EUROPEAN SYNCHROTRON RADIATION FACILITY
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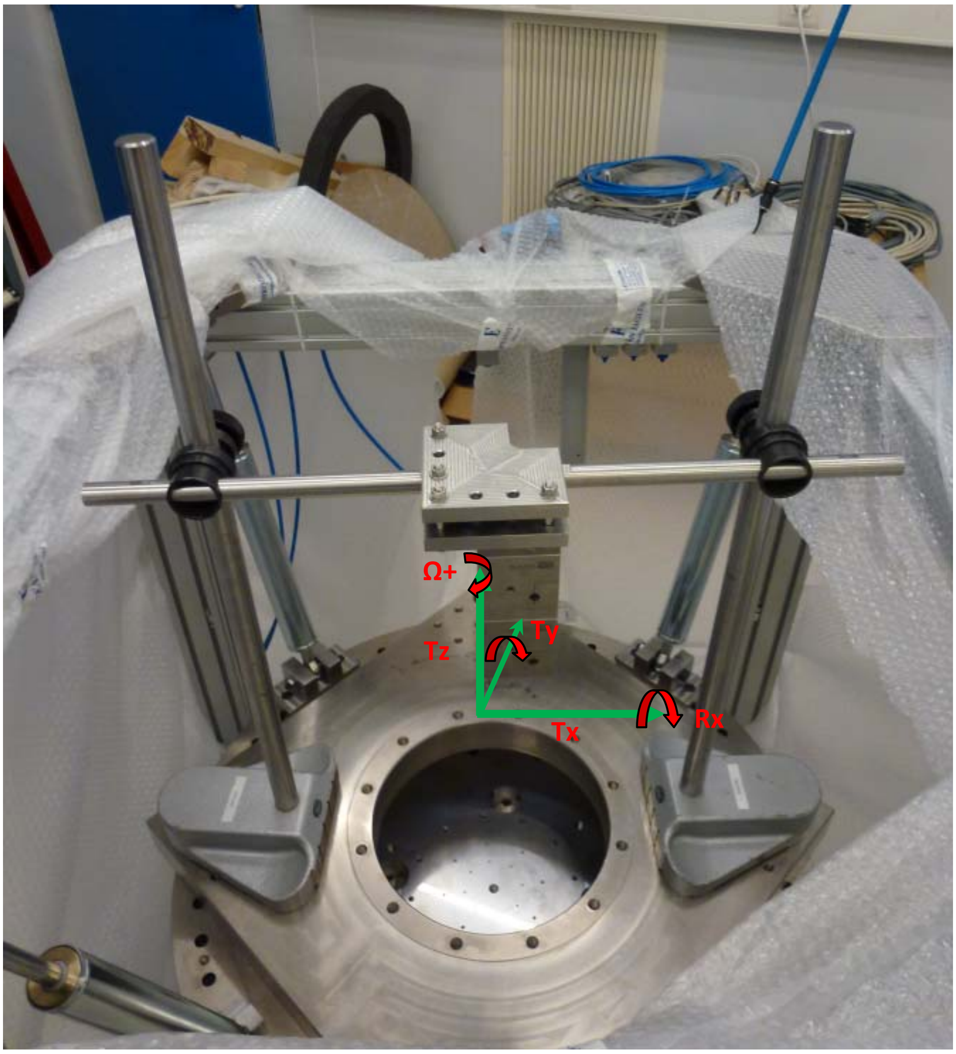
ISDD
Mechanical Engineering Group
Precision Dynamics & Mechatronics Unit – Precision Engineering Laboratory (PEL)

TEST REPORT: ID-31 Spindle

Grenoble: April 25th 2017

From: HP v.d.Kleij, L.Rousset

Object: **Measurements acceptance test after reception from Leuven Air Bearing**



Revisions

Indice	Date	Modification(s)
V1	02-05-2017	First release
V2	02-05-2017	Revised by L.Ducotté & HP v.d.Kleij

