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BEHAVIOR OF PURE TORQUE AND TORQUE WITH CROSS FORCE MEASUREMENT OF TORQUE TRANSDUCER

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Abstract – This paper presents the study of behavior of torque four transducers under pure torque and torque with cross force. This explains how cross force causes the measurement result deviating from pure torque. Output signals at every 45°loading angle around measurement axis of pure torque and torque with cross forces at minimum arm length and middle arm length were compared. The result shows that cross force causes sinusoidal-like relationship between the output signals and loading angles. Moreover, cross force effect shifts the sinusoidal graph from x-axis or average of output signals was shifted from pure torque. Sine wave amplitude and degree of deviation from pure torque are directly proportional to cross force magnitude. The same transducers were tested with new developed method, called multi-cross force load procedure. The result from this method agrees with result from torque with cross force measurement. This paper also proposes the concept of evaluating torque with cross force of transducer, which had been calibrated by pure torque. The concept is to compensate the cross force effect using result from multi-cross force load procedure and to include the effect in measurement uncertainty. Furthermore, this research shows the behavior of repeatability and hysteresis error of transducers under pure torque and torque with cross force measurement.

Keywords: Pure torque, Torque with cross force, Load lateral force

1. INTRODUCTION

It is well accepted that a torque transducer responses to pure torque measurement and torque with cross force measurement differently. Besides the structural design of each transducer, degree of difference also depends on magnitude of cross force and angular position of transducer axis that cross force acts on. Thus, using a transducer, calibrated under either pure torque or torque with cross force, to measure both applications would cause some measurement error.

When torque with cross force is measured at the loading angle that best tolerates lateral force, the measurement result will be close to pure torque measurement. Cross force load procedure [1] is currently the applicable method to find the proper loading angle. Force is applied on measurement axis to find the loading angle at “zero” point of sine output signal. It is believed that this angle can best tolerate the cross force effect.

Although torque measurement was done at the appropriate loading angle, the researchers believed that the cross force effect still remains and deviation of measurement result from pure torque can be predictable. Comparison between torque with cross force and pure torque measurement were done to reveal the cross force effect, repeatability and hysteresis error. This paper led to evaluation of torque with cross force measurement from pure-torque-calibrated transducer by using reasonable uncertainty evaluation.

2. EXPERIMENTAL PLAN

Three types of commonly used torque transducers, hollow shaft, solid shaft and axial shear, were chosen in this experiment. The ranges of transducers are 200 N.m for hollow shaft and solid shaft as well as 1000 N.m for axial shear. The experiment was done at increasing torque 50% and 100 % of full range and decreasing torque 50% of full range in counter-clockwise direction. Torque standard machine 1000 N.m, model Dm-BNME 1000 N·m, manufactured by Gassmann Theiss Messtechnik was used as reference

The experiment started from installing torque transducer to torque standard machine to measure pure torque and recording the output signals for every 45° rotation around measurement axis. Then, torque with cross force was measured at middle arm length and minimum arm length as measurement diagram in figure 1. The measurement result was analyzed to find the cross force effect on output signal and loading angle at minimum cross force sensitivity.

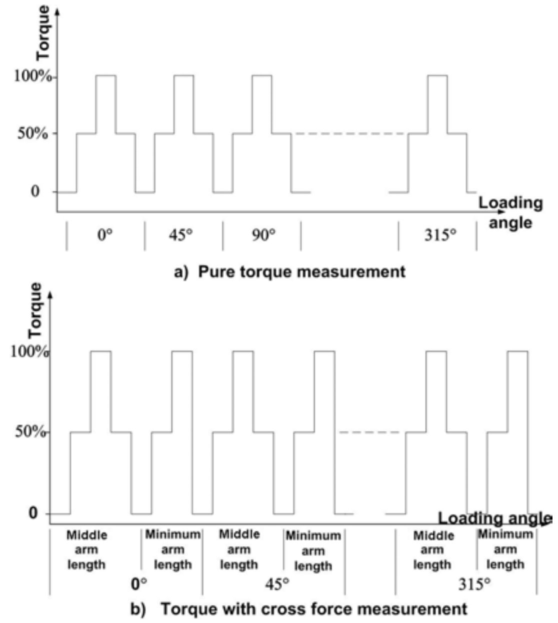

Fig. 1. Measurement diagram a) pure torque measurement b) torque with cross force measurement

The next step of experiment was multi-cross force load procedure on transducers. Forces with different magnitude were applied on measurement axis and output signals were recorded for every 45° axis rotation. The result was used to determine the conformity of this cross force effect with one from earlier experiment. Sensitivities of cross force effect from multi-cross force load procedure and pure torque measurement were used to evaluate torque with cross force.

