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CALIBRATION OF REFERENCE TORQUE TRANSDUCER IN ONE DIRECTION AND USE OF ITS CUBIC COEFFICIENTS IN BOTH DIRECTIONS WITH IMPROVED INTERPOLATION ERROR

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Abstract

The current research work presents an investigation into use of the fitting coefficients resulting from the cubic curve fitting of the torque transducer calibration results in one direction to calculate the actual torque in the other torque direction with two methods: one is direct substitution with the nominal torque which gives a propagated linear relative interpolation error and the other is changing the sign of the second coefficient in the cubic function when using in the other torque direction. This proposed modification improves the absolute relative interpolation error by 5 to 16 times in the clockwise and counterclockwise directions based on the torque transducer's classification.

Keywords: torque, calibration, fitting function, clockwise, counterclockwise.

1. Introduction

One way to assemble parts is tightening them with screws, and accurate tightening plays a vital role in the reliability of the assembly. Hand torque tools are appropriate tools to tighten screws to avoid loss or fracture of the screws. Hand torque tools are calibrated using simple torque devices with a torque loader to ensure uniform and accurate application for the torque. These torque devices are equipped with a reference torque transducer, and ideally, can be calibrated by using a reference torque wrench or by disassembling the reference torque transducer and then sending it for calibration on a secondary reference torque machine or a primary one that realizes the SI units.

Different calibration standards and guidelines are widely used to detail the procedures and the data analysis in torque measurement. ISO 6789 is directed at hand torque tools, it was first published in 1982 and recently revised in 2017 [1-2]. The last update of this standard was split up into two parts, one for hand torque tools conformity and the other for requirements of calibration and determination of measurement uncertainty. Once the last version was released, several researchers were inclined to investigate its added value and applicability [3-6]. For the torque transducers, which can be considered the backbone in torque measurements, DIN 51309 [7] and BS 7882 [8] are the most used standards. The last versions were issued in 2005 and 2017 respectively. Figure 1 shows the sequence for the calibration procedure (D.1) mentioned in DIN 51309.

Traceability of torque transducers either by electromagnetic force for the small range [9] or even in the MN·m range for nacelle test benches [10] is still a challenge for scientists. On the other hand, more efforts are presented in the procedure developments and analysis of torque transducer calibrations [11-12] and the influencing parameters [13-14].

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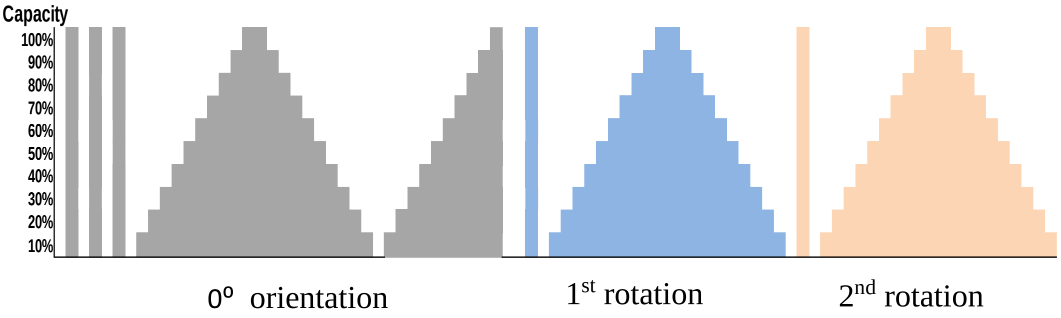

Fig. 1. Calibration procedure D.1 in DIN 51309.

The objective of this research work is to investigate the probabilities and effect of using the cubic fitting function calculated from the calibration of the torque transducer in one direction to calculate the actual torque in the other direction by direct substitution with the nominal torque. The results of this investigation are considered advantageous for the one side lever arm primary torque standard machines, reducing the time and efforts in torque calibration laboratories, for torque transducer manufacturers, and reducing the calibration fees paid by customers for calibration in both torque directions.

2. Measurement analysis

Eight torque transducers, the TN model manufactured by HBM, two for each capacity, with nominal capacities of 10 N·m to 1000 N·m were calibrated according to DIN 51309 by increasing and decreasing torque in clockwise and counterclockwise directions (Fig. 1), all of them were classified as 0.05 as per DIN 51309. These torque transducers were calibrated several times and each calibration has a code from 1 to 38 as shown in Table 1. In addition; two torque transducers, TB2 model manufactured by HBM with a nominal capacity of 3000 N·m (Code 39) and 100 N·m (Code 40) are included in the study to represent unprecise transducers in this study. Code 39 is classified as 0.2 as per DIN 51309 for both directions, whereas torque transducer Code 40 is classified as 0.2 class for the CW direction and from 40 % in the CCW direction and has 0.5 class from 10 % up to 40 % in the CCW direction. Torque transducer Code 40 has observable dissimilarity in its rated output of both CW and CCW directions.

Table 1. Torque transducers data.

Capacity	Calibration Code	Model
10 N·m	1 - 4	TN
50 N·m	5 - 14	
200 N·m	15 - 25	
1000 N·m	26 - 38	
3000 N·m	39	TB2
100 N·m	40	

Table 2 shows the coefficients of a third-degree fitting equation in the *clockwise* (CW) and *counterclockwise* (CCW) directions for the examined torque transducers. The coefficients (a_1, a_2, a_3) were deduced as a result of fitting a third-degree fitting function passing through the origin of the coordinates (1) to correlate the actual torque (M_{ai}) with the transducer deflection (S_i). (This type of error contributes to the measurement uncertainty as not all the plotted torque-deflection points are on the optimum fit line.)

$$M_{\mathrm{ai}} = a_1 \cdot S_{\mathrm{i}} + a_2 \cdot S_{\mathrm{i}}^2 + a_3 \cdot S_{\mathrm{i}}^3. \tag{1}$$

Table 2. Coefficients of a 3rd degree fitting equation.

