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Measurement Uncertainty Evaluation for Yaw Error Reduction

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***Abstract*— The previous research compared the yaw measurement error between a rotary encoder and a couple of single beam laser (CSL) module, that those result emphasized only repeatability of yaw measurement error. In order to complete correspondingly with the metrological algorithm. This research presents the measurement uncertainty evaluation of yaw measurement error with the CSL module that based on the guide to the expression of uncertainty in measurement. The measurement uncertainty of the CSL module calibration is 12.30 arcsec.**

***Index Terms*— a couple of single beam laser, yaw measurement error, CSL module, calibration, measurement uncertainty,**

I. INTRODUCTION

THE last research designed to reduce the yaw error measurement by using the couple of single beam laser (CSL) that has been developing since 2017 [1],[2], this technique is more accurate than the rotary encoder. However, the result is without the measurement uncertainty (MU).

The measurement uncertainty analysis of yaw measurement error with CSL technique. Their repeatability, long-term stability and accuracy of yaw sensor [3] obviously reduced by using the CSL optical techniques. Although the previous research, their repeatability 0.85 arcsec, the measurement error reduction would need to achieve within 0.1%. However, the result lacked of the MU evaluation that is an importance part of measurement error. In order to complete measurement error of their result, hence the MU evaluation would appropriately to be consideration. There are many source of uncertainty budgets that it would effectively measurement error such as optical part, mechanical part, and angular measurement system. Moreover, it includes technically review of probability distribution, flow chart, and mathematic model analysis, as well.

This paper evaluated the measurement uncertainty of yaw measurement error [4] with CSL technique following the guide to the expression of uncertainty in measurement (GUM, JCGM 100, 2008) [5]. Generally, yaw measurement error depends on the factor of parameters such as, repeatability, stability, eccentric error, and sensitivity (table of result) with the appropriately probability distributions. The analysis of measurement error distribution was significantly discussion. The result of yaw measurement error with the measurement uncertainty is 12.0 arcsec appropriately.

The next research planning of the CSL module would applied to the commercial inclinometer or electronic level.

II. A COUPLE SINGLE BEAM LASER AND YAW MODULE

There are consist of two main parts, this optical yaw module with the angular measurement system used the two frequencies laser interferometer [6] - [8] to create the couple single beam laser module. These principle based on single beam laser technique that mixed incidence beam together with reflection beam. The single beam laser used bilaterally for short-range angular application ± 600 arcsec.

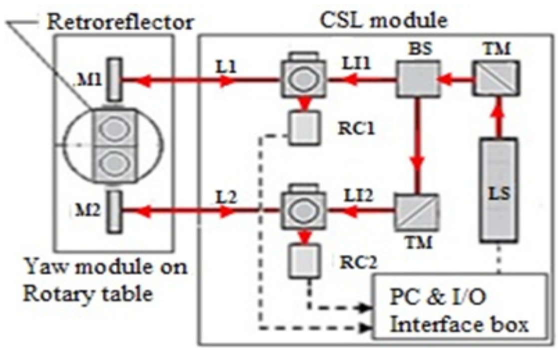

Fig. 1. The couple single beam laser setup on CSL module.

The calibration method used directly comparison method with the angular measurement system of laboratory. The CSL module setup on high precision rotary table as shown in Fig. 1, with upper range + 600 arcsec (positive direction) and lower range -600 arcsec (negative direction). The repeatability observed both direction as well, the calibration setup as Fig. 2 .

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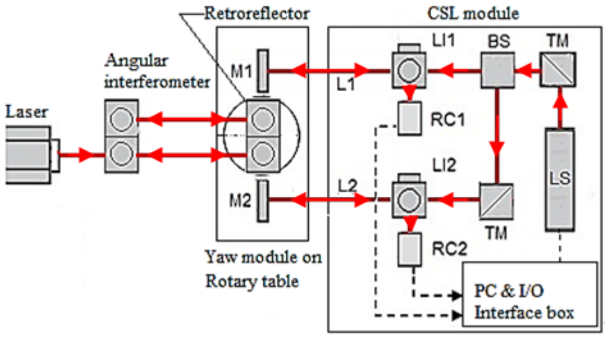

Fig. 2.The CSL module setup on high precision rotary table.

III. MEASUREMENT UNCERTAINTY EVALUATION

This measurement uncertainty evaluation based on the guideline to the expression of uncertainty in measurement, as mentioned above. Hence, the source of measurement uncertainty budgets as following.

- Repeatability is the deviation of CSL: u_D
- Reference standard is angular measurement system: u_S
- Drift of standard is specification of angular measurement system : u_d
- Resolution is standard and CSL: $u_{rs,rcsl}$
- Misalignment is standard and CSL: $u_{ms,\ mcsl}$
- Eccentricity error : u_e

The eccentricity error (*e*) of retro-reflector would aligned with small eccentric error of forward and backward direction in Fig. 3.

