Optimization of linear transducer calibration system using laser interferometer based on the Abbe principle

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Abstract. The validity of the measurement results can be guaranteed by performing calibration using a measurement standard traced to the international system of units (SI). The linear transducer is a measurement standard that is used to calibrate calibration tester, dial gauge tester, and gauge block in the calibration and testing laboratories. The critical position of the linear transducer in the traceability chain leads to the need for an optimal system to calibrate it with the smallest error and highest accuracy. As an optimization step, this research was carried out to improve linear transducer calibration performance using a laser interferometer combined with a universal length machine (ULM). The laser interferometer, ULM, and linear transducer were aligned with the Abbe and cosine principles. The results show a significant reduction of the linear transducer measurement error in the forward and backward directions by 548% and 119%, respectively. The measurement uncertainty could also be decreased by 8% to 0.18 μm.

1. Introduction
The measurement process requires four components: measuring objects, measuring instruments, measurement agents, and conditioned environment. Imperfections of the four components can cause errors so that no measurement process can provide absolute accuracy [1]. In the manufacturing, food, beverage, chemical, and cosmetics industrial processes, dimensional quantities are among the four most widely used quantities. Therefore, the equipment for dimensional quantities becomes one of the types of equipment that need to be given priority in its maintenance. Calibration plays an essential role in controlling the quality of measuring instruments used in daily life. Calibration provides knowledge about measuring instrument errors so that the reading can be corrected, along with the measurement uncertainty. As mentioned, calibrated measuring instruments can guarantee the validity of quality control, such as in the manufacturing process, the production process of agricultural and forestry tools, and measuring noise and environmental pollution [2–4].

One of the industrial and laboratory calibration measuring equipment that must be calibrated, especially in length metrology, is a linear transducer, better known as a linear variable displacement transducer (LVDT). Measuring equipment and standards such as calibration tester, inclination table, electronic level, dial gauge tester, roughness, autocollimator, and gauge block are calibrated using LVDT [5–7]. Linear transducers are even used for routine tests of asphalt mixtures, quality control of bridges with vibration measurements, fuel control at power plant facilities, and an online adaptive calibration system [8–10].

A laser interferometer is widely applied as a precision measuring instrument. Based on the Michelson interferometer, the laser is used as a measurement to reveal the phenomenal gravitational wave [11]. Besides, the laser interferometer is also used for measuring shifts with high accuracy [12,13]. This article
describes a laser interferometer as a measurement standard to calibrate linear transducer / LVDT. In the process, cosine error was reduced with proper optical alignment. Also, the Abbe principle for reducing sinus errors was applied.

2. Materials and methods

Inside the linear transducer, there is a periodic grating scale made of optics. Figure 1(a) shows the multilevel scale shape contained in the linear transducer. The LVDT position information was obtained by calculating the number of steps passed relative to their initial position. It worked based on the principle of interferential scanning, which would determine the position information. Figure 1(b) shows the principle of interfering scanning principle where it utilized diffraction and interference from light that was stratified to produce a signal to determine the position/distance measured—a light source (see figure 1(b) for scanning a silent reticle [14,15]. Reflections from multilevel scales on measuring standards would cause diffraction and light interference, converted by photocells into electronic signals.

Figure 1. (a) Grating scale inside the Linear transducer; (b). Sensing principle of LVDT [15].

Laser interferometer, which was to calibrate the linear transducer, worked with two types of polarized wavelengths and had a very close frequency difference between 1.5 to 2.0 MHz [16]. A beam splitter separated the two rays, and the first beam was directed towards the target while the second beam was deflected into a retroreflector. The second beam was reflected by the retroreflector and was forwarded to the counter located inside the laser housing. The target reflected the first ray to the counter, so the difference in the length of the two rays' path can be recorded (see figure 2). In the linear transducer calibration process, cosine error could occur due to the incompleteness of measuring lines and dimension lines. This error would cause the measurement data to be larger than the actual dimensions [17].