Torque transducer		**a_1**	**a_2**	**a_3**	**Torque transducer**		**a_1**	**a_2**	**a_3**
Code1 10 N·m	CW	6.619684	-0.001251	0.000027	Code 21 200 N·m	CW	125.9676	-0.032114	0.009385
	CCW	6.619843	0.001381	0.000106		CCW	125.9682	0.031199	0.007565
Code 2 10 N·m	CW	6.620990	-0.001071	-0.000030	Code 22 200 N·m	CW	125.9675	-0.014630	0.005910
	CCW	6.62115	0.00115	0.000010		CCW	125.9706	0.017537	0.006112
Code 3 10 N·m	CW	6.621448	-0.001153	0.000021	Code 23 200 N·m	CW	116.6422	-0.013260	0.003612
	CCW	6.621274	0.001025	-0.000050		CCW	116.6306	0.001939	-0.000750
Code 4 10 N·m	CW	6.53218	-0.001280	-0.000020	Code 24 200 N·m	CW	116.7638	-0.023180	0.005920
	CCW	6.532415	0.001050	0.000080		CCW	116.7888	0.026272	0.006430
Code 5 50 N·m	CW	32.56463	-0.002710	-0.000050	Code 25 200 N·m	CW	116.6722	-0.008170	0.003146
	CCW	32.56557	0.004281	0.000946		CCW	116.6709	0.008527	0.003109
Code 6 50 N·m	CW	32.56289	-0.003580	0.000487	Code 26 1000 N·m	CW	618.3182	-0.143790	0.043360
	CCW	32.56385	0.003743	0.000652		CCW	618.3322	0.153878	0.049085
Code 7 50 N·m	CW	32.56465	-0.004810	0.000898	Code 27 1000 N·m	CW	618.3757	-0.170690	0.051758
	CCW	32.56466	0.003556	0.000555		CCW	618.3604	0.131317	0.037627
Code 8 50 N·m	CW	32.56536	-0.003890	0.000649	Code 28 1000 N·m	CW	618.3631	-0.160346	0.046378
	CCW	32.56641	0.004452	0.001042		CCW	618.3636	0.149613	0.043484
Code 9 50 N·m	CW	32.83721	-0.002000	0.000021	Code 29 1000 N·m	CW	571.4122	-0.133470	0.036872
	CCW	32.83907	0.004043	0.000622		CCW	571.4109	0.117146	0.031035
Code 10 50 N·m	CW	32.83864	-0.003770	0.000680	Code 30 1000 N·m	CW	571.4109	0.117146	0.031035
	CCW	32.83911	0.004353	0.000836		CCW	571.23	0.125253	0.032800
Code 11 50 N·m	CW	32.83879	-0.004200	0.000822	Code 31 1000 N·m	CW	571.2088	-0.158710	0.038455
	CCW	32.83901	0.003997	0.000639		CCW	571.2141	0.103739	0.027308
Code 12 50 N·m	CW	32.83984	-0.003860	0.000762	Code 32 1000 N·m	CW	617.5982	-0.130820	0.040607
	CCW	32.84062	0.004766	0.000999		CCW	617.5884	0.125064	0.027600
Code 13 50 N·m	CW	30.97146	-0.005760	0.000123	Code 33 1000 N·m	CW	617.5961	-0.169380	0.049382
	CCW	30.97195	0.004558	-0.000160		CCW	617.5822	0.173167	0.041859
Code 14 50 N·m	CW	30.96133	-0.006450	0.000954	Code 34 1000 N·m	CW	617.6027	-0.133840	0.037760
	CCW	30.96117	0.008022	0.000759		CCW	617.6129	0.182563	0.046747
Code 15 200 N·m	CW	127.7665	-0.027400	0.007265	Code 35 1000 N·m	CW	617.6120	-0.126690	0.034445
	CCW	127.7705	0.032351	0.009924		CCW	617.5988	0.138125	0.031209
Code 16 200 N·m	CW	127.7719	-0.031160	0.008582	Code 36 1000 N·m	CW	569.6033	-0.174797	0.047589
	CCW	127.7738	0.031005	0.008809		CCW	569.6207	0.158487	0.039805
Code 17 200 N·m	CW	117.8408	-0.026950	0.00726	Code 37 1000 N·m	CW	570.1247	-0.124700	0.032588
	CCW	117.8427	0.025095	0.007168		CCW	570.2425	0.196449	0.059243
Code 18 200 N·m	CW	117.8655	-0.028280	0.007422	Code 38 1000 N·m	CW	569.9870	-0.122846	0.032249
	CCW	117.8665	0.026847	0.007731		CCW	569.9975	0.124977	0.033138
Code 19 200 N·m	CW	125.9706	-0.017993	0.006757	Code 39 3000 N·m	CW	2999.495	-1.014023	0.331809
	CCW	125.9667	0.010899	0.003203		CCW	2999.344	0.785665	0.187986
Code 20 200 N·m	CW	125.9816	-0.035614	0.013059	Code 40 100 N·m	CW	99.89956	0.098343	-0.03556
	CCW	125.9671	0.007676	0.001209		CCW	100.0700	0.208092	0.114355

3. Results and discussion

The core of this research are the relative interpolation errors. The interpolation error is calculated normally from the fitting equation resulting from the calibration results in the calibration direction. However, in this research the interpolation error is calculated twice; first, using the fitting function of the opposite direction and second, using a proposed fitting.

3.1. Fitting function of opposite direction

The following figures (Figs 2-8) show the relative interpolation errors for selected calibrations as an example to present the idea of using fitting equation coefficients resulting from calibration in one direction to calculate torques in both directions. Lines in red (square pullets) represent appplying the CW calibration coefficients to calculate the actual torque in CW and CCW directions while lines in black (circle pullets) represent applying the CCW calibration coefficients to calculate the actual torque in both CCW and CW directions. Fig. 9 and Table 3 show the absolute maximum relative interpolation error resulting from using the fitting equation coefficients deduced from the clockwise calibration to calculate torques in the counterclockwise direction and vice-versa for all the 40 calibrations. The relative interpolation error (f_a) is calculated as in (2).

$$f_a\,(M_K) = \left[\frac{\left(Y(M_K) - Y_a(M_K)\right)}{Y_a(M_K)}\right] \cdot 100, \qquad (2)$$

where:

$Y(M_K)$ are the actual applied torque steps M_K (N·m)

$Y_a(M_K)$ are the interpolated calibration results at calibration torque M_K without hysteresis (N·m)

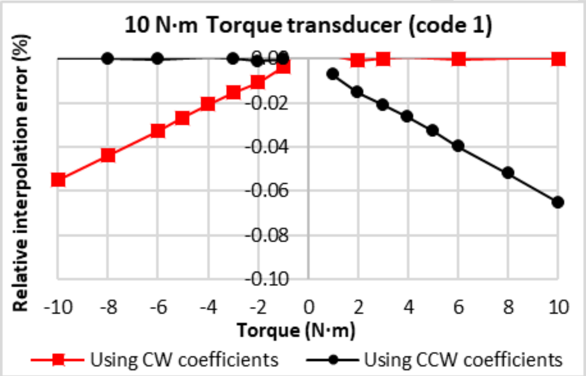

Fig. 2. Cubic relative interpolation error for the 10 N·m torque transducer (Code 1).

