow a simple function and can be as large as 60 μm (Figure 17). The shape of that curve is influenced by surface and incident angle, invalidating any attempt to correct it with a higher order polynomial fit.

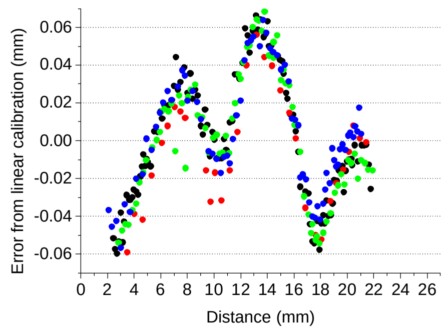

Figure 17: Deviation from linear fit for consecutive scans.

5.2. Standard step height gauge

A series of step height measurements are performed using the standard step height. The results on Figure 18 speak for themselves. The sensor cannot measure heights to the desired accuracy and performs poorly compared to the LK031 results (Figure 6).

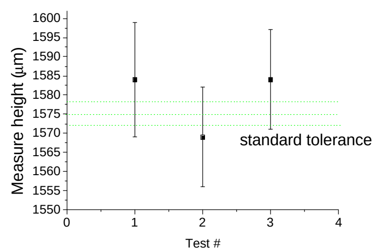

Figure 18: Standard height measurement using a LMI 2401 displacement sensor.

5.3. Edge definition

This sensor, in contrast to the CCD based ones, gives an intermediate state between the top and bottom of the step because it averages the top and bottom positions. For this reason the edges shown in Figure 19 are smooth.

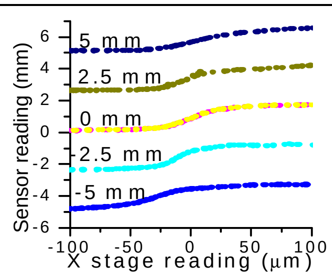

Figure 19: Edge determination as a function of sensor height. The data for the 0 mm height were taken twice to verify repeatability.

5.4 Data rate

An advantage of the PSD sensor is that there is only one detector to be read and, therefore, the data rate is actually much larger. Depending on the degree of accuracy desired it can be used up to 1.6 KHz. The response is very different than the one observed in the CCD based because the response is given by an analog low pass filter instead of a digital bandwidth processing controller.

6. Summary of experimental results and data analysis

The data show that the LK 031 sensor can measure heights and angles very well. It is also capable to locate the step edge reproducibly, in spite of the large laser spot size. However, the edge determination does vary with sensor distance, impacting directly on the pitch measurement unless they are done following the thread taper and, therefore, maintaining the sensor-sample distance.

Other undesirable characteristic is the presence of a large hysteresis when the edges are scanned in opposite direction. This artifact reflects the algorithm used by the controller to filter spurious reflections. Nevertheless, the sensor seems to have a robust way to choose between spots (high repeatability of edge location) and as long as the stage is moved always in the same direction this error does not impact the pitch measurement.

The most negative characteristic of this sensor is by far the true refresh data rate, which is 20 times smaller than the actual sampling rate. The reason for this low data rate is that the controller is not able to read the data, perform the auto-gain, filter and process the data in one sampling cycle. Therefore, it posts the last value recorded until it is sure of the new value. This makes the sensor robust but slow. It is difficult to work with a data rate of 100 Hz in long threads where the inspection time can be as long as a few minutes.

The last observation is that the sensor cannot measure angles larger than 45 degrees and, consequently, a single sensor cannot determine the taper, the load and the stab angles of the thread, even if the latter are positive.

7. Conclusions

The commercial Keyence LK 031 sensor can measure, under laboratory conditions, the thread step height, taper and pitch with the required accuracy. However, the measurement has to be done at slow data rates (100 Hz) and with limitations on the height variations. These limitations do impose some constraints in the usage of the sensor, but do not disqualify it for the intended use.

References and footnotes

1. Keyence ILD-2200 Operator manual (www.keyence.com)