In measurements using a laser interferometer, cosine error and Abbe error can occur. The cosine error occurs when the moving axis and laser beam axis are not parallel in practical. The cosine error is caused by the inconsistency of the measuring line and the dimension line so that it forms an angle $\theta$, as shown in figure 2. This error causes the measurement data to be larger than the actual dimension. Reducing cosine error is done by perfecting optical alignment, where the beam splitter and target must be placed in a straight line so that the incoming beam from the laser will be reverse parallel to the counter. The value of the deviation from the dimension line getting smaller is the indicator of the decreasing of cosine error. The other error, related to angle is the sine error or Abbe error [18]. It occurs when the axis of measurement (target/retroreflector) is offset from the scale axis. The angular motion
error, e.g., pitch and yaw, causes the measurement error due to displacement. The sine error causes the measured displacement to appear longer or shorter than the actual displacement, depending on angular motion. Usually, the angular motion error of the mechanical stage can be within 20 to 30 arcsec. The Abbe error does not depend on the displacement value. Making the axis of measurement in the same axis as the scale will neglect the Abbe error.

![Figure 2](image)

**Figure 2.** Cosine error in the alignment of laser interferometer optical components [17], where: (a) retroreflector; (b) beam splitter; (c) target.

The research equipment that was used in the study is shown in figure 3. Heidenhain has made a 25 mm length of a linear transducer with the type of MT 2501. It was calibrated at the SNSU-BSN Laboratory in South Tangerang, Indonesia, using a laser interferometer made by Agilent with a type of 5519B, which had a resolution of 0.01 µm. The linear transducer was associated with a universal length measuring machine system. The universal length measuring machine shaft of motion was placed on a laser interferometer retroreflector. The transducer and shaft of motion's linear motion would cause a change in the distance of the retroreflector to the stationary beam splitter. This change in the distance would be seen on the computer screen.

![Figure 3](image)

**Figure 3.** The configuration of linear transducer calibration using the laser interferometer.

A level indicator made by Digi-fitting type DWL 280 with a resolution of 0.01° helped set the slope of the universal table measuring machine. The tilted universal table measuring machine, the beam splitter's pedestal, caused the laser beam to not align with the linear transducer movement. In this research, the slope of the universal measuring machine was adjusted by turning the two screws located at the bottom of the universal length measuring machine (see figure 3) so that the appointment of level indicators at both ends of the measuring machine showed the same value. As a result, the beam splitter
position would be parallel to the target (retroreflector). It was indicated by the beam returning to the counter on the laser head was correctly received / not deviated, or it can be said that angle $\theta$ approaches zero (see figure 2). Finally, the cosine error would be reduced significantly.

Several publications mentioned some works in designing the system based on the Abbe principle [19–22]. The same principle was applied to the research scheme, as shown in figure 3, the dashed red line shows that the axis of measurement (laser head-beam splitter-retroreflector) and the scale (linear transducer) were on the same axis. It can be said that the configuration in the research scheme had followed the Abbe principle. In the sequel, Abbe error, or other terms, sine error can be ignored.

The laser interferometer used in this study was calibrated by NMIA, Australia so that the laser displacement readings had been traced to the international system of units (SI). The calibration process was carried out by comparing the linear transducer and laser interferometer readings to produce a correction value. The universal length machine's rod moved to press the linear transducer so that the linear transducer could move forward and backward. On the same hand, the retroreflector also moved forward or backward following the universal length machine's rod movement. In this research, the percentage of cosine error decreases were calculated by comparing the forward and backward corrections of the experimental results with the previous linear transducer calibration data. It was done to see how optimal the effort had been made. The previous linear transducer calibration was done by measurement of the linear transducer without using a laser interferometer. On the contrary, the laser interferometer acted as a calibration standard in the experiments.