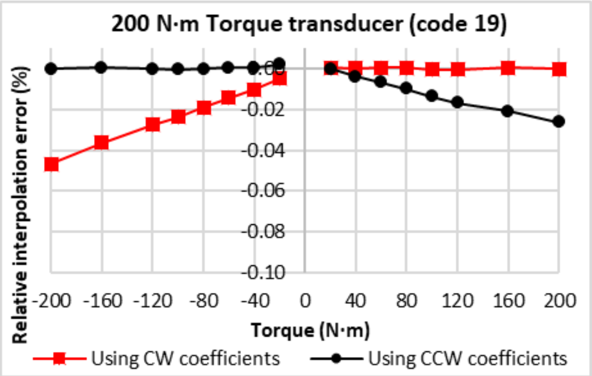

Fig. 3. Cubic relative interpolation error for the 200 N·m torque transducer (Code 19).

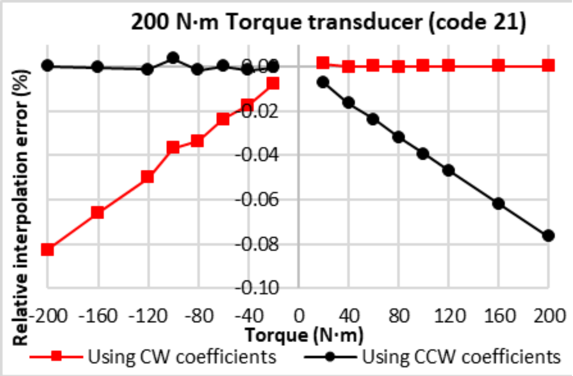

Fig. 4. Cubic relative interpolation error for the 200 N·m torque transducer (Code 21).

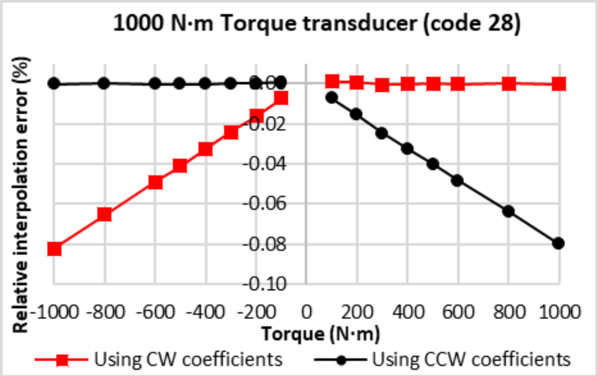

Fig. 5. Cubic relative interpolation error for the 1000 N·m torque transducer (Code 28).

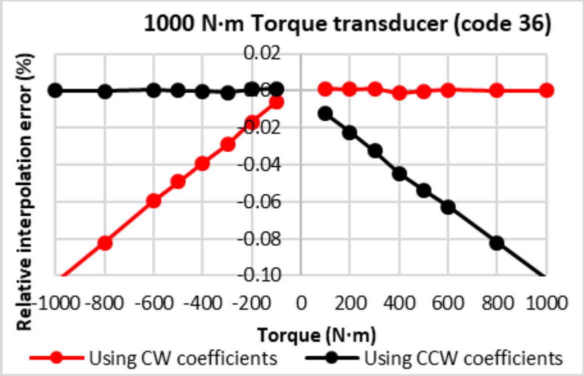

Fig. 6. Cubic relative interpolation error for the 1000 N·m torque transducer (Code 36).

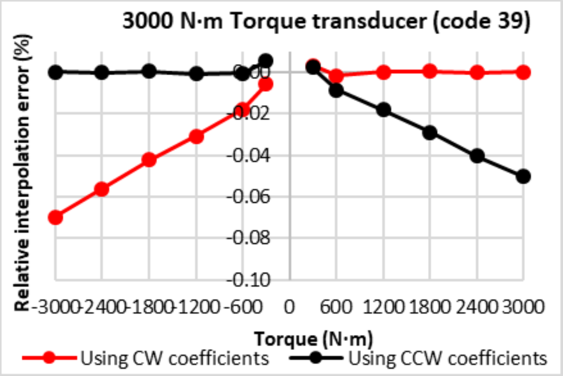

Fig. 7. Cubic relative interpolation error for the 3000 N·m torque transducer (Code 39).

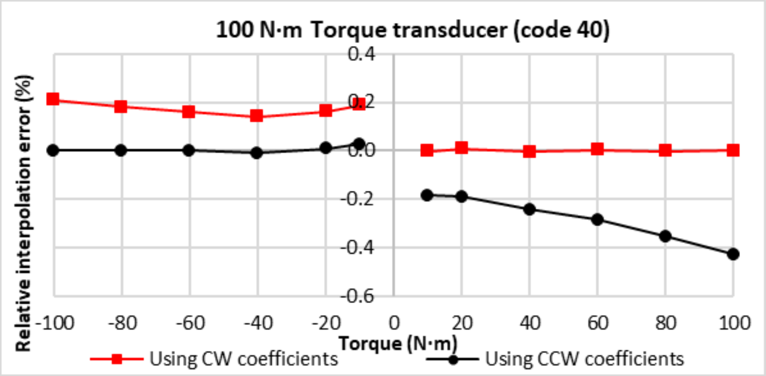

Fig. 8. Cubic relative interpolation error for the 100 N·m torque transducer (Code 40).

Figures (2-8) show that using the CW calibration coefficients to calculate torque in the CW direction yields a very low relative interpolation error and it increases linearly proportional to the calculated torque when used in the CCW direction and vice versa for the other torque direction. This observation means that using the coefficients of one direction to calculate the torque in the other direction increases the relative interpolation error linearly proportional to the calculated torque.