Summary

Contents

I) Measurement of the rotation using capacitive sensors

1-Measurement conditions

The measurement of the rotating positioning system has been done at the PEL under the following conditions:

- Each measurement has been performed with a low resolution (80mV/µm) capacitive sensor set from Lion Precision, composed of 5 sensors conditioned by a CPL290 and mounted on a probe nest (i.e appendix for the datasheets). The measurements are performed at the PEL in a controlled temperature room ±0.2°C
- A dual Master-Ball target was mounted on the rotor (25.4mm), used as reference surface for the measurement, and aligned at the center of the nest (i.e photo below). The master ball roundness is <20nm and it is considered negligible. The upper master ball is at sample high (about 555 mm height)
- <u>There are 2 rotation speeds tested</u>: **60rpm** and **1rpm**: 55040 samples/rev & 10 revolutions.
- <u>There are 2 tested settings</u>: **with** and **without** Icepap controller: 55040 samples/rev & 10 rev.
- <u>No filtering</u> on data is done.
- A temperature measurement has been done over 12h during the night, using 8 sensors dispatched on the spindle and close surroundings.
- The sense of the rotation is the same than used at LAB (clockwise in top view, from +X toward +Y).

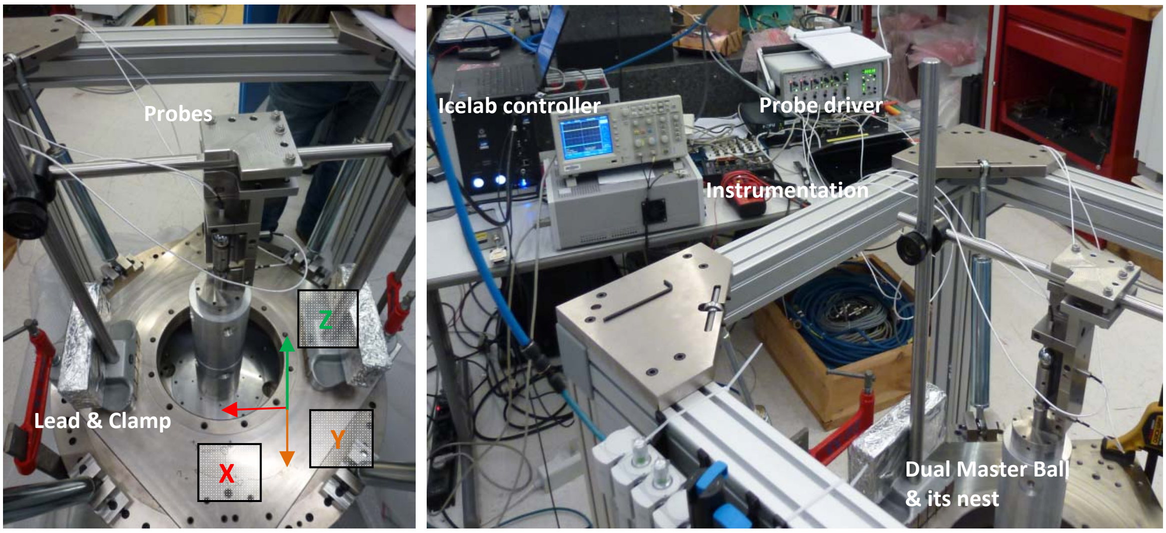


Photo: Master ball in its nest (left), CPL290 (right).

