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Calibration of a 400 mm helical master gear at INRIM

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Introduction

Gears are extremely important mechanical components in very many manufactured products, and crucial in powertrain applications: whenever mechanical power is to be transmitted and/or transformed in angular speed and/or rotation axis, gears enter the game. Just as any other mechanical component, gears range the full scale of size and requirements. Of interest here are the ones with the topmost quality, i.e. bearing the strictest tolerances. In particular, gear masters are intended to provide measurement traceability to gears, and are then required the highest accuracy.

In spite of the very large economic impact of gears, only seven NMI's world wide (three in Euramet) have CMC's registered in the KCDB in this calibration field, and not all covering all areas. In particular, only four (one in Euramet) have got CMC's for lead masters.

The European project **Drivetrain** (**EMRP ENG56**, ended on August 2017) is about large drivetrain components particularly for wind energy systems. Among its objectives, it aims at improving the gear calibration infrastructure, providing committed project partners – including the INRIM – with the opportunity of investigating and exercise.

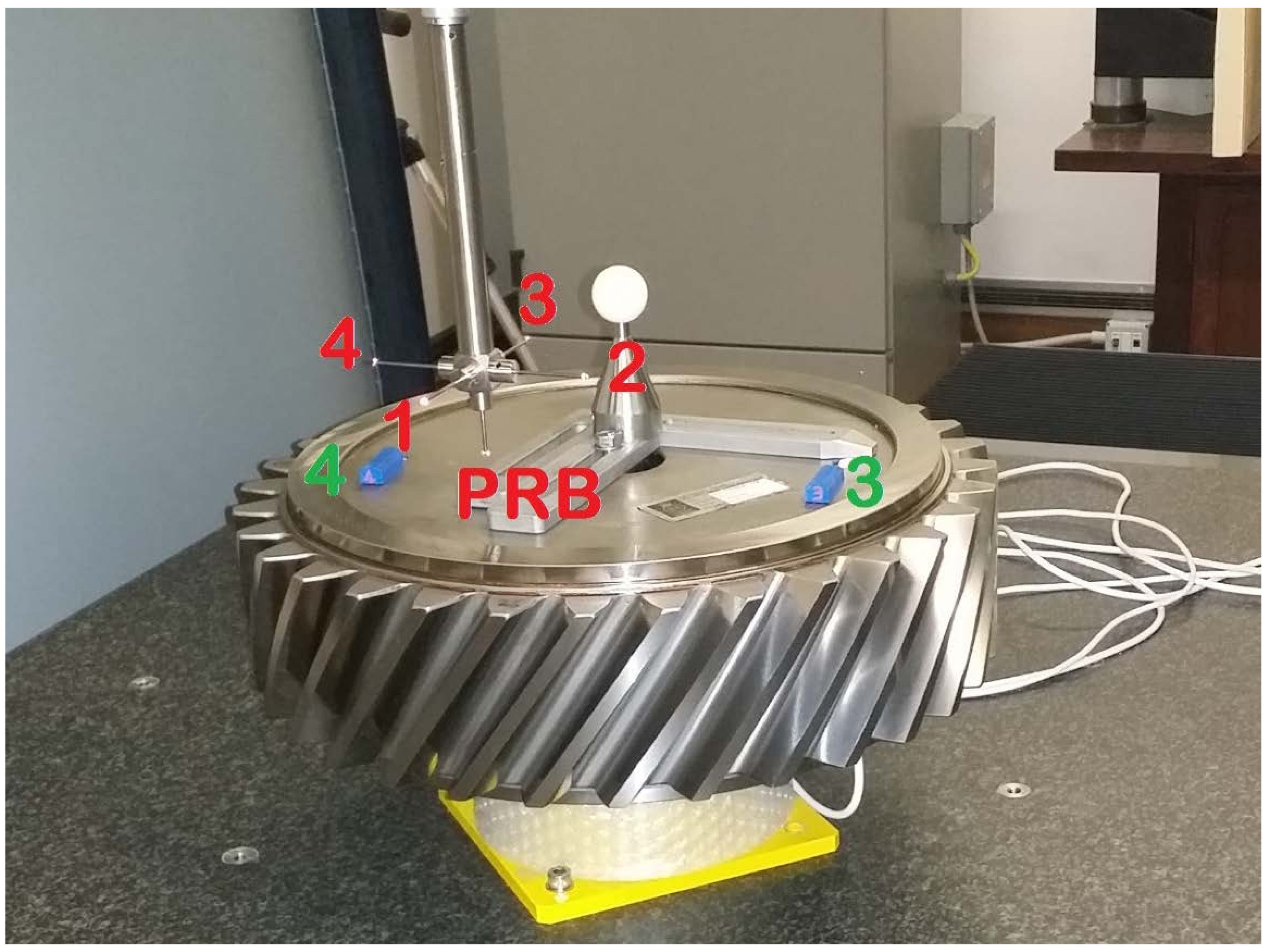
The work reported here resulted from the project **deliverable D.1.9** and was an exercise of calibration of a master gear.