3. Results and discussion
The correction of forward and backward directions for previous calibration and the experiment results are shown in figure 4 and figure 5, respectively. In general, forward and backward corrections for previous calibration data had a sharper slope compared to the results of experiments that had been carried out. The vast range of correction data in the previous calibration was indicated by the vast range of correction data, namely 1.66 $\mu$m in the forward direction and 0.76 $\mu$m in the backward direction. It was very contradictory compared to the range of correction data in the experiment, namely 0.62 $\mu$m in the forward direction and 0.07 $\mu$m in the backward direction. Some references [17,23,24] explain that this phenomenon shows that there had been a considerable cosine error in the previous calibration data. The Experiments that had been done show that the laser interferometer's optimal optical alignment could significantly reduce cosine errors. Note that the zero reading of the linear transducer was the starting point of the calibration process so that the forward correction would be zero.

Another interesting thing was that both forward and backward directions at the linear transducer readings above 17 mm indicated a nearly horizontal curve. Correction values tend to be constant. If this constancy was around zero correction value, probably this indicated a better thing. However, based on figure 4 and figure 5, this constancy was at a correction value above 1.2 $\mu$m.

Table 1 shows the error calculation decreased at each measurement point. The percentage of error gives the idea of how significant the laser interferometer's optical alignment of the experiments is. The maximum correction value of the previous calibration data was 1.34 $\mu$m and 1.82 $\mu$m, respectively, in the forward and backward directions, while in this experiment was 0.57 $\mu$m and 0.73 $\mu$m, respectively, in the forward and backward directions. The maximum values in the forward and backward directions for both methods (previous and experimental data) were located at the nearly same point around the linear transducer reading of more significant than 20 mm.

There was a more than ten times decrease in cosine error in the forward direction as the result of experiments. It was achieved at a 2 mm linear transducer reading. Figure 4 at the 2 mm point also reinforced this fact, where the previous calibration data correction reached the highest positive correction point. On the other hand, the 2 mm point correction in this experiment was close to zero. In contrast, a decrease in cosine error in the backward direction of 169% occurred in the linear transducer reading of 23 mm. Figure 5 shows that at the 23 mm linear calibration reading, the calibration correction value of the previous data was in the lowest valley while in the experimental curve was uphill.
Figure 4. The comparison of previous calibration data and experiment results in the forward direction.

Figure 5. The comparison of previous calibration data and experiment results in the backward direction.
Table 1. The decreased of error at each measurement point.

| Linear transducer readings (mm) | Experiment results | Previous calibration | Cosine error decrease (%) |
|---------------------------------|--------------------|-----------------------|--------------------------|
|                                 | Forward correction (µm) | Backward correction (µm) | Forward correction (µm) | Backward correction (µm) |                      |
| 0                               | 0.00               | -0.49                 | 0.00                     | -0.58                   | 0                     |
| 1                               | 0.05               | -0.54                 | 0.32                     | -0.78                   | 495                   |
| 2                               | 0.00               | -0.53                 | 0.32                     | -0.80                   | 10064                 |
| 3                               | -0.03              | -0.51                 | 0.16                     | -0.92                   | 710                   |
| 4                               | -0.05              | -0.53                 | 0.02                     | -0.96                   | 143                   |
| 5                               | -0.12              | -0.56                 | -0.18                    | -1.12                   | 46                    |
| 6                               | -0.15              | -0.59                 | -0.22                    | -1.22                   | 48                    |
| 7                               | -0.19              | -0.60                 | -0.38                    | -1.32                   | 104                   |
| 8                               | -0.21              | -0.62                 | -0.48                    | -1.32                   | 134                   |
| 9                               | -0.26              | -0.63                 | -0.60                    | -1.36                   | 127                   |
| 10                              | -0.31              | -0.66                 | -0.68                    | -1.42                   | 117                   |
| 11                              | -0.32              | -0.67                 | -0.78                    | -1.46                   | 143                   |
| 12                              | -0.34              | -0.63                 | -0.86                    | -1.46                   | 151                   |
| 13                              | -0.39              | -0.66                 | -0.98                    | -1.54                   | 152                   |
| 14                              | -0.41              | -0.70                 | -1.00                    | -1.62                   | 142                   |
| 15                              | -0.41              | -0.70                 | -1.06                    | -1.62                   | 159                   |
| 16                              | -0.45              | -0.71                 | -1.08                    | -1.66                   | 138                   |
| 17                              | -0.47              | -0.70                 | -1.12                    | -1.68                   | 141                   |
| 18                              | -0.44              | -0.73                 | -1.26                    | -1.80                   | 184                   |
| 19                              | -0.48              | -0.70                 | -1.26                    | -1.78                   | 163                   |
| 20                              | -0.51              | -0.73                 | -1.28                    | -1.80                   | 153                   |
| 21                              | -0.53              | -0.73                 | -1.32                    | -1.80                   | 149                   |
| 22                              | -0.54              | -0.66                 | -1.30                    | -1.78                   | 140                   |
| 23                              | -0.57              | -0.68                 | -1.30                    | -1.82                   | 130                   |
| 24                              | -0.49              | -0.67                 | -1.32                    | -1.80                   | 168                   |
| 25                              | -0.56              | -0.67                 | -1.34                    | -1.52                   | 140                   |