To estimate the suitable uncertainty of torque with cross force measurement, comparisons of repeatability and hysteresis error between pure torque and torque with cross force measurement are presented.

3. RESULT AND DISCUSSION

Average value of output signals was derived from at least 5 single measurements. Results at 0° and 360° loading angle are the same set of data, but they are both shown in figure 3 for legible presentation. Magnitudes of torque, cross force and arm length of each transducer used in the experiment are described in table 1.

Table 1. Torques, cross forces, and arm lengths for transducers.

Torque Transducer	Measurement point (N×m)	Minimum lever arm length	Normal lever arm length
		Length (mm) / Cross force (N)	
Short hollow TTS1	-100 N·m -200 N·m	400 mm / 250 N, 500 N	700 mm / 143 N, 286 N
Long hollow TTS2	-100 N·m -200 N·m	400 mm / 250 N, 500 N	700 mm / 143 N, 286 N
Axial shear TTS3	-500 N·m -1,000 N·m	600 mm / 833 N, 1667 N	940 mm / 532 N, 1064 N
Solid shaft TTS4	-100 N·m -200 N·m	400 mm / 250 N, 500 N	700 mm / 143 N, 286 N

3.1 Cross force effect on output signal

Three sets of experimental result, pure torque, torque with cross force at middle arm length and torque with cross force at minimum arm length, are illustrated in figure 2 and 3 at 50% and 100% of full range. Relationship between output signal and 360° loading angle around measurement axis is sinusoidal-like graph biased from x-axis with constant value close to the result from pure torque measurement.

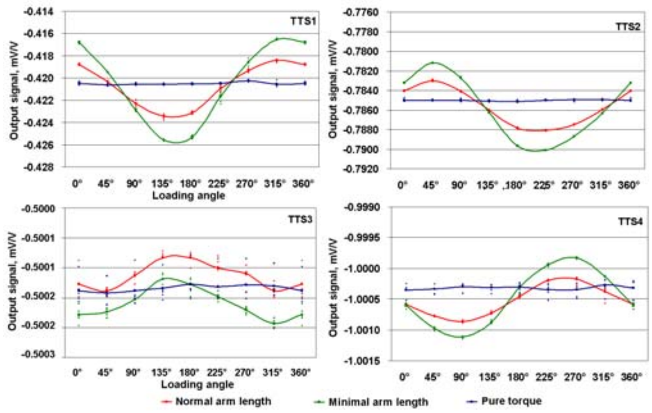

Fig. 2. Transducer output signals in mV/V at 50% of full range.

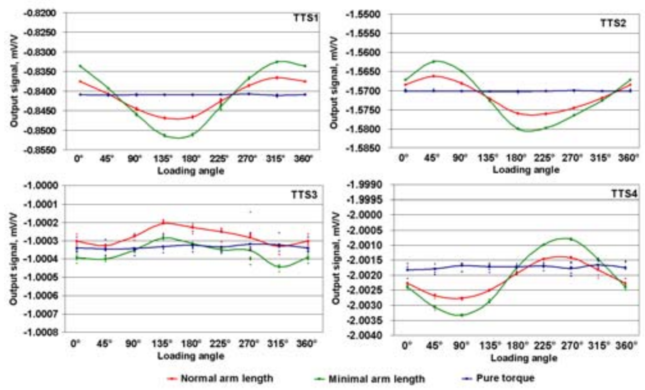

Fig. 3. Transducer output signals in mV/V at 100% of full range.

Deviations in percentage of all output signals from averaged output signal of pure torque are shown in figure 4 and 5 at 50% and 100% of full range. It was found that in each torque transducer, the zero points of sine waves were at the same loading angle for any magnitude of applied torque or magnitude of applied cross force.

