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Uncertainty Evaluation of a multi-axis Force/Moment Sensor

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ABSTRACT

This paper describes the methods for calibration and evaluation of the relative expanded uncertainty of a multi-axis force/moment sensor. In order to use the sensor in the industry, it should be calibrated and its relative expanded uncertainty should be also evaluated. At present, the confidence of the sensor is shown with only interference error. However, it is not accurate, because the calibrated multi-axis force/moment sensor has an interference error as well as a reproducibility error of the sensor, etc. In this paper, the methods for calibration and for evaluation of the relative expanded uncertainty of a multi-axis force/moment sensor are newly proposed. Also, a six-axis force/moment sensor is calibrated with the proposed calibration method and the relative expanded uncertainty is evaluated using the proposed uncertainty evaluation method and the calibration results. It is thought that the methods for calibration and evaluation of the uncertainty can be usually used for calibration and evaluation of the uncertainty of the multi-axis force/moment sensor.

Keywords : Relative expanded uncertainty, Interference error, Multi-component force/moment sensor, Rated output, Rated load, Calibration

1. Introduction

The multi-axis force/moment sensor, which is a body that more than two force sensors (Fx (x-direction force), Fy and Fz) or moment sensors (Mx (x-direction moment), My, Mz), measures forces Fx, Fy and Fz and moments Mx, My and Mz which are applied to it simultaneously. The force/moment sensor is used for controlling the force exerted by robots and machine tools and also for measuring forces and moments in the automobile industry, the shipbuilding industry, the electronics industry etc.

In order to use the sensor in the industry, it should be calibrated and its relative expanded uncertainty should be also evaluated. At present, the confidence of the sensor is shown with only an interference error. However, it is not accurate, because the calibrated multi-axis force/moment sensor has an interference error as well as a reproducibility error of the sensor, an error (relative expanded uncertainty) of the six-axis force/moment sensor calibrator, an error due to indicator resolution, an error due to non-zero status without a load before and after calibration and a hysteresis error. Thus, the concept of uncertainty, which is a scientific analysis of the expression for confidence, should be introduced in order to improve the accuracy of confidence[1,2,3,4]. The IOS (International Organization for Standardization) advise that one show the uncertainty instead of the confidence of the measurement result.

In this paper, the methods for calibration and evaluation of the relative expanded uncertainty of a multi-axis force/moment sensor are newly proposed. The proposed calibration method is a calibration series, which is continuing increase procedure and decrease procedure. The proposed relative expanded uncertainty is calculated by adding the confidence factor to the combined standard uncertainty, the standard uncertainty due to hysteresis error and the standard uncertainty due to interference error. Also, an example, a six-axis force/moment sensor is calibrated with the proposed calibration method and its relative expanded uncertainty is evaluated using the proposed uncertainty evaluation method and the calibration results.

2. The theory for the evaluation of uncertainty

The uncertainty is a parameter that reasonably shows the dissolution characteristic of a measurement value[1,2]. In the calibration of the multi-axis force/moment sensor, a interference error as well as a reproducibility error of the sensor, an error (relative expanded uncertainty) of the six-axis force/moment sensor calibrator, an error due to indicator resolution, an error due to non-zero at freeload before and after calibration and a hysteresis error are generated. These influence the relative expanded uncertainty of the multi-axis force/moment sensor. Therefore, the relative expanded uncertainty has to include these errors.

The relative expanded uncertainty is calculated by the following procedure. First, the net value, the average and the standard deviation are calculated for each calibration point and the A type standard uncertainty is calculated using these. Second, the B type standard uncertainty is calculated by combining the standard uncertainty of the six-axis force/moment sensor calibrator, the standard uncertainty due to the resolution of indicator and the standard uncertainty due to the non-zero status without a load before and after calibration. Third, the combined standard uncertainty is calculated by combining the A type standard uncertainty and the B type standard uncertainty. Fourth, the standard uncertainty due to hysteresis error and the standard uncertainty due to interference error are calculated. Finally, the relative expanded uncertainty is calculated by adding the confidence factor arising from the standard uncertainty combined A type standard uncertainty and B type standard uncertainty combined, the standard uncertainty due to hysteresis error and the standard uncertainty due to interference error[1,2,3,4,5,6].

2.1 The A type standard uncertainty

The A type standard uncertainty is calculated using the components that are evaluated from the results of repeated measurement in each series.