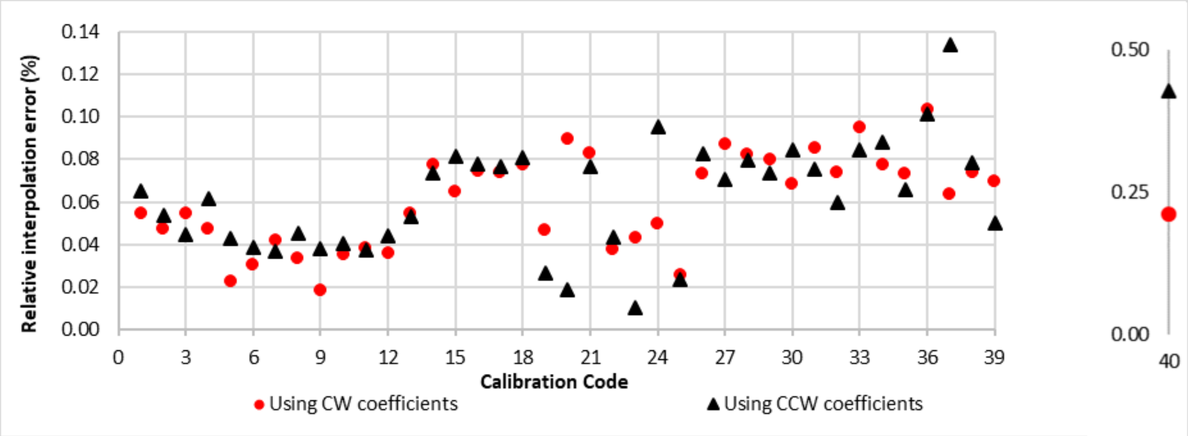

Fig. 9. Maximum relative interpolation error of the 40 calibrations. Note: Code 40 has a different scale.

Table 3. Maximum relative interpolation error of the 40 calibrations/codes by applying Equation (1).

Capacity (N·m)	Calibration Code	Maximum relative interpolation error (%)		Capacity (N·m)	Calibration Code	Maximum relative interpolation error (%)	
		Using CW coefficients	Using CCW coefficients			Using CW coefficients	Using CCW coefficients
10	1	0.055	0.065	200	21	0.083	0.077
	2	0.047	0.054		22	0.038	0.043
	3	0.055	0.045		23	0.043	0.011
	4	0.047	0.062		24	0.050	0.095
50	5	0.023	0.043		25	0.026	0.023
	6	0.030	0.039		26	0.073	0.083
	7	0.042	0.037	1000	27	0.087	0.071
	8	0.033	0.045		28	0.082	0.080
	9	0.018	0.038		29	0.080	0.073
	10	0.035	0.040		30	0.068	0.084
	11	0.039	0.037		31	0.086	0.075
	12	0.036	0.044		32	0.074	0.060
	13	0.055	0.053		33	0.095	0.084
	14	0.078	0.073		34	0.077	0.088
200	15	0.065	0.081		35	0.073	0.066
	16	0.074	0.078		36	0.104	0.102
	17	0.074	0.076		37	0.064	0.134
	18	0.078	0.081		38	0.074	0.079
	19	0.047	0.026	3000	39	0.070	0.050
	20	0.090	0.019	100	40	0.210	0.428

The results show that the maximum relative interpolation error resulting from using CW coefficients in the CCW direction is 0.210 %, and the maximum relative interpolation error resulting from using CCW coefficients in the CW direction is 0.428 %. In addition, it is clear that the maximum relative interpolation errors are observed at maximum nominal capacity for each torque transducer. These interpolation error values are considered high for reference torque transducers classified as 0.05, 0.1, 0.2 and 0.5, but could be sufficient enough for working-level torque transducers classes 1, 2 and 5 as per DIN 51309.

3.2. Proposed fitting

It is common to use different degrees of polynomial equations as interpolation fitting functions to reach the best fit relating the mean deflection to the increasing calibration torques. Equal weighting is given to all calibration points to compute the polynomial series such that the sum of the squares of the residuals is a minimum. These polynomial equations aim mainly to predict the deflections and compensate effectively for the nonlinearity of the calibration curve. The common torque transducers calibration standards DIN 51309 [7] and BS 7882 [8] insist on the fitting function to pass through the origin. Force transducer calibration as a very similar branch has two common calibration standards; ISO 376 [15] and ASTM E74 [16]. They use different degrees of polynomial equations to best fit the calibration results. Different reputable publications present the polynomial interpolation techniques and the influence of the polynomial degree on the fitting error and also how to determine the best degree within the measurement uncertainty [17-18].

In Equation (1), coefficient "a_1" represents the slope of the graph or the part that expresses the linearity of the relationship, while "a_2" is the rate at which the slope of the graph is increasing which reflects in the parabolic behaviour of the graph, while "a_3" represents the cubic “s” shape add in effect to the graph. Changing "a_1" affects the slope, changing "a_2" changes the curvature of the parabolic element, and changing "a_3" mutates the steepness of the cubic “s” curve. Known calibration coefficients in one direction are the starting point while taking into consideration the complexity effect and the difficulty to generalize the changing of more than one coefficient. Different approaches are tested to decrease the relative interpolation error resulting from using the fitting equation to calculate the actual torque in the opposite direction. The first model is to change the sign of both the second and third coefficients, the next model is to change the sign of the third coefficient only, and the last model is to change the sign of the second coefficient. Figures 10 and 11 show the application of these 3 models to 2 different calibrations (Code 1 and Code 36) to investigate the influence in order to apply the best model to the whole 40 calibrations.