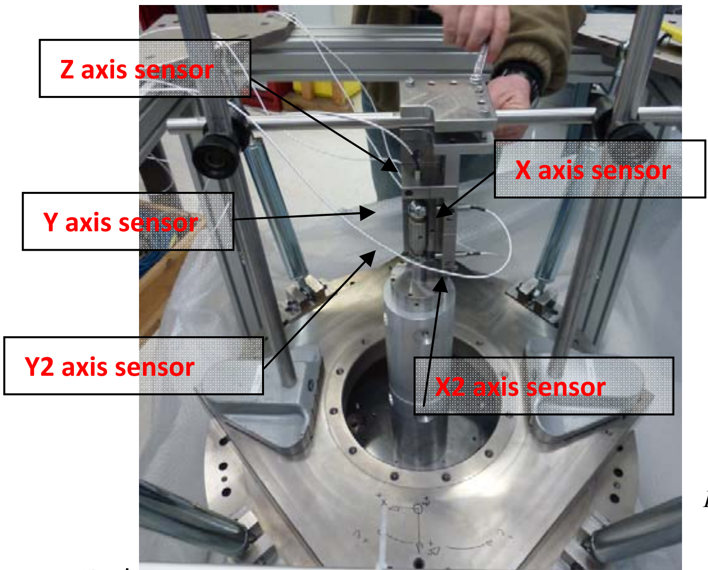


Photo: Setup with 5 capacitive probes.

2-Error motion types

According to the ISO230-7, there are different standard spindle errors, as:

- Fixed axial & radial error motion
- Rotating Sensitive direction error motion
- Synchronous and asynchronous error motion

These analyses may include when necessary a thermal drift compensation.

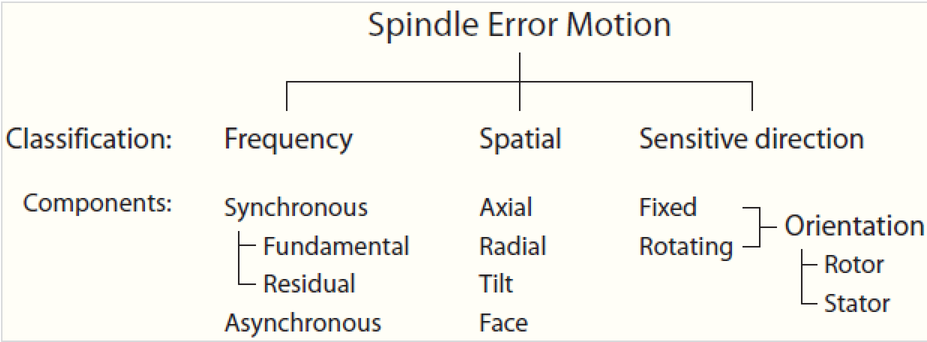


Figure: At least one component from each of the three columns is needed to describe a measurement/Courtesy of Eric R. Marsh

Asynchronous error motion - the portion of the total error motion that occurs at frequencies other than integer multiples of the rotation frequency. Asynchronous error motion comprises those components of error motion that are:
- not periodic
- periodic but occur at frequencies other than the spindle rotational frequency and its integer multiples
- periodic at frequencies that are sub harmonics of the spindle rotational frequency.
By analogy with linear stages measurements, it corresponds to the repeatability of the straightness error.

Synchronous error motion - the portion of the total error motion that occurs at integer multiples of the rotation frequency. The term average error motion is equivalent but no longer preferred. The method of averaging remains acceptable for the determination of synchronous error motion.
By analogy with linear stages measurements, it corresponds to the maximum error of the straightness.

The axial error is measured with the Z sensor, which is parallel to the rotating axis. The measurement is shown in a polar and Cartesian plot. It is possible to show the data with or without the fundamental. The harmonic represents one total revolution (upr: once-per-revolution).

The radial error is measured with the X/X2 and Y/Y2 sensors, perpendicular to the Z reference axis and at 2 specified axial locations (allowing us to calculate the tilt).