2.1.1 The net value $d_{h,ij}$

The multi-axis force/moment sensor has an initial value in freeloading state. Therefore, in order to calculate the uncertainty of the multi-axis force/moment sensor, the net value is necessarily calculated for each calibration point. For the jth repeated measurement of the calibration point for the ith step in h-direction forces and moments, the equation for calculation of net value can be written as

$$d_{h,ij} = d'_{h,ij} - d_{h,0j} \quad (h=1,\cdots,6,\ i=1,\cdots,\ j=1,\cdots) \quad (1)$$

where, $d_{h,ij}$ is the net value for the jth repeated measurement of the calibration point for the ith step in h-direction forces and moments, $d'_{h,ij}$ is the indicating value from an indicator for the jth repeated measurement of the calibration point for the ith step in h-direction forces and moments, $d_{h,0j}$ is the indicating value from an indicator at freeloading state before calibration in h-direction forces and moments. i is the order of the calibration point, j is the number of calibrations at each calibration point and h is each force and moment sensor; that is, h=1 is x-direction force sensor (Fx), h=2 is y-direction force sensor(Fy), h=3 is z-direction force sensor(Fz), h=4 is x-direction moment sensor(Mx), h=2 is y-direction moment sensor(My), h=3 is z-direction moment sensor(Mz).

2.1.2 The average value $\overline{d_{h,i}}$

The average value is calculated by the net value for each calibration point and the average value at last calibration point is used by the rated output of the multi-axis force/moment sensor. At the calibration point ith step in h-direction forces and moments. It can be calculated from the following equation:

$$\overline{d_{h,i}} = \frac{1}{n}\sum_{j=1}^{n} d_{h,ij} \quad (h=1,\cdots,6,\ i=1,\cdots,\ j=1,\cdots) \quad (2)$$

where, $\overline{d_{h,i}}$ is the average value of the net values at the calibration point for the ith step in h-direction forces and moments, n is the number of the repeated measurement for the calibration point ith step in h-direction forces and moments.

2.1.3 The standard deviation $S_{h,i}$

The standard deviation is the amount that shows the result of the dissolution characteristic in the n times measurement for each calibration point. The equation of calculation for the standard deviation can be written as

$$S_{h,i} = \sqrt{\frac{\sum_{j=1}^{n}(d_{h,ij} - \overline{d_{h,i}})^2}{n-1}} \quad (h=1,\cdots,6,i=1,\cdots,j=1,\cdots) \quad (3)$$

2.1.4 The A type standard uncertainty $u_{A,h}$

The A type standard uncertainty $u_{A,h}$ for the result of the repeated measurement for the calibration point ith step in h-direction forces and moments is calculated using the standard deviation $S_{h,i}$ and the number of the repeated measurement for the calibration point ith step. It can be expressed as

$$u_{A,h} = \left|\frac{S_{h,i}}{\sqrt{n}}\right|_{\max} \quad (h=1,2,\cdots,6,\ i=1,2,\cdots) \quad (4)$$

2.2 The B type standard uncertainty

The B type standard uncertainty is calculated from the standard uncertainty of the multi-axis force/moment sensor calibrator, the standard uncertainty due to the resolution of indicator and the standard uncertainty due to the non-zero status under freeloading before and after each calibration series.

2.2.1 The standard uncertainty of the multi-axis force/moment sensor calibrator $u_{CM,h}$

The relative expanded uncertainty of the multi-axis force/moment sensor should include the relative expanded uncertainty of the multi-axis force/moment sensor calibrator. Because this affects the relative expanded uncertainty of the multi-axis force/moment sensor. The standard uncertainty of the multi-axis force/moment sensor calibrator, $u_{CM,h}$, for the calibration point for the ith step in h-direction forces and moments is calculated from the relative expanded uncertainty of the multi-axis force/moment sensor calibrator $U_{CM,h}$, the confidence factor k and the average value $\overline{d_{h,R}}$ and it can be represented as

$$u_{CM,h} = \frac{U_{CM,h}}{k} \times \overline{d_{h,R}} \quad (h=1,2,\cdots,6,\ i=1,2,\cdots) \quad (5)$$

where, $\overline{d_{h,R}}$ the average value of the rated output of each sensor, the national standard institute generally use k=2(95%) as the confidence factor.