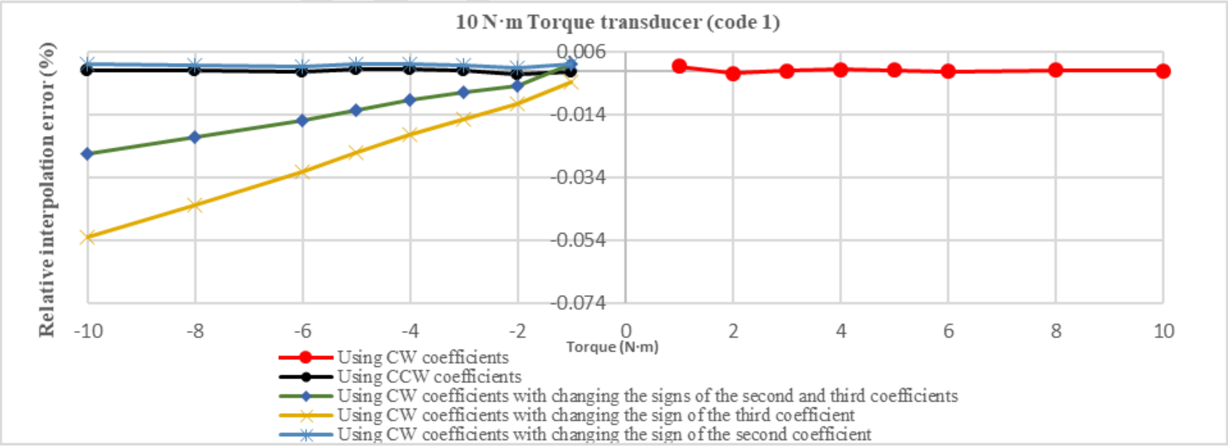

Fig. 10. Relative interpolation errors calculated by different models for the 10 N·m torque transducer (Code 1).

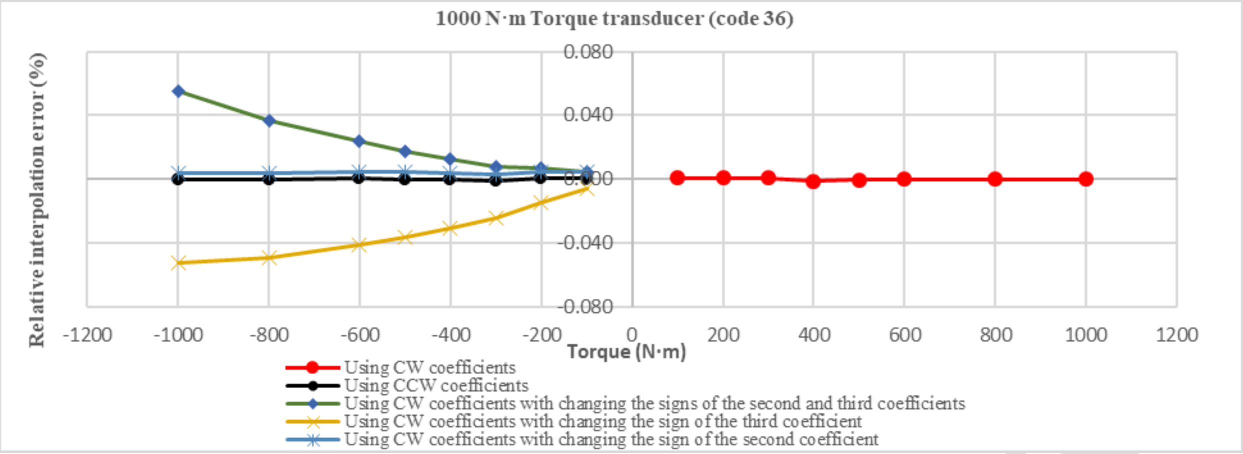

Fig. 11. Relative interpolation errors calculated by different models for the 1000 N·m torque transducer (Code 36).

Figures 10 and 11 show that changing the sign of the second coefficient "a_2" in the cubic function when using in the other torque direction (Mo_{ai}) gives minimal relative interpolation error out of the other two models as presented in the following equation.

$$Mo_{ai} = a_1 \cdot S_i - a_2 \cdot S_i^2 + a_3 \cdot S_i^3 \qquad (3)$$

Figures 12-18 show the relative interpolation errors resulting from applying (1) to calculate torque in the same calibration direction and applying the proposed (3) to calculate torque in the opposite torque direction. The line with a solid marker fill in red represents applying the CW calibration coefficients to calculate the actual torque in CW (1) and the line with no marker fill in red represents applying CW calibration coefficients with changing the sign of the second coefficient to calculate the actual torque in CCW (3). At the same time, the line with a solid marker fill in black represents applying the CCW calibration coefficients to calculate the actual torque in CCW (1) and the line with no marker fill in red represents applying CCW calibration coefficients with changing the sign of the second coefficient to calculate the actual torque in CW (3).

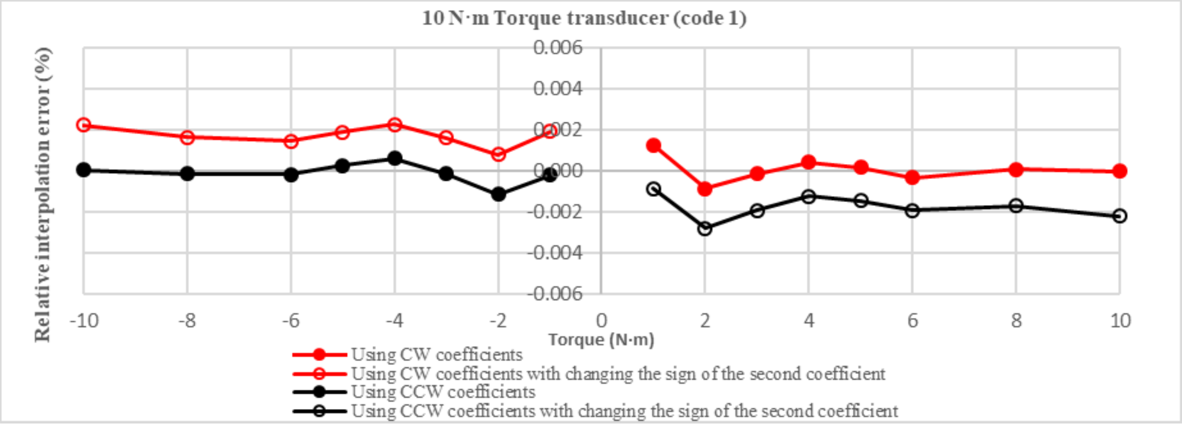

Fig. 12. Cubic relative interpolation errors for the 10 N·m torque transducer (Code 1) by applying (1) and (3).