The rotating sensitive direction is measured with the X (or Y) and X2 (or Y2) sensors and calculate by the formula bellow. It gives the error at a precise point at a given orientation:

$$R(\alpha) = X\cos(\alpha) + Y\sin(\alpha)$$

Decomposition of synchronous error motion into fundamental and residual components

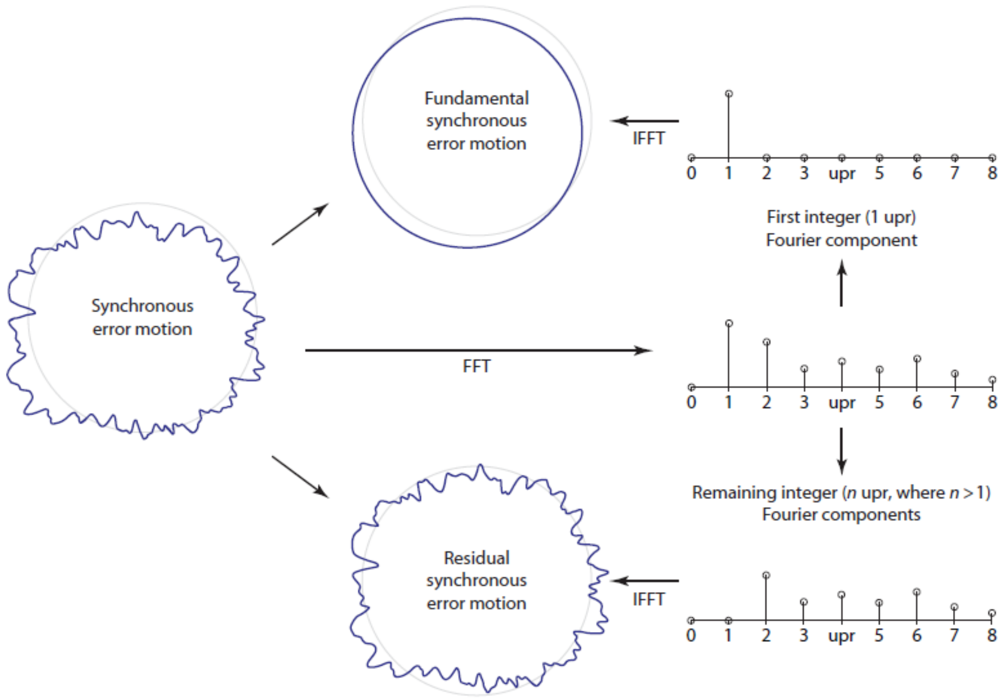


Figure: Example of decomposition by fast Fourier transform of the residual synchronous error and its fundamental. /Courtesy of Eric R. Marsh