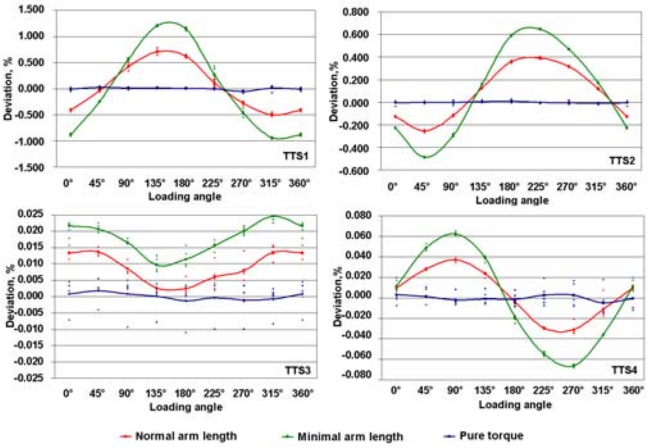

Fig. 4. Percentage deviation from averaged pure torque at 50% of full range.

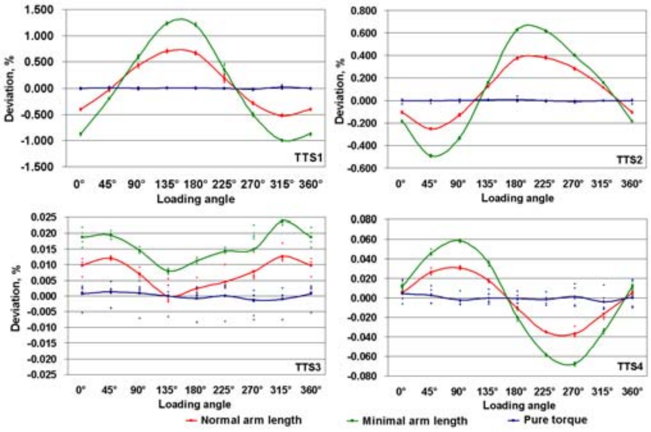

Fig. 5. Percentage deviation from averaged pure torque at 100% of full range.

Deviation between output signal of torque with cross force at middle arm length and one at minimum arm length expresses the error due to varied cross force. In figure 4 and 5, for transducers TTS1, TTS2 and TTS4, there is an intersection of two graphs: torque at middle arm length and torque at minimum arm length at a loading angle. This loading angle is assumed to be angle with minimum varied cross force error which or the point close to zero point of sine wave because at this loading angle, output signal were the same for all cross forces.

However, graphs of TTS3 did not show an intersection of output as TTS1, TTS2, and TTS4. The cross force had much less effect on sine wave amplitude; so the effect on bias of averaged output signal can be distinctly observed. In this case, loading angle at zero point of sine wave could not be the loading angle that best tolerates cross force.

Deviations in terms of deflection (mV/V) of sine wave amplitude and bias of averaged out put versus cross force magnitude is shown in figure 5 and 6. These demonstrate that cross force influenced sine wave amplitude and bias of averaged output signal. The amplitude is directly proportional to the magnitude of cross force while bias is inversely proportional.

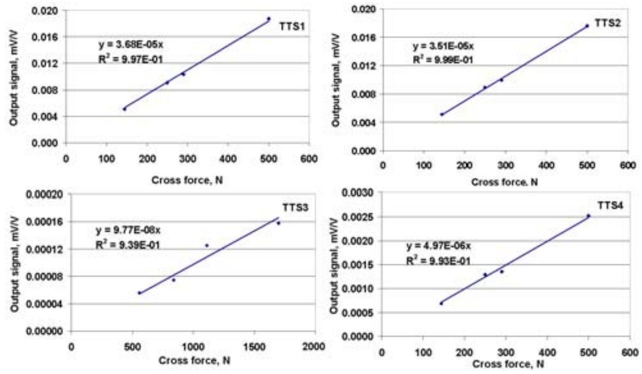

Fig. 5. Deviations in mV/V of sine wave amplitude due to cross force magnitude.

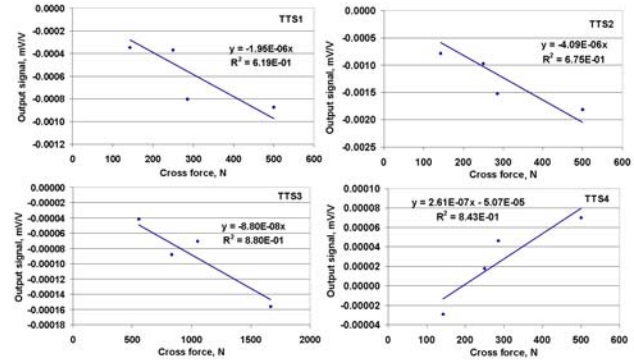

Fig. 6. Deviations in mV/V of bias of averaged output signal due to cross force magnitude.