2.2.2 The standard uncertainty due to the resolution of indicator u_r

The relative expanded uncertainty of multi-axis force/moment sensor has to include the resolution of indicator, because it can generate an error of the sensor. The standard uncertainty due to the resolution of indicator u_r can be expressed by rectangular probability distribution and can be written as

$$u_r = \sqrt{\frac{r^2}{12}} \quad (6)$$

where, r is the resolution of indicator.

2.2.3 The standard uncertainty due to the non-zero status under freeloading $u_{z,h}$

The non-zero status of a multi-axis force/moment sensor under freeloading before and after each calibration series can be revealed and it affects the relative expanded uncertainty of the sensor. Thus, the standard uncertainty of the sensor should include the non-zero status. The standard uncertainty of the sensor due to the non-zero status under freeloading $u_{z,h}$ is calculated from the values of indicator under freeloading before and after calibration series. It can be expressed by the rectangular probability distribution and can be obtained as

$$u_{z,h} = \sqrt{\frac{(d_{h,fj} - d_{h,0j})^2}{12}} \quad (h=1,\cdots,6,j=1,\cdots) \quad (7)$$

where, $d_{h,fj}$ is the indicating value after the applied load has been removed for the calibration series 1, 2 and 3 in h-direction forces and moments and $d_{h,0j}$ is the indicating value before the calibration load is applied for the calibration series 1, 2 and 3 in h-direction forces and moments.

2.2.4 The B type standard uncertainty $u_{B,h}$

The B type standard uncertainty $u_{B,h}$ can be calculated from the standard uncertainty of the multi-axis force/moment sensor calibrator $u_{CM,h}$, the standard uncertainty due to the resolution of indicator u_r , the standard uncertainty due to the non-zero status under freeloading before and after each calibration series $u_{z,h}$. And, it can be written as

$$u_{B,h} = \sqrt{u^2{}_{CM,h} + u^2{}_r + u^2{}_{z,h}} \quad (8)$$

2.3 The combined standard uncertainty

The combined standard uncertainty $u_{c,h}$ can be calculated from the A type standard uncertainty $u_{A,h}$ and the B type standard uncertainty $u_{B,h}$ and can be written as

$$u_{c,h} = \sqrt{u^2{}_{A,h} + u^2{}_{B,h}} \tag{9}$$

2.4 The standard uncertainty due to hysteresis $u_{hys,h}$

The multi-axis force/moment sensor made of an elasticity body has a characteristic hysteresis. This affects the relative expanded uncertainty of the multi-axis force/moment sensor. Therefore, the relative expanded uncertainty has to include it. The standard uncertainty due to hysteresis $u_{hys,h}$ is calculated by subtracting the net value for the decreasing procedure from the net value for the increasing procedure, and can be expressed as

$$u_{hys,h} = \left|(d_{h,ij} - d''_{h,ij})_{\max}\right| \text{(h=1,}\cdots\text{,6,i=1,}\cdots\text{,j=1,}\cdots\text{)} \tag{10}$$

where, $d_{h,ij}$ is the net value for the increasing procedure for the jth repeated measurement of the calibration point for the ith step in h-direction forces and moments, and $d''_{h,ij}$ is the net value for the decreasing procedure for the jth repeated measurement of the calibration point in the ith step in h-direction forces and moments.

2.5 The standard uncertainty due to interference error $u_{\text{int},h}$

The interference error of the multi-axis force/moment sensor is generated from other sensors except the sensor with the rated load applied. It contributes the most the relative expanded uncertainty of the multi-axis force/moment sensor. The standard uncertainty due to interference error $u_{\text{int},h}$ can be written as

$$u_{\text{int},h} = \left[e_{\text{int},h,h'}\right]_{\max} \text{(h=1,}\cdots\text{, 6, h'=1,}\cdots\text{, 6,)} \tag{11}$$

where, $e_{\text{int},h,h'}$ is the interference error of multi-axis force/moment sensor. $e_{\text{int},1,1'}$, $\cdots$, $e_{\text{int},6,6'}$ are not the interference error, but rather the rated output of each sensor from each rated load (rated forces or moments), $e_{\text{int},1,2'}$ is the interference error from Fy force sensor when a force Fx is applied and $e_{\text{int},2,1'}$ is the interference error from Fx force sensor when a force Fy is applied.