Measurands

The standard under calibration was a 400 mm helical master gear, provided by the University of Newcastle (GB). The measurands were the profiles and the leads of four selected teeth angularly spaced 90° about the gear axis, and the pitch and runout.

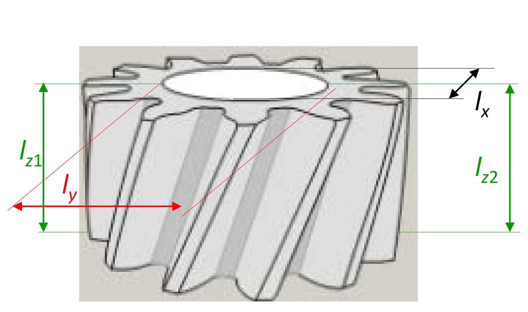
Procedure

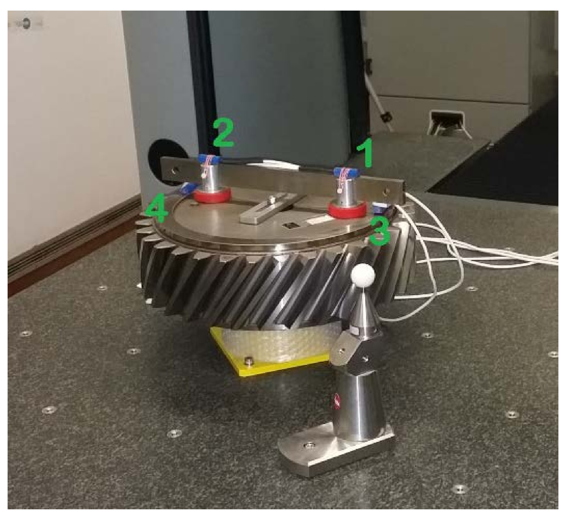
The calibration occurred at the INRIM in December 2016 and January 2017 and was done with a CMM (Leitz PMM C 12107) not equipped with a rotary table. Because of that, the stylus system was set up with four horizontal equally spaced styli. A fifth vertical stylus was added for alignment of the master – thus completing the conventional star set up.

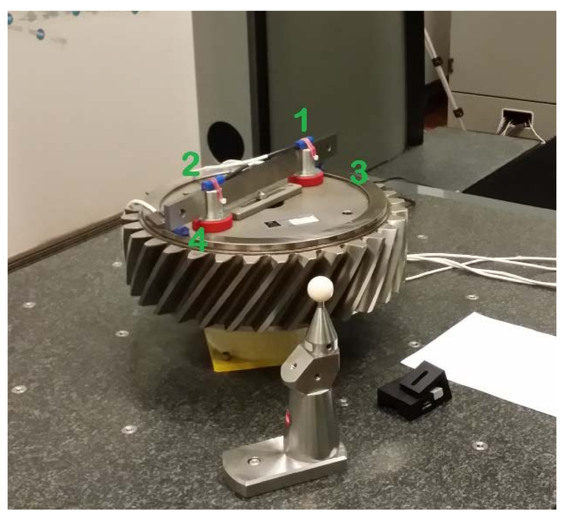


The calibration was carried out in two steps, following common practice at INRIM for calibrations in coordinate metrology.