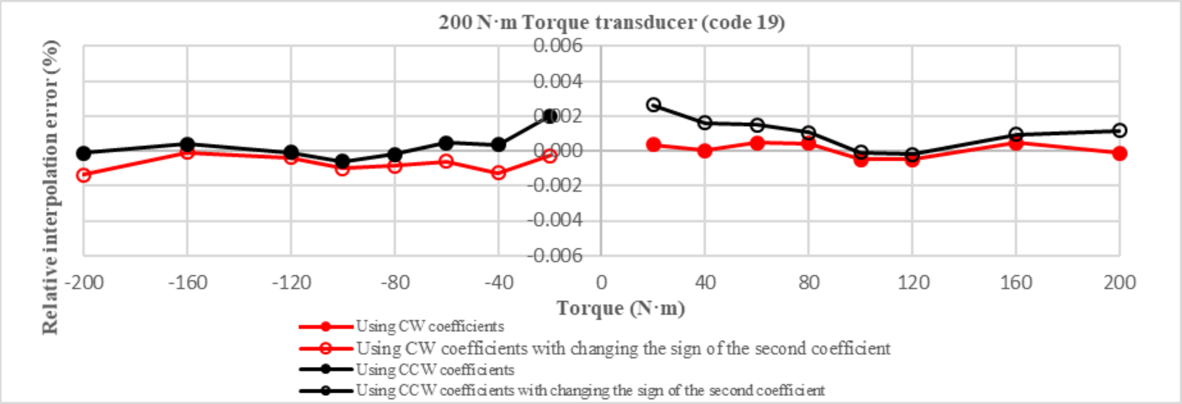

Fig. 13. Cubic relative interpolation errors for the 200 N·m torque transducer (Code 19) by applying (1) and (3).

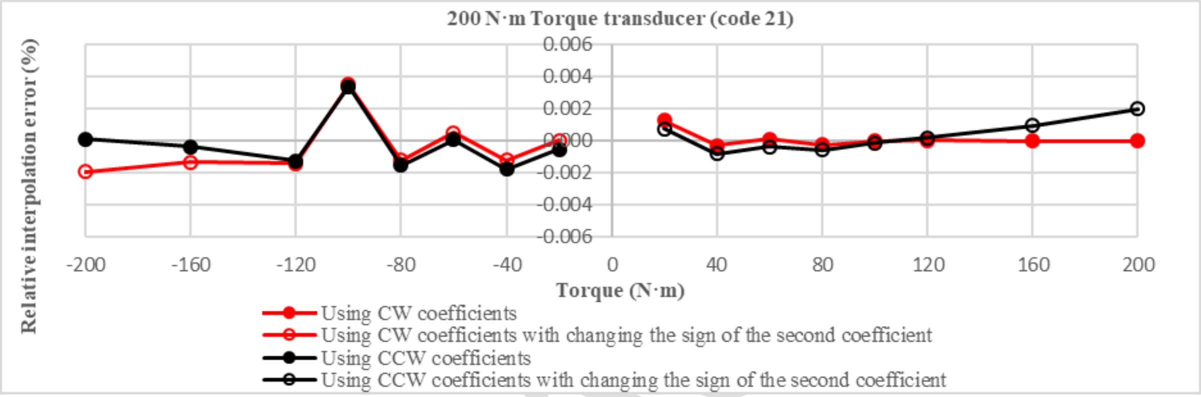

Fig. 14. Cubic relative interpolation errors for the 200 N·m torque transducer (Code 21) by applying (1) and (3).

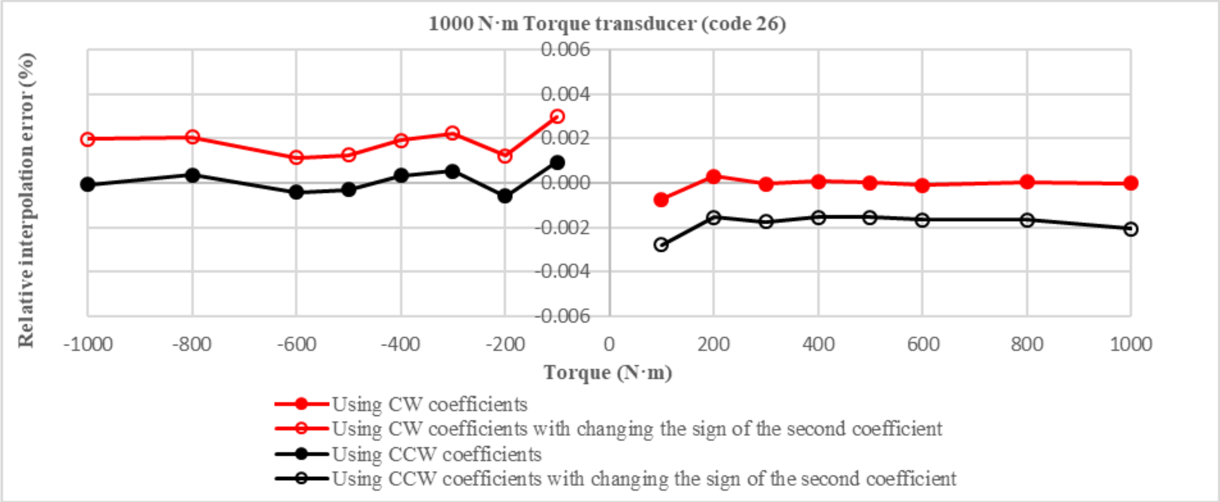

Fig. 15. Cubic relative interpolation errors for the 1000 N·m torque transducer (Code 26) by applying (1) and (3).