2.6 The relative expanded uncertainty

The relative expanded uncertainty shows the confidence limits of the multi-axis force/moment sensor. The relative expanded uncertainty U_h can be calculated by adding the confidence factor k to the combined standard uncertainty $u_{c,h}$, the standard uncertainty due to hysteresis $u_{hys,h}$ and the standard uncertainty due to interference error $u_{\text{int},h}$. It can be written as

$$U_h = \left|u_{hys,h} + u_{\text{int},h} + k \times u_{c,h}\right|_{\max} \tag{12-a}$$

National standard institute generally use k=2(95%) as the confidence factor. The unit of the relative expanded uncertainty U_h is the indicating value of indicator, the equation expressed as a percent (%) can be obtained as

$$U'_h = \frac{U_h}{\overline{d_{h,R}}} \times 100(\%) \tag{12-b}$$

The relative expanded uncertainty U''_h expressed in units of force (N) or moment (Nm) can be represented as

$$U''_h = \frac{U_h}{\overline{d_{h,R}}} \times L_{F,M} \text{ (N or Nm)} \tag{12-c}$$

where, $\overline{d_{h,R}}$ is the rated output of each sensor, $L_{F,M}$ is the rated force or the rated moment.

3. The calibration method

The calibration is that force or moment which is applied to the multi-axis force/moment sensor using the multi-axis force/moment sensor calibrator and the indicating value from indicator is measured. Finally, the uncertainty of the sensor is evaluated in order to get the confidence limit. This should be performed according to the procedure of the calibration method. So, a calibration method is needed.

Fig. 1 shows the six-axis force/moment sensor calibration machine[7] that consists (1) the body, (2) the control system, (3) the measuring device. The body generates the forces Fx, Fy, Fz, and moments Mx, My, Mz, and transfers them to the multi-axis force/moment sensor installed for calibration. The control system moves up and down the weights for generating the forces Fx, Fy, Fz, and moments Mx, My, Mz. The measuring device indicates the value from the multi-axis force/moment sensor.

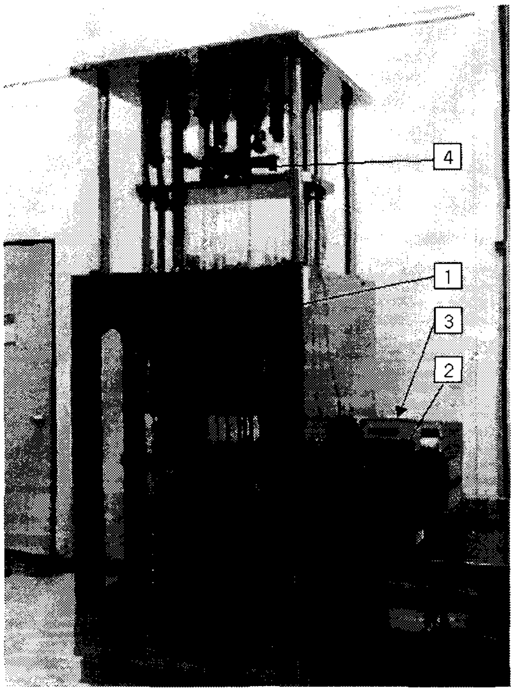

Fig. 1 The six-axis force/moment sensor calibration machine

The number of calibration points of the multi-axis force/moment sensor should be selected more than five and they should have a constant distribution over the full range, if possible. If five calibration points are selected, they are load with rated loads of 20 %, 40 %, 60 %, 80 % and 100 %.

The pre-loading test applying the rated load is performed three times in order to check the reproducibility, the state of the multi-axis force/moment sensor calibration machine, the multi-axis force/moment sensor, the indicator and so on. Its series is as shown in Fig. 2 (a). The calibration machine maintains the freeloading state for 120 s and the rated load for 30 s. The indicating value is measured after the rated load has been applied and removed.

The calibration is started within 120 s of the pre-loading test and is performed three times. Its series is as shown in Fig. 2 (b). The calibration machine is maintained in freeloading state for 120 s, and under calibration load for 30 s. The indicating value is measured after calibration load has been applied and removed.