1. The first step was intended to introduce traceability. Three mutually orthogonal elementary features of the master, each aligned to a CMM axis, were calibrated. As these calibrations were done prior to the rest, they were referred to as *pre-calibrations*. The features were two point-to-point internal diameters of the upper flange (along x and y) and the axial separation of the upper and lower faces (along z). Because the shaft seat prevented a direct axial measurement and for sake of symmetry, the face separation was defined more precisely as the mean separation of two corresponding point pairs on the upper and lower flanges, symmetrically to the gear axis. Each feature was calibrated by comparison with an aligned calibrated gauge block of similar length.







2. The second step performed the full measurement of the master, as well as a repetition of the measurement of the three pre-calibrated features. The x coordinates of all measured points were stretched (i.e. multiplied by a common factors close to unity) to make the repeated measurement value of the pre-calibrated x feature match the pre-calibrated value. The same was done separately for y and z.

This way, the traceability brought in by the pre-calibrated features was extended to all other features. The first step only suffered uncertainty due to thermal expansion, as the stretches occurring in the second automatically recovered any expansion (no thermal compensation done in the second step).

Uncertainty evaluation

The evaluation of the uncertainty was particularly challenging.

- The input uncertainties were evaluated based on experimental data or expert judgment. The important effect of scanning was evaluated by scanning a reference sphere along paths with normal material directions mimicking those of the actual tooth measurement.
- The most difficult sensitivity coefficients to predict were derived by simulation. The scanned points were collectively perturbed in software to simulate known individual errors, the gear re-evaluated, and the sensitivity coefficients derived as incremental ratios.

Budget for profiles

	u (xi)		fHalpha ci		ui (y) µm	Falpha ci		ui (y) µm	ffalpha ci		ui (y) µm
Transfer of unit, x	0,67	ppm	0,019	µm/ppm	0,01	0,017	µm/ppm	0,01	0,000	µm/ppm	0,00
Transfer of unit, y	0,71	ppm	0,018	µm/ppm	0,01	0,016	µm/ppm	0,01	-0,001	µm/ppm	0,00
Transfer of unit, z	1,20	ppm	-0,002	µm/ppm	0,00	-0,001	µm/ppm	0,00	0,000	µm/ppm	0,00
Coordinate system origin, x	0,17	µm	-0,096	µm/µm	-0,02	0,018	µm/µm	0,00	-0,002	µm/µm	0,00
Coordinate system origin, y	0,17	µm	-0,089	µm/µm	-0,02	0,020	µm/µm	0,00	0,001	µm/µm	0,00
Coordinate system origin, z	0,17	µm	0,000	µm/µm	0,00	0,000	µm/µm	0,00	0,000	µm/µm	0,00
Coordinate system orientation, about x	3,92	µrad	0,002	µm/µrad	0,01	-0,005	µm/µrad	-0,02	0,000	µm/µrad	0,00
Coordinate system orientation, about y	3,92	µrad	0,006	µm/µrad	0,02	0,006	µm/µrad	0,02	-0,001	µm/µrad	0,00
Temperature variations	0,087	K	0,175	µm/K	0,02	0,155	µm/K	0,01	0,004	µm/K	0,00
Probing anisotropy profile	0,45	µm	1		0,45	1		0,45	1		0,45
Probing anisotropy helix	0,44	µm			0,00			0,00			0,00
Probing anisotropy pitch	0,35	µm			0,00			0,00			0,00
Stylus tip correction					0,00			0,00			0,00
CMM geometry (over a scan)	0,2	µm	1		0,20	1		0,20	1		0,20
CMM geometry (over a tooth)	0,15	µm			0,00			0,00			0,00
CMM geometry (over full gear section)	0,2	µm			0,00			0,00			0,00
Riproducibility fHa	0,16	µm	1		0,16			0,00			0,00
Riproducibility Fa	0,17	µm			0,00	1		0,17			0,00
Riproducibility ffa	0,17	µm			0,00			0,00	1		0,17
Riproducibility fHb	0,10	µm			0,00			0,00			0,00
Riproducibility Fb	0,16	µm			0,00			0,00			0,00
Riproducibility ffb	0,09	µm			0,00			0,00			0,00
Riproducibility fp	0,14	µm			0,00			0,00			0,00
Riproducibility Fp	0,51	µm			0,00			0,00			0,00
Riproducibility Fr	0,59	µm			0,00			0,00			0,00
		uc (y)			0,52			0,52			0,52
k	2	Uc (y)			1,05			1,05			1,05