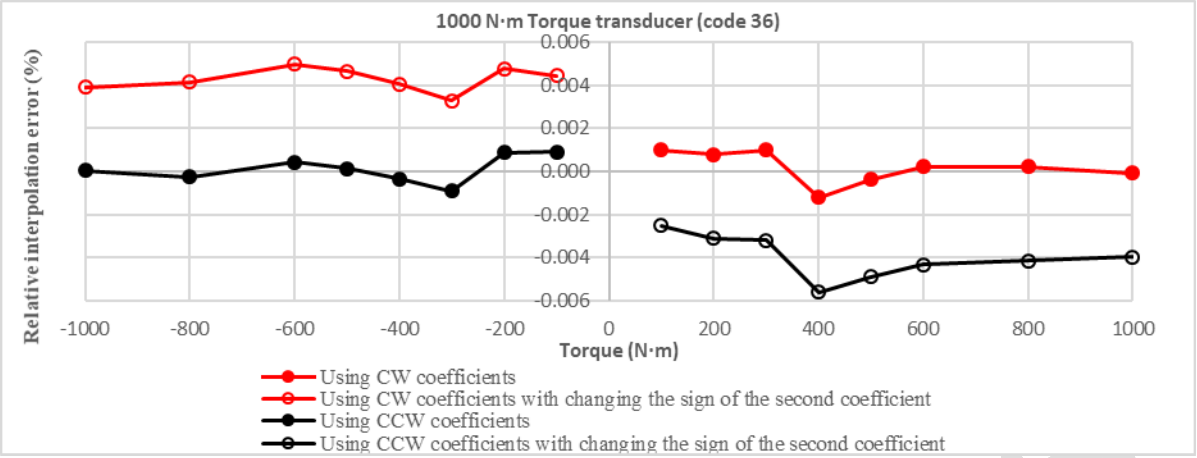

Fig. 16. Cubic relative interpolation errors for the 1000 N·m torque transducer (Code 36) by applying (1) and (3).

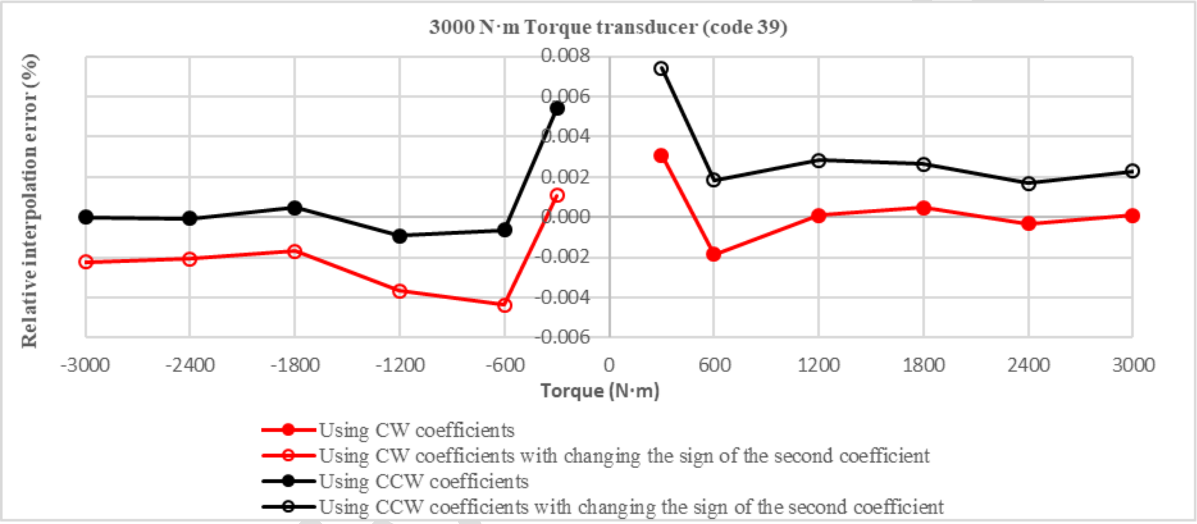

Fig. 17. Cubic relative interpolation errors for the 3000 N·m torque transducer (Code 39) by applying (1) and (3).

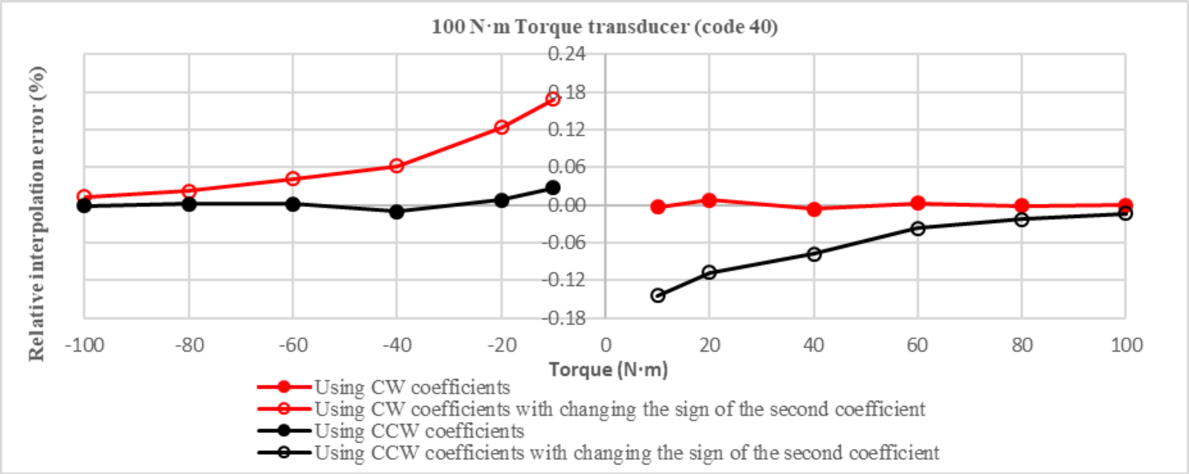

Fig. 18. Cubic relative interpolation errors for the 100 N·m torque transducer (Code 40) by applying (1) and (3).

Figures 12-18 show that applying the proposed fitting (3) revealed giving a good enhancement by reducing the relative interpolation error to reach values comparable of those deduced from the original calibrations. It is clear from Fig.19 and Table 4 that the maximum relative interpolation errors observed using the clockwise coefficients to calculate the counterclockwise torque for calibration Code 1 was reduced from 0.055 % to 0.002 %, while the maximum relative interpolation error observed when using the counterclockwise coefficients to calculate the clockwise torque for calibration Code 1 was reduced from 0.065 % to 0.003 %. Calibrations of torque transducers class 0.05 presented from Code 1 to Code 38 have shown valuable improvements in both torque directions which proves the applicability of the proposed fitting. The calibration Code 39, which has 0.2 class, shows significant error reduction from 0.07 % to 0.004 % in CW and from 0.05 % to 0.007 % in CCW. The torque transducer Code 40, which has observable dissimilarity in its rated output of CW and CCW directions, shows considerable error reduction from 0.210 % to 0.169 % in CW and from 0.428 % to 0.144 % in CCW.