Table 1 also shows the average percentage decrease in cosine error at forward and backward directions were 548% and 119%. As mentioned before, the maximum correction value after this research was smaller than 0.80 µm, a significant decrease compared to previous calibration data, the maximum correction value reaching 1.80 µm.

Table 2 shows eight sources of uncertainty. The measurement uncertainty analysis was based on [25]. The readability of the laser interferometer came from the resolution of the laser interferometer itself. The calibration certificate of laser interferometer from NMIA Australia contributed to two sources of uncertainty: scale and air compensation errors and the laser compensation wavelength. Abbe error still appeared in the budget due to the imperfect axis alignment that could still occur. Linear transducer contributed to two sources: readability (from the resolution of LVDT) and repeatability (gained by repetitive measurement on the same point of reading). Temperature difference came from the variation.
of temperature in the laser interferometer system and linear transducer. The ultimate source, geometric and periodic error, came from the linear transducer sensing system (see figure 1). At some points, it drifts the reading so that it will cause measurement bias.

Table 2. Linear transducer calibration by using a laser interferometer uncertainty budget.

| No. | Uncertainty sources                                      | Distribution type | Standard Uncertainty (µm) |
|-----|----------------------------------------------------------|-------------------|---------------------------|
| 1   | Readability of laser interferometer                      | Rectangular       | 0.0058                    |
| 2   | Scale error and air compensation error (from laser calibration certificate) | Normal            | 0.0402                    |
| 3   | The wavelength of laser compensation                     | Normal            | 0.0000                    |
| 4   | Abbe error                                               | Rectangular       | 0.0087                    |
| 5   | Readability of linear transducer                         | Rectangular       | 0.0058                    |
| 6   | Repeatability of linear transducer                       | Type-A            | 0.0095                    |
| 7   | Temperature difference                                   | Rectangular       | 0.0035                    |
| 8   | Geometric and periodic errors                            | Rectangular       | 0.0808                    |

Combined uncertainty (µm) 0.09
Expanded uncertainty (µm), k = 2 0.18

The most significant source of uncertainty was obtained from geometric and periodic errors. The second significant source was the scale and air compensation errors from the estimated influence of temperature, humidity, and air pressure when measuring. Finally, the expanded uncertainty of the calibration system of 0.18 µm was obtained with a confidential interval of 95%. Measurement uncertainty of the previous calibration was 0.19 µm. It can be said that the uncertainty was decreased up to 8%.

4. Conclusion
A calibration system of the linear transducer using a traceable laser interferometer has been realized concerning the Abbe principle. It showed a significant reduction of the linear transducer measurement error in the forward and backward directions by 548% and 119%, respectively. The measurement uncertainty could also be decreased by 8% to 0.18 µm. This article is expected to be useful for metrologists and industries directly related to the application of dimensional measurement. As a suggestion, it is necessary to develop a new system that can vertically calibrate linear transducers to eliminate the geometric effects due to gravity.

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