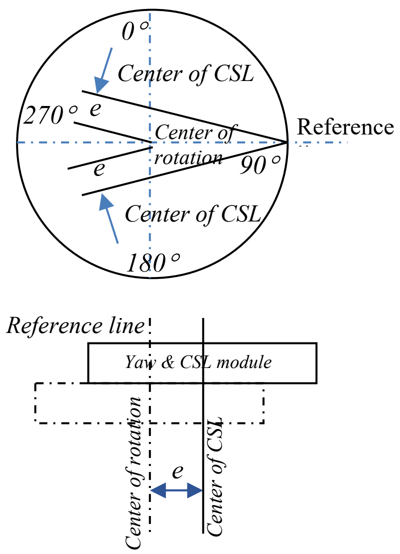

Fig. 3. Eccentric error of yaw and CSL module setup.

However, the magnetic bearing would not evaluate as a source of uncertainty budget. Because the electro-magnetic field strength is very low that means the contactless magnetic levitation (maglev) bearing has no any effect to measurement system, when compare with the others sources, such as repeatability, resolution etc. The measurement uncertainty of magnetic is equal to zero ($u_{mag}=0$). However, this would be considering the yaw measurement error reduced by using together with the maglev.

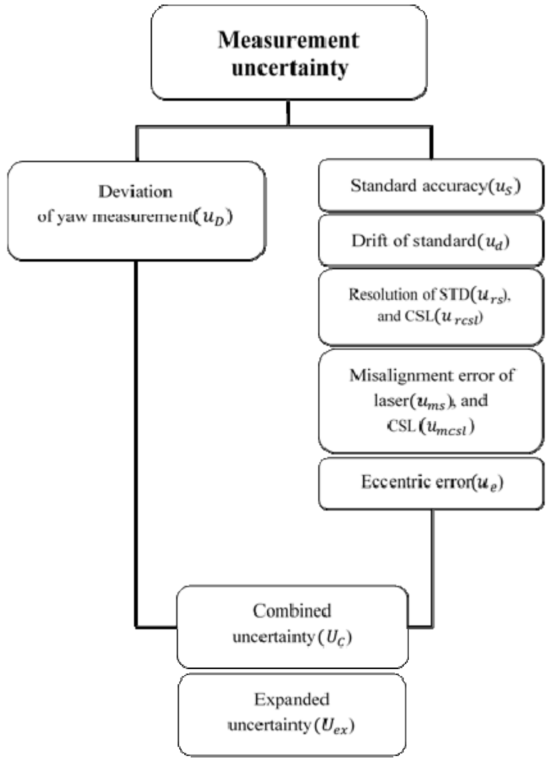

Fig. 4. Flowchart sources of uncertainty budget evaluation.

The combination of uncertainty sources as flowchart in Fig.4, can write in mathematical model of yaw measurement uncertainty from Eq. (1) and the sum square, as Eq. (2) , the measurement uncertainty of the measured yaw angle, $U\phi_{(xi)}$ the accumulated yaw angle *is* $\phi_{(xi)}$, as equations following.

$$U_y = U\phi_{(xi)} \quad (1)$$

$\phi_{(xi)}$ is the measured yaw angle

$$U_y^2 = u_D^2 + u_s^2 + u_d^2 + u_{(rs,rcsl)}^2 + u_{(ms,mcsl)}^2 + u_e^2 \quad (2)$$

Each sources of measurement uncertainty budgets were declared such as, u_D^2, u_s^2, u_d^2, $u_{rs,rcsl}^2$, $u_{ms,mcsl}^2$, and in case of eccentric error uncertainty u_e^2 still not change from the previous value, caused by limitation of setup equipment.

A. Deviation of yaw measurement with CSL (u_D), set as type A uncertainty from the repeatability is 0.85 arcsec. Therefore, uncertainty contribution is estimated as, $0.85/\sqrt{3}$ = 0.491 arcsec.

B. Reference standard (u_S), specification of angular laser measurement system is 0.05 arcsec, with the rectangular distribution Therefore, uncertainty contribution estimated as, $0.05/\sqrt{3}$ = 0.0288 arcsec.

C. Drift of standard (u_d), evaluated from specification of standard is 0.05 arcsec, with the rectangular distribution, therefore uncertainty contribution estimated as, $0.05/\sqrt{3}$ = 0.0288 arcsec.

D. Resolution of standard and CSL ($u_{rs,rcsl}$), uncertainty due to resolution of standard and CSL estimated as, $0.1/\sqrt{3}$ = 0.058 arcsec, and $0.8/\sqrt{3}$ = 0.46 arcsec respectively.

E. Misalignment of standard and CSL ($u_{(ms,mcsl)}$), uncertainty for misalignment of standard and CSL with the rectangular distribution estimated as, $0.5/\sqrt{3}$ = 0.288 arcsec, and $0.5/\sqrt{3}$ = 0.288 arcsec respectively.