Budget for helixes

	u (xi)		fHbeta ci		ui (y) µm	Fbeta ci		ui (y) µm	ffbeta ci		ui (y) µm
Transfer of unit, x	0,67	ppm	0,000	µm/ppm	0,00	0,000	µm/ppm	0,00	0,000	µm/ppm	0,00
Transfer of unit, y	0,71	ppm	0,000	µm/ppm	0,00	0,000	µm/ppm	0,00	0,000	µm/ppm	0,00
Transfer of unit, z	1,20	ppm	0,000	µm/ppm	0,00	0,000	µm/ppm	0,00	0,000	µm/ppm	0,00
Coordinate system origin, x	0,17	µm	0,000	µm/µm	0,00	0,000	µm/µm	0,00	0,000	µm/µm	0,00
Coordinate system origin, y	0,17	µm	0,000	µm/µm	0,00	0,000	µm/µm	0,00	0,000	µm/µm	0,00
Coordinate system origin, z	0,17	µm	0,000	µm/µm	0,00	-0,092	µm/µm	-0,02	0,000	µm/µm	0,00
Coordinate system orientation, about x	3,92	µrad	0,038	µm/µrad	0,15	0,000	µm/µrad	0,00	-0,001	µm/µrad	0,00
Coordinate system orientation, about y	3,92	µrad	0,014	µm/µrad	0,05	0,025	µm/µrad	0,10	0,002	µm/µrad	0,01
Temperature variations	0,087	K	0,001	µm/K	0,00	0,003	µm/K	0,00	0,004	µm/K	0,00
Probing anisotropy profile	0,45	µm			0,00			0,00			0,00
Probing anisotropy helix	0,44	µm	1		0,44	1		0,44	1		0,44
Probing anisotropy pitch	0,35	µm			0,00			0,00			0,00
Stylus tip correction					0,00			0,00			0,00
CMM geometry (over a scan)	0,2	µm	1		0,20	1		0,20	1		0,20
CMM geometry (over a tooth)	0,15	µm			0,00			0,00			0,00
CMM geometry (over full gear section)	0,2	µm			0,00			0,00			0,00
Riproducibility fHa	0,16	µm			0,00			0,00			0,00
Riproducibility Fa	0,17	µm			0,00			0,00			0,00
Riproducibility ffa	0,17	µm			0,00			0,00			0,00
Riproducibility fHb	0,10	µm	1		0,10			0,00			0,00
Riproducibility Fb	0,16	µm			0,00	1		0,16			0,00
Riproducibility ffb	0,09	µm			0,00			0,00	1		0,09
Riproducibility fp	0,14	µm			0,00			0,00			0,00
Riproducibility Fp	0,51	µm			0,00			0,00			0,00
Riproducibility Fr	0,59	µm			0,00			0,00			0,00
		uc (y)			0,52			0,52			0,49
k	2	Uc (y)			1,04			1,04			0,99

Results

The results were compared with reference calibration values provided by the NGML (GB).

INRIM	Left				Right				Uncert.
Tooth	25	17	9	1	1	9	17	25	U
fHalpha	2,85	4,44	2,30	0,87	6,97	7,54	6,56	7,89	1,05
Falpha	3,71	4,75	3,05	2,57	7,49	8,07	6,72	7,99	1,05
ffalpha	1,55	1,57	1,56	2,47	2,23	2,54	1,97	2,05	1,05
fHbeta	-2,87	-5,78	-2,83	2,47	2,76	-4,79	-7,71	-4,47	1,04
Fbeta	4,37	6,84	3,70	4,02	2,83	5,54	8,29	5,27	1,04
ffbeta	2,02	1,15	1,56	4,13	1,25	1,63	0,93	1,20	0,99