3.2Multi-cross force load

The result shows that cross force load procedure can determine loading angle from the angle at zero point of sine wave. At this location, cross force had least effect on sine wave amplitude. However, the effect on bias of averaged output signal cannot be found by this method.

To explain the mentioned effect, the developed version, multi-cross force load, was done by loading multiple lateral forces. At least 4 applied loads were used to cover the largest torque at minimum arm length through the smallest torque at maximum arm length. Forces for torque 50% and 100% of full range at minimum arm length and maximum arm length were used as in table 1. Signals from 360° around measurement axis are shown in figure 7.

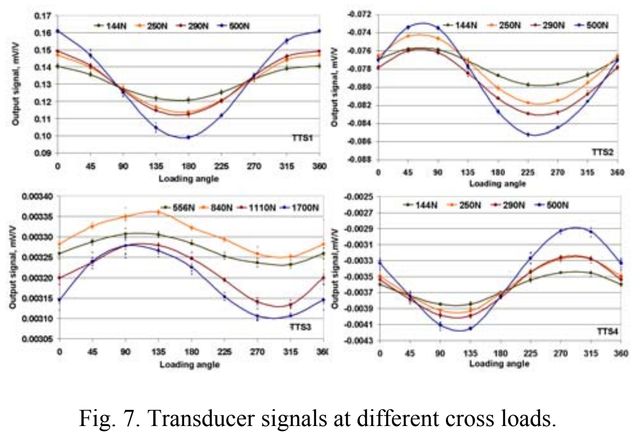

Fig. 7. Transducer signals at different cross loads.

It was found that loading angle at zero point of sine wave was the same angle from torque with cross force experiment. Sine wave amplitude and bias of averaged output signal varied proportionally to magnitude of cross force. This behavior agreed to the behavior form torque with cross force experiment as shown under 3.1.

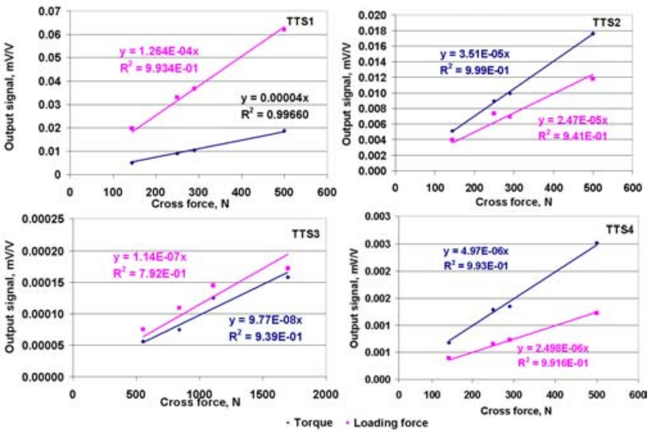

Fig. 8. Cross force effect on sine wave amplitude.

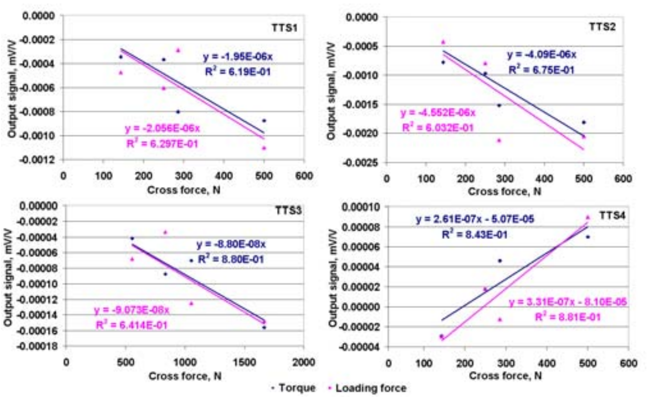

Fig. 9. Cross force effect on bias of averaged output signal.

Figure 8 and 9 illustrates the cross force effects on sine wave amplitude and bias of averaged output signal from torque with cross force loading and multi-cross force loading. Both experiments show the similar effect. Sensitivities of bias of averaged output signal (S_B) of TTS from both experiments are agreeable. Sensitivities of sine wave amplitude (S_A) are greatly varied at high cross force, but slightly different if small cross force loading angle such as ±10° was used.

3.3 Estimation of torque with cross force

The experimental result shows the possibility of using torque transducer, calibrated under pure torque condition, to measure torque with cross force. To make the measurement result more accurate, this paper proposes to compensate the cross force effect from bias of averaged output signal (O_B) and expand the measurement uncertainty with cross force effect on the sine wave amplitude, O_A as the following example.