F. Eccentric error (u_e), uncertainty for axis error setting of rotation, with the rectangular distribution estimated as, $10/\sqrt{3}$ = 5.774 arcsec.

The combined uncertainty (U_c) is about 5.84 arcsec and the expanded uncertainty (U_{ex}) is approximately 11.68 arcsec or report uncertainty (U_r) 12 arcsec at the confidence level 95% (k=2) as Table I.

TABLE I
THE SOURCE OF UNCERTAITY BUDGET

Symbol	Source of uncertainty	Values (arcsec)	Distribution	Standard uncertainty (arcsec)
u_D	Repeatability	0.85	t-distribution	0.491
u_S	Standard accuracy	0.05	Rectangular	0.029
u_d	Drift of standard	0.05	Rectangular	0.029
u_{rs}	Resolution of standard	0.10	Rectangular	0.058
u_{ry}	Resolution of CSL	1.00	Rectangular	0.577
u_{ms}	Misalignment of laser	0.50	Rectangular	0.289
u_{my}	Misalignment of CSL	0.50	Rectangular	0.289
u_e	Eccentric error	10.00	Rectangular	5.774
	Combined uncertainty			5.84
	Expanded uncertaint	k = 2.0		11.68
	Report uncertainty			12.00

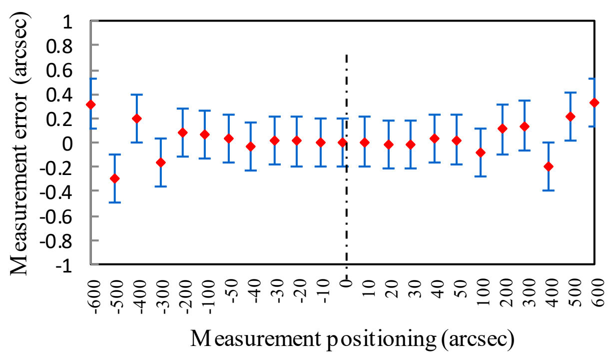

Fig.5. The calibration of CSL& yaw module.

The result of yaw and CSL module calibration as shown in Fig. 5. The bilateral measurement maximum error approximately is 0.33 arcsec observation with range ± 600 arcsec. The measurement maximum error approximately is about 0.08 arcsec observation with range ± 100 arcsec, and measurement maximum error approximately is about 0.04 arcsec observation with range ± 50 arcsec as shown in Table II.

TABLE II
THE MAXIMUM ERROR OF CSL MODULE

Range (arcsec)	Maximum error (arcsec)	Ur (arcsec)
600	0.32	12
100	-0.08	12
50	0.03	12
0	0	12
-50	0.04	12
-100	0.07	12
-600	0.33	12

IV. Conclusion

The calibration result of yaw and CSL module as shown in Fig. 5 with achieves the measurement uncertainty 12.0 arcsec. The discussion of the residual source that is eccentric error about 10 arcsec. It is very hard to cancel this big uncertainty budget in measurement uncertainty.

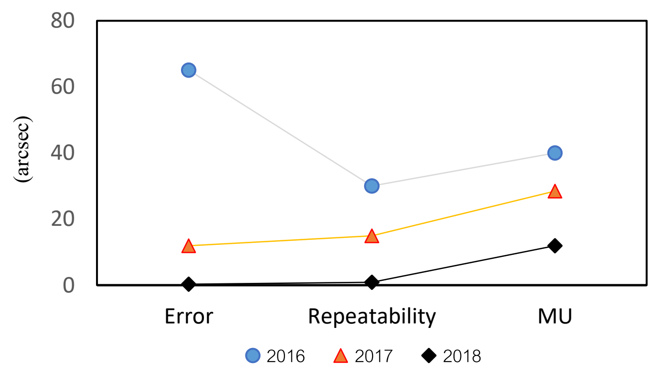

Fig.6. Technical comparison of yaw measurement error.

The historical result of yaw measurement error have been developing since 2016 in Fig. 6, repeatability and measurement uncertainty in year 2016 are approximately 65 arcsec and 30 arcsec respectively, with measurement uncertainty approximately 40 arcsec. In year 2017, the yaw measurement are approximately 12 arcsec and 14.9 arcsec respectively, with measurement uncertainty approximately 28.5 arcsec. Moreover, the last year result of measurement error reduced 11.7 arcsec, and the repeatability compared with the last result is better than 14.1 arcsec at the same measuring point (± 600 arcsec).

The development of yaw sensor employs the interferometer technique which is a couple single beam module, it built-in a small optical device in the module. This is smart choice for the application of yaw measurement error. Their results showed obviously that the measurement accuracy is less than a commercial rotary encoder in the

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same measurement conditions. In addition, it has no limit and it is easier to setup for the long-range measurement applications.

The next research would investigate long-term stability of CSL module or yaw capacitive sensor while setting in the inclinometer for roll, pitch, and yaw measurement application.

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