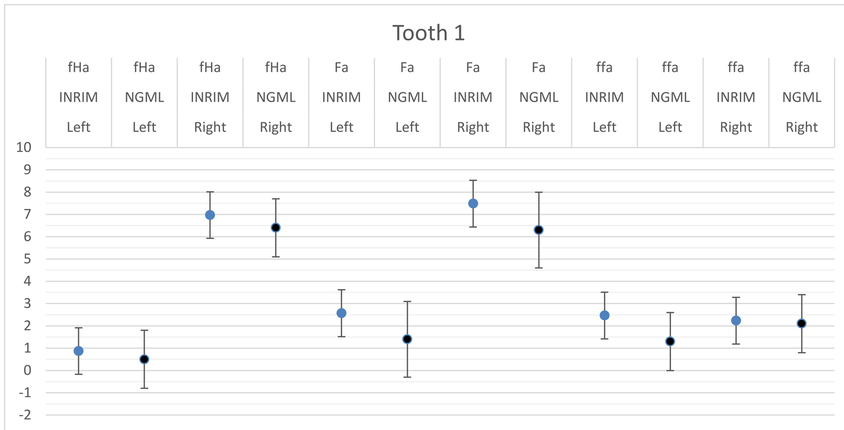
INRIM			Uncert.
Flank	Left	Right	U
fp	5,23	4,13	0,85
Fp	12,40	23,27	2,77
Fr	26,27		1,87

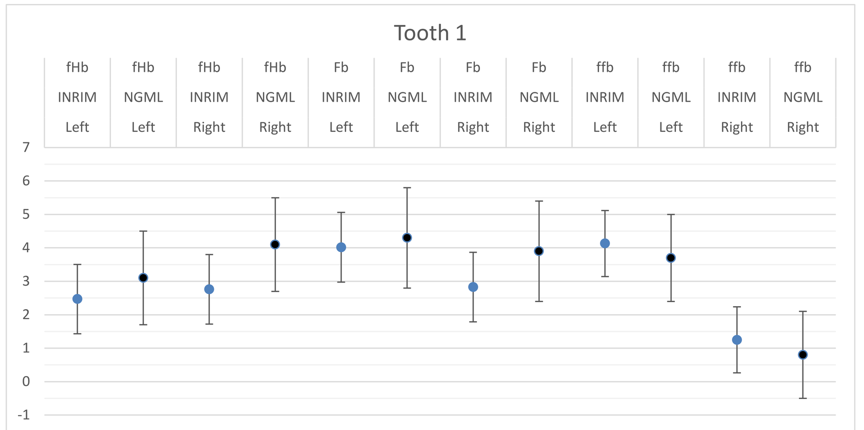
NGML	Left				Right				Uncert.
Tooth	25	17	9	1	1	9	17	25	U
fHalpha	3,00	4,50	2,10	0,50	6,40	7,20	6,50	7,20	1,3
Falpha	3,10	4,40	2,20	1,40	6,30	7,20	6,00	6,80	1,7
ffalpha	1,30	0,70	1,00	1,30	2,10	2,50	1,30	1,40	1,3
fHbeta	-1,00	-4,50	-2,90	3,10	4,10	-4,60	-7,00	-2,00	1,4
Fbeta	2,40	5,20	3,60	4,30	3,90	5,10	7,40	2,50	1,5
ffbeta	1,80	1,00	1,30	3,70	0,80	1,50	0,90	0,80	1,3

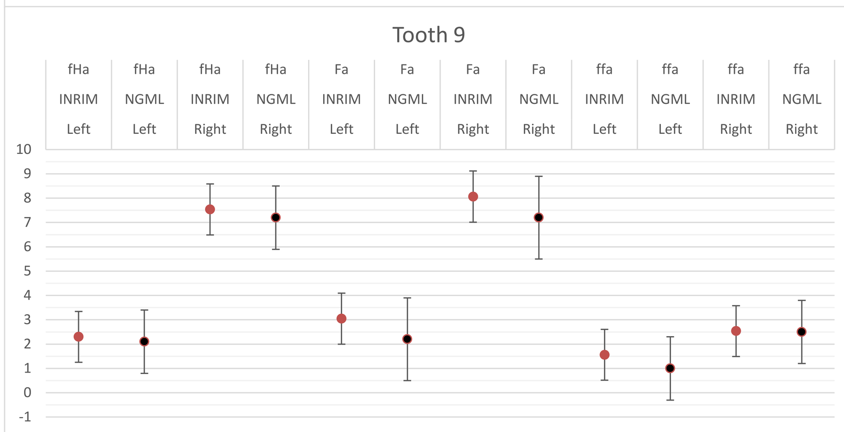
NGML			Uncert.
Flank	Left	Right	U
fp	5,70	4,60	0,7
Fp	9,50	21,80	1,0
Fr	24,10		1,4