This example is to evaluate torque with cross force of TTS4 at –500 N.m and 1000 N.m of 0.6 m and 0.94 m arm length.

From figure 5, sensitivity, S_B mV/V/N and sensitivity, S_A mV/V/N were used to calculate effect on bias of averaged output signal, O_B and effect on sine wave amplitude, O_A as in (1) and (2)

$$O_B = S_B \times CrossForce \tag{1}$$

$$O_A = S_A \times CrossForce \times \sin(\omega) \tag{2}$$

ω is loading angle, which is ±10° in this calculation. Magnitude of torque with cross force was evaluated from (3). The calculated values are shown in table 2.

$$T_{CF}^{'} = (T_P + O_B) \pm O_A \tag{3}$$

Where T_P is pure torque output signal

$T_{CF}^{'}$ is torque with cross force from calculation

T_{CF} is torque with cross force measurement result

Table 2 Example of torque with cross force calculation.

TTS1

Norminal value (N·m)	-100		-200	
T_p (mV/V)	-0.420500		-0.840994	
Arm length (mm)	400	700	400	700
Cross force (N)	250	143	500	286
S_B ($mV/V/N$)	-2.056E-06			
O_B (mV/V)	-0.00051	-0.00029	-0.00103	-0.00059
S_A ($mV/V/N$)	1.264E-04			
O_A (mV/V)	0.00549	0.00314	0.01097	0.00627
T'_{CF} (mV/V)	-0.42101	-0.42079	-0.84202	-0.84158
T_{CF} (mV/V)	-0.42087	-0.42085	-0.84187	-0.84180
Deviation (mV/V)	-0.00015	0.00005	-0.00015	0.00022
T_p-T_{CF} (%)	-0.087	-0.082	-0.104	-0.096
T'_{CF} - T_{CF} (%)	0.035	-0.013	0.018	-0.026

TTS2

Norminal value (N·m)	-100		-200	
T_p (mV/V)	-0.785005		-1.570138	
Arm length (mm)	400	700	400	700
Cross force (N)	250	143	500	286
S_B ($mV/V/N$)	-4.552E-06			
O_B (mV/V)	-0.00114	-0.00065	-0.00228	-0.00130
S_A ($mV/V/N$)	2.470E-05			
O_A (mV/V)	0.00107	0.00061	0.00214	0.00123
T'_{CF} (mV/V)	-0.78614	-0.78566	-1.57241	-1.57144
T_{CF} (mV/V)	-0.78598	-0.78579	-1.57195	-1.57166
Deviation (mV/V)	-0.00017	0.00013	-0.00047	0.00022
T_p-T_{CF} (%)	-0.124	-0.100	-0.115	-0.097
T'_{CF} - T_{CF} (%)	0.021	-0.017	0.030	-0.014

TTS 3

Norminal value (N·m)	-500		-1,000	
T_p (mV/V)	-0.500070		-1.000204	
Arm length (mm)	600	940	600	940
Cross force (N)	833	532	1667	1064
S_B ($\frac{mV/V}{N}$)	-9.07E-08			
O_B (mV/V)	-0.00008	-0.00005	-0.00015	-0.00010
S_A ($\frac{mV/V}{N}$)	1.14E-07			
O_A (mV/V)	0.00002	0.00001	0.00003	0.00002
T'_{CF} (mV/V)	-0.50015	-0.50012	-1.00035	-1.00030
T_{CF} (mV/V)	-0.50016	-0.50011	-1.00036	-1.00027
Deviation (mV/V)	0.00001	-0.00001	0.00001	-0.00003
$Tp-T_{CF}$ (%)	-0.018	-0.008	-0.016	-0.007
$T'_{CF} - T_{CF}$ (%)	-0.002	0.002	-0.001	0.003

TTS 4

Norminal value (N·m)	-100		-200	
T_p (mV/V)	-1.000492		-2.002158	
Arm length (mm)	400	700	400	700
Cross force (N)	250	143	500	286
S_B ($\frac{mV/V}{N}$)	3.3E-7*cross force -7.6E-5			
O_B (mV/V)	0.00001	-0.00003	0.00009	0.00002
S_A ($\frac{mV/V}{N}$)	2.50E-06			
O_A (mV/V)	0.00011	0.00006	0.00022	0.00012
T'_{CF} (mV/V)	-1.00049	-1.00052	-2.00207	-2.00214
T_{CF} (mV/V)	-1.00047	-1.00052	-2.00209	-2.00211
Deviation (mV/V)	-0.00001	0.00000	0.00002	-0.00003
$Tp-T_{CF}$ (%)	0.002	-0.003	0.003	0.002
$T'_{CF} - T_{CF}$ (%)	0.001	0.000	-0.001	0.001