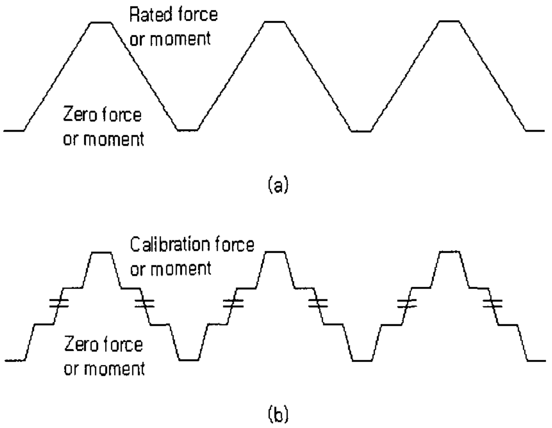

Fig. 2 Calibration series

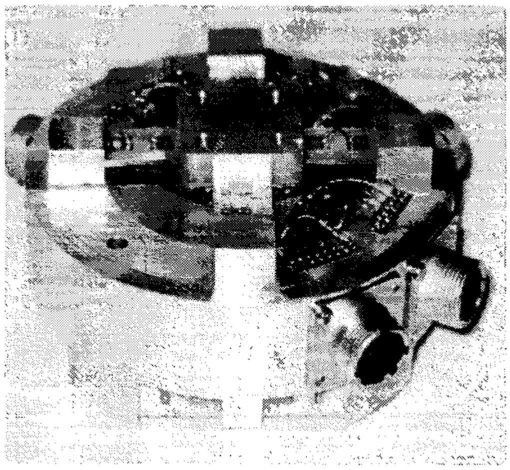

Fig. 3 Six-axis force/moment sensor

4. Results and considerations

Fig. 3 shows the used six-axis force/moment sensor for evaluating the uncertainty. This can be used for measuring forces Fx, Fy, Fz, and moments Mx, My, Mz simultaneously. The rated load of Fx snesor, Fy snesor, and Fz sensor are 100 N, and Mx snesor, My sensor and Mz sensor are 1 Nm respectively. In order to evaluate the rated strain and relative expanded uncertainty, the sensor was calibrated using the six-axis force/moment calibration machine shown in Fig. 1. The selected calibration points are 20 N, 40 N, 60 N, 80 N and 100 N for Fx snesor, Fy sensor and Fz sensor, and 0.2 Nm, 0.4 Nm, 0.6 Nm, 0.8 Nm and 1.0 Nm for Mx snesor, My sensor and Mz sensor, because the full range of each sensor is divided into five equally. The calibration was carried out three times with the increasing procedure and the decreasing procedure according to the calibration method using the six-axis force/moment sensor calibration machine. The indicating value from each sensor was measured three times for each calibration point.

Table 1 Rated output and zero error of each sensor

Sensor	Rated load	Rated output (mV/V)	Non-zero error (mV/V)
Fx	100 N	0.52782	0.00051
Fy	100 N	0.47948	0.00078
Fz	100 N	0.48070	0.00096
Mx	1 Nm	0.64724	0.00102
My	1 Nm	0.65273	0.00099
Mz	1 Nm	0.60874	0.00121

Table 2 Interference error of each sensor

Sensor	Interference error (mV/V)					
Fx	-	0.00310	0.00335	0.00159	0.00261	0.00362
Fy	0.00468	-	0.00207	0.00287	0.00032	0.00021
Fz	0.00426	0.00102	-	0.00712	0.00100	0.00263
Mx	0.00516	0.00100	0.00606	-	0.00854	0.00896
My	0.01621	0.00116	0.00114	0.00414	-	0.00148
Mz	0.00521	0.00406	0.00057	0.00166	0.00231	-

Table 1 shows the rated load, the rated output of each sensor calculated by using equations (1) and (2), and the non-zero error calculated by subtracting the value after the calibration load has been removed from the value before the calibration is started for the calibration series 1, 2, 3 in h-direction forces or moments. Table 2 shows the interference error of each sensor from calibration under each rated load.

Table 3 shows the A type standard uncertainty, the B type standard uncertainty, the combined standard uncertainty, the standard uncertainty due to hysteresis error and the standard uncertainty due to interference error from the equation for the evaluation of uncertainty according to each sensor.

The A type standard uncertainty was calculated using equation (3) and (4), and the B type standard uncertainty was calculated using equation (5)~(8). The relative expanded uncertainty of the six-axis force/moment sensor calibrator to be used for calculating the standard uncertainty of the six-axis force/moment sensor calibrator is as follows: for the Fx-axis 0.00021, for the Fy-axis 0.00018, for the Fz-axis 0.000012, for the Mx-axis 0.00031, for the My-axis 0.00029, for the Mz-axis 0.00024, and the confidence factor k is 2. The resolution of indicator (DK38 S6, made in HBM) to be used for calculating the standard uncertainty due to the resolution of indicator is 0.00001 mV/V.