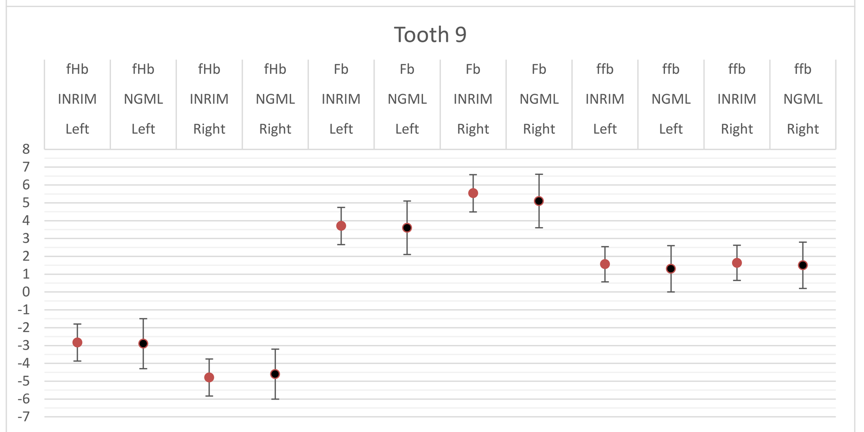
En	Left				Right			
Tooth	25	17	9	1	1	9	17	25
fHalpha	-0,09	-0,04	0,12	0,22	0,34	0,20	0,03	0,41
Falpha	0,31	0,17	0,42	0,59	0,59	0,43	0,36	0,60
ffalpha	0,15	0,52	0,34	0,70	0,08	0,02	0,40	0,39
fHbeta	-1,08	-0,74	0,04	-0,36	-0,77	-0,11	-0,41	-1,42
Fbeta	1,08	0,90	0,06	-0,15	-0,59	0,24	0,49	1,52
ffbeta	0,13	0,09	0,16	0,26	0,28	0,08	0,02	0,24

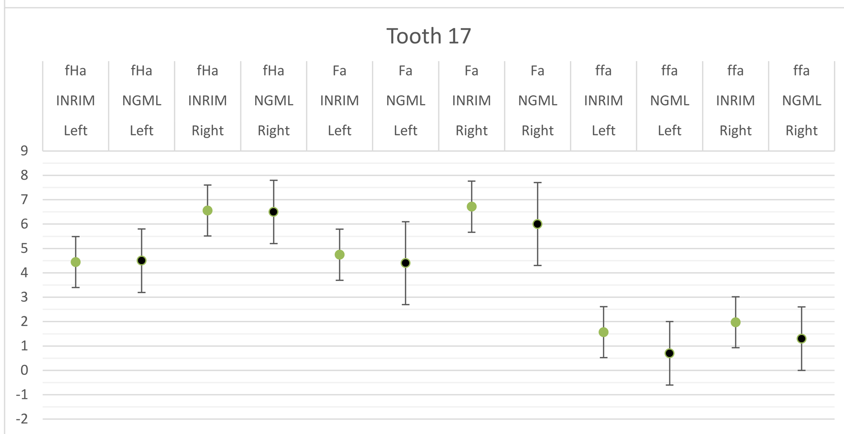
En		
Flank	Left	Right
fp	-0,42	-0,42
Fp	0,98	0,50
Fr	0,93	