The calculated torque is ±0.35%, ±0.30%, ±0.003%, and ±0.001% different from torque with cross force measurement result for TTS1, TTS2, TTS3, and TTS4 respectively. This shows the possibility of evaluating torque with cross force from pure torque calibration result and multi-cross force loading procedure.

3.4 Repeatability and hysteresis error

Besides the bias of averaged output signal and deviation of output signal at each loading angle, repeatability and hysteresis must also be considered. Figure 10 and 11 illustrate repeatability error and hysteresis error of pure torque and torque with cross force measurement.

Both graphs clearly show that average and variation around 360° measurement axis of hysteresis error from torque with cross force experiment is always larger than those of pure torque measurement. For repeatability error, average is not different between the measurements, but the variation of repeatability around measurement axis of torque with cross force is always larger than one of pure torque.

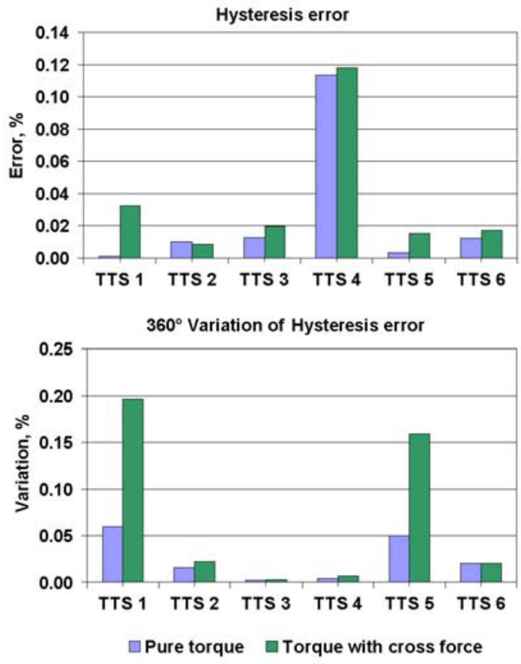

Fig. 10. Hysteresis Error.

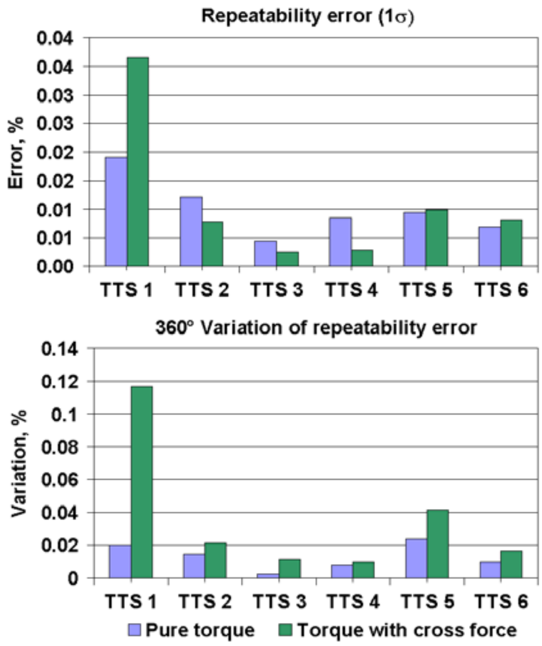

Fig. 10. Repeatability error.

4. CONCLUSION

Cross force is the main factor affecting transducer signal. It causes deviation in output signals for different loading angles and bias of averaged output signals. Sensitivities of deviation and bias were evaluated from multi-cross force loading procedure. Hysteresis error and repeatability of torque with cross force measurement is always larger than those of pure torque.

This paper proposes the method to evaluate torque with cross force by pure torque calibration and multi-cross force loading procedure. To evaluate reasonable value, uncertainty of bias of averaged output signal should be included and deviation of output signal for loading angle at zero of sine wave must cover at least ±10°. Hysteresis error should be at least 2 times of error from pure torque. However, bending moment is one factor affecting torque with cross force measurement. It should be further studied for more accurate on evaluating torque with cross force.

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