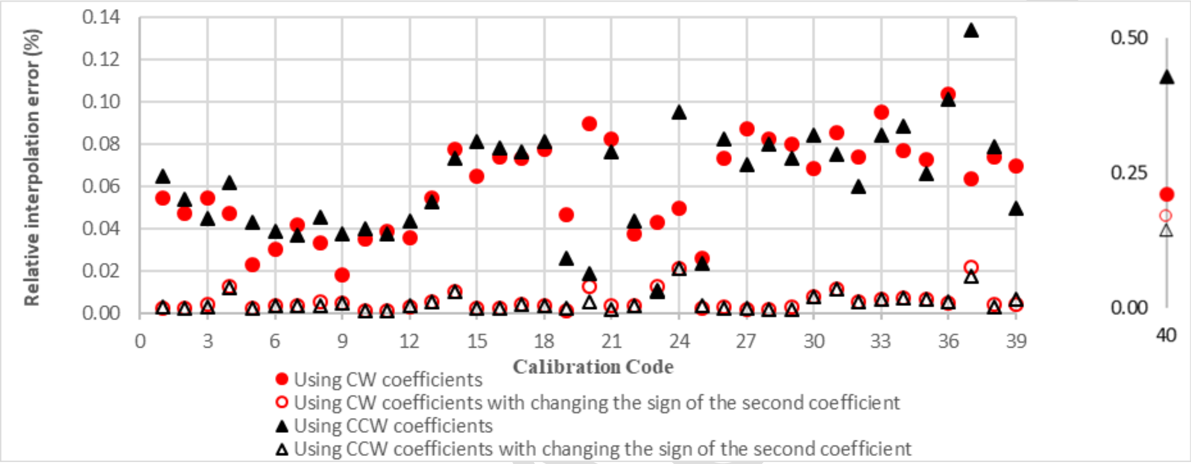

Fig. 19. Maximum relative interpolation error of the 40 calibrations by applying Equations (1) and (3). Note: Code 40 has a different scale.

Table 4 shows that the maximum relative interpolation errors observed when using the coefficients in one torque direction with changing the sign of the second coefficient to calculate the torque in the opposite direction among the 39 calibrations are 0.022 % in the CW direction and 0.021 % in the CCW direction and the minimum error is 0.001 % in both clockwise and counterclockwise directions. These interpolation error values are considered good enough for reference torque transducers classified as 0.05. The results of the torque transducer Code 40 (Fig. 18), which is classified as 0.2 for the CW direction and from 40 % in CCW direction and has 0.5 class from 10 % up to 40 % in CCW direction, revealed that the original class could be obtained for the CCW and for the CW direction almost above 20 % of the capacity. To calculate the new relative expanded uncertainty associated with using the proposed fitting, the original relative interpolation error could be replaced by the maximum relative interpolation error (0.022 %).

It has been reported over the past decades that there is a difference between the tensile and the compressive strength of almost all metallic materials. This difference is called the *strength differential* (SD) effect which is supposed to be the main reason for the difference in sensitivity values of the force transducer under tension and compression modes. In the field of torque measurements, torsion itself introduces pure shear stress to the torque transducer's membrane. This shear stress is similar if it is induced from CW or CCW torque, which works to stretch the outer surface of the torque transducer's membrane. Therefore, the sensitivity difference between CW and CCW torque is supposed to be small. The torque application direction is ecpected to influence the deformation values based on the dislocation between grain boundaries, but this difference would be much smaller than the difference between the tensile and compression forces. In practical calibrations, there are several reasons for this difference such as: changing the direction of mechanical stress along the transducer's measuring axis and its influence on the elastic and viscoelastic behaviour of the adhesion layers, residual stress resulting from previous use, changing the contact surfaces between the reference machine and the calibrated torque transducer, especially if it has square drive ends, and change of reference torque machine’s uncertainties in each torque direction.

Table 4: Maximum relative interpolation error of the 40 calibrations/codes by applying (3).

Capacity (N·m)	**Calibration Code**	**Maximum relative interpolation error (%)**		**Capacity (N·m)**	**Calibration Code**	**Maximum relative interpolation error (%)**	
		Using CW coefficients	**Using CCW coefficients**			**Using CW coefficients**	**Using CCW coefficients**
10	1	0.002	0.003	200	21	0.004	0.002
	2	0.002	0.003		22	0.003	0.003
	3	0.004	0.003		23	0.013	0.011
	4	0.013	0.012		24	0.021	0.021
50	5	0.003	0.003		25	0.003	0.004
	6	0.004	0.003		26	0.003	0.003
	7	0.003	0.003	1000	27	0.002	0.003
	8	0.005	0.003		28	0.002	0.002
	9	0.005	0.005		29	0.003	0.002
	10	0.001	0.001		30	0.008	0.008
	11	0.001	0.001		31	0.012	0.012
	12	0.003	0.003		32	0.006	0.006
	13	0.005	0.005		33	0.006	0.006
	14	0.010	0.010		34	0.007	0.007
200	15	0.002	0.002		35	0.007	0.007
	16	0.002	0.002		36	0.005	0.006
	17	0.004	0.004		37	0.022	0.018
	18	0.004	0.004		38	0.004	0.003
	19	0.001	0.003	3000	39	0.004	0.007
	20	0.013	0.005	100	40	0.169	0.144

4. Conclusions

This research work presents an investigation into the use of the cubic fitting function mentioned in the DIN 51309 and BS 7882 torque transducer calibration standards as a result of the calibration in one direction to calculate the actual torque in the other torque direction by direct substitution with the nominal torque, which gives a propagated linear relative interpolation error. The proposed modification is presented by changing the sign of the second coefficient in the cubic function when used in the other torque direction. The proposed modification reduces the relative interpolation error by an average of 16 times for torque transducers classes 0.05 and 0.1, and only 5 times for classes 0.2 and 0.5 if the proposed fitting is used instead of using the coefficients of one direction in the other direction directly. At the same time, the proposed modification increases the relative interpolation error by an average of 6 times for torque transducers classes 0.05 and 0.1, and 10 times for classes 0.2 and 0.5 if the proposed fitting is used instead of the coefficients in its direction. The outcomes of this investigation can be applied to the torque transducers classified as 0.05, 0.1, 0.2, and 0.5 as per DIN 51309. Furthermore, it can be of interest in tension and compression force calibrations.

Further theoretical investigation can be considered as a future task together with the application of this study to low accuracy torque transducers.

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