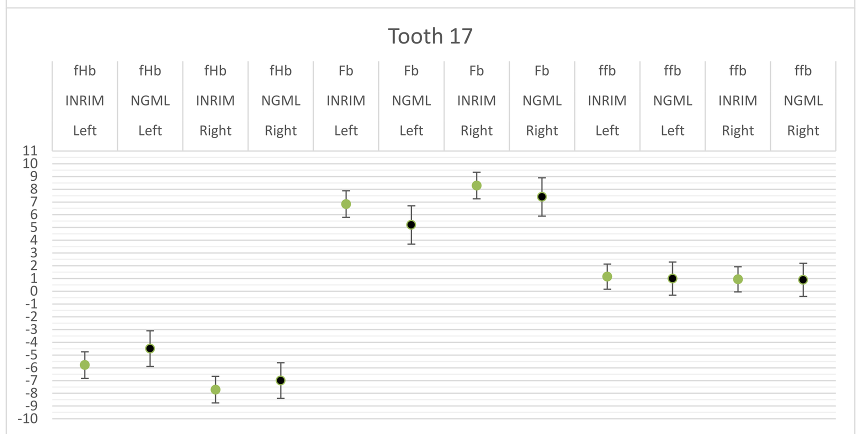


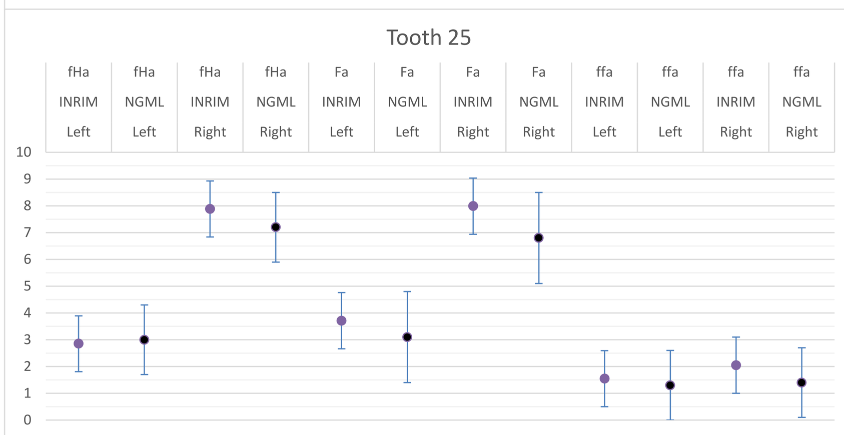


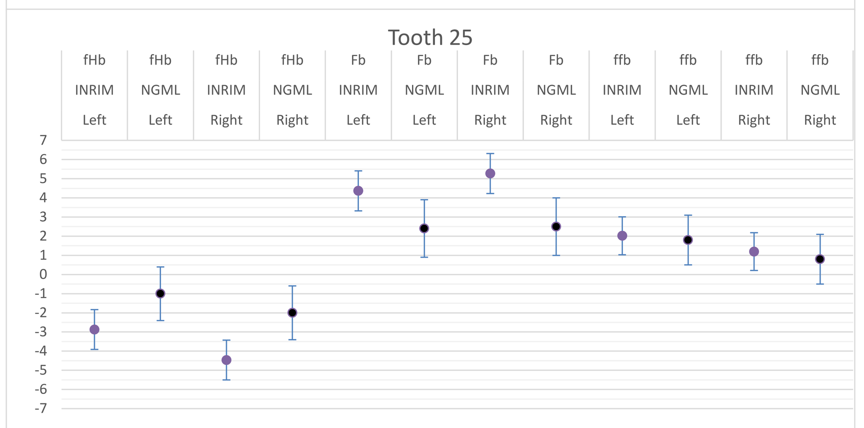












Conclusions

The comparison was satisfactory, with all normalized errors less than unit but one isolated case slightly in excess. The uncertainty achieved was in line with other NMIs' holding gear CMC's.

Not using a rotary table for the calibration cleared from a number of table-related uncertainty components. On the other hand, the scanning probing system was exercised over a range of spatial directions, instead of essentially a single direction as in the case of the rotary table. Not surprisingly, the uncertainty budget was dominated by the scanning probing system.

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DriveTrain

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https://www.ptb.de/emrp/eng56-home.html

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