The combined standard uncertainty was calculated by using equation (9), and the standard uncertainty due to hysteresis error and the standard uncertainty due to interference error were calculated by using equation (10) and (11) respectively. Finally, the relative expanded uncertainty was calculated by adding the confidence factor k to the combined standard uncertainty, the standard uncertainty due to hysteresis error, the standard uncertainty due to interference error as shown in equation (12-a)~(12-c).

The relative expanded uncertainty of each sensor was as follows: for the Fx sensor 0.91 %, for the Fy sensor 1.22 %, for the Fz sensor 1.67 %, for the Mx sensor 1.68 %, for the My sensor 2.78 % and for the Mz sensor 1.20 %. The maximum the relative expanded uncertainty of the calibrated six-axis force/moment sensor is within 2.78 %.

Table 4 shows the interference error of each sensor in percent (%). It has been used instead of the uncertainty of the sensor up to now. The calculated maximum interference error of each sensor was as follows: for the Fx sensor 0.69 %, for the Fy sensor 0.98 %, for the Fz sensor 1.48 %, for the Mx sensor 1.55 %, for the My sensor 2.48 % and for the Mz sensor 0.86 %. Therefore, the uncertainty used up to now was less expressed than its own quantity. It is as follows: for the Fx sensor 0.22 %, for the Fy sensor 0.24 %, for the Fz sensor 0.19 %, for the Mx sensor 0.13 %, for the My sensor 0.30 % and for the Mz sensor 0.34 %. That is, maximum 0.34 %.

Table 3 Uncertainty of the sensors

Sensor	A type maximum uncertainty	B type maximum uncertainty	Hysteresis maximum uncertainty	Interference maximum uncertainty	Combined uncertainty	Relative uncertainty (mV/V)	Relative uncertainty (%)	Relative uncertainty (N or Nm)
Fx	0.00021	0.00027	0.00051	0.00362	0.00034	0.00481	0.91	0.9122
Fy	0.00018	0.00031	0.00046	0.00468	0.00035	0.00585	1.22	1.2198
Fz	0.00012	0.00028	0.00029	0.00712	0.00030	0.00801	1.67	1.6671
Mx	0.00031	0.00041	0.00089	0.00896	0.00051	0.01087	1.68	0.0168
My	0.00029	0.00040	0.00094	0.01621	0.00050	0.01814	2.78	0.0278
Mz	0.00024	0.00062	0.00078	0.00521	0.00067	0.00733	1.20	0.0120

Table 4 Interference error of each sensor

Sensor	Interference error (%)						Max.
Fx	-	0.59	0.64	0.30	0.49	0.69	0.69
Fy	0.98	-	0.43	0.60	0.07	0.04	0.98
Fz	0.89	0.21	-	1.48	0.21	0.55	1.48
Mx	0.80	1.55	0.94	-	1.32	1.38	1.55
My	2.48	0.18	0.17	0.63	-	0.23	2.48
Mz	0.86	0.67	0.09	0.27	0.38	-	0.86

This is because the A type standard uncertainty, the standard uncertainty of the six-axis force/moment sensor calibrator, the standard uncertainty due to the resolution of indicator, the standard uncertainty due to non-zero status without a load before and after calibration and the standard uncertainty due to hysteresis error except the standard uncertainty due to interference error are generated. Therefore, it is guessed that the methods for calibration and evaluation of uncertainty proposed are more accurate than those used in the past.

5. Conclusions

This paper was newly proposed the methods for calibration and evaluation of uncertainty, and the six-axis force/moment sensor was calibrated with the proposed calibration method and its uncertainty was also evaluated with evaluation of uncertainty. The uncertainty (interference error) used up to now was less expressed than its own quantity. Its maximum is 0.34 %. Therefore, the proposed method for evaluation of the uncertainty can give with high confidence an evaluation of the uncertainty of the multi-axis force/moment sensor.

Thus, it is thought that the calibration method and the method for evaluation of the uncertainty can be used for calibration and evaluation of the uncertainty of a multi-axis force/moment sensor.

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