Synchronous and asynchronous components

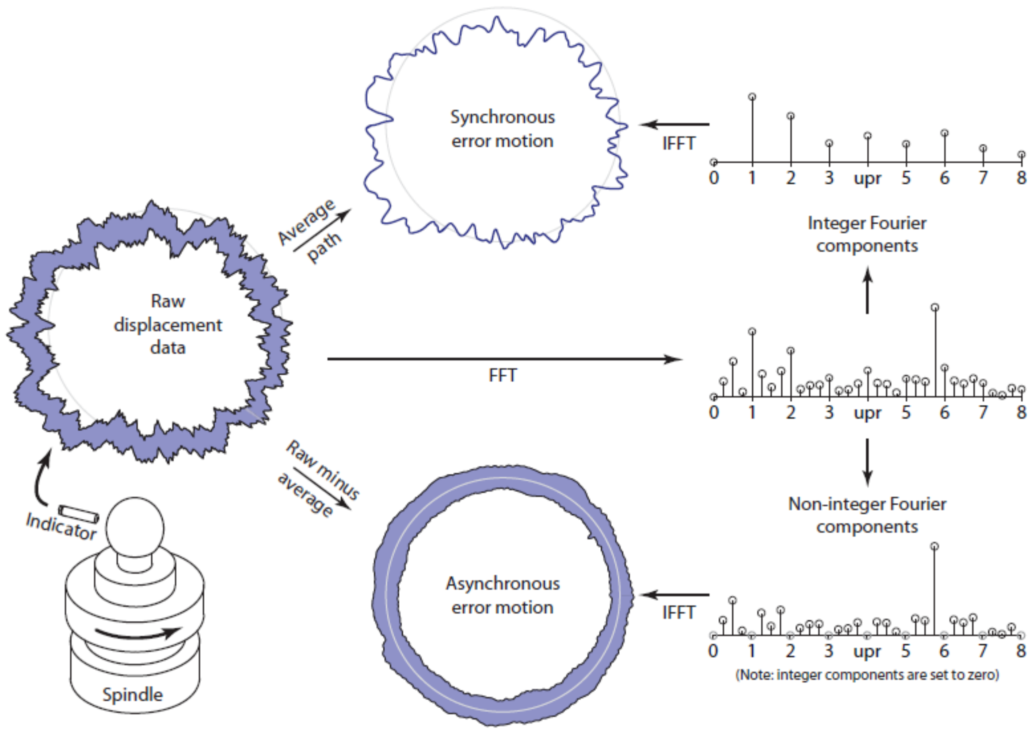


Figure: Example of decomposition of synchronous and asynchronous error motion using a fast Fourier transform. /Courtesy of Eric R. Marsh

3-Results

All the documents, pictures and the raw data can be found at:
R:\home\PDMU\PEL\Measurement_library\ID31\Spindle_ID31

The synthesis of the measurements is shown in the table below. Moreover, there are some relevant points to notice due to practical issues caused by the environment:
- Data acquisition noise (not filtered, but less than 10nm).
- The measurement setup is prone to vibrations.
- Dependence of speed.

3.a Differences between both controller at 1 RPM

The fist table here below show the differences between both controllers at **1 RPM** each, when Icepap is taking control over Icelab and when it is not the case.

Axis/Plane	Component	Measure 1a (nm)	Measure 2a (nm)
		• 10 turns • 1 RPM • **USB** (ICELAB only)	• 10 turns • 1 RPM • **ICEPAP (1step Icelab/1 step Icepap)**
X axis	Radial	483	484
	Residual Synchronous	144	160
	Asynchronous	380	397
Y axis	Radial	360	338
	Residual Synchronous	148	145
	Asynchronous	282	226
XY plane	Rotating Sensitive direction	411	415
X2 axis	Radial	389	459
	Residual Synchronous	91	101
	Asynchronous	379	430
Y2 axis	Radial	410	416
	Residual Synchronous	65	69
	Asynchronous	394	381
X2Y2 plane	Rotating Sensitive direction	447	495
Z axis	Axial Error	93	103
	Synchronous	32	34
	Asynchronous	86	96

This table above shows quite similar results with both control method at low speed. The control method using Icepap in this setting seems to be compliant. Let’s now see what happen with higher speeds.

3.b Differences between both controller at 60 RPM + no motor

The second table below compares 3 settings at 60 RMP and over 10 turns. The first one is when Icelab only controls the spindle, the second one is when Icepap is mastering Icelab (and with a Finite Impulse Response filter added in the controller), the third one is without motorization (we launch the rotation at 60 rpm then we cut the power off).

Axis/Plane	Component	Measure 1b (nm)	Measure 2b (nm)	Measure 3b (nm)
		• 10 turns • 60 RPM • **USB** (ICELAB only)	• 10 turns • 60 RPM • **ICEPAP+FIR**	• 10 turns • 60 RPM • **No motor**
X axis	Radial	405	387	451
	Residual Synchronous	164	158	148
	Asynchronous	285	295	324
Y axis	Radial	268	242	247
	Residual Synchronous	165	160	143
	Asynchronous	131	110	139
XY plane	Rotating Sensitive direction	379	352	390
X2 axis	Radial	323	335	340
	Residual Synchronous	104	110	86
	Asynchronous	259	259	322
Y2 axis	Radial	332	320	336
	Residual Synchronous	77	81	67
	Asynchronous	279	279	300
X2Y2 plane	Rotating Sensitive direction	383	364	392
Z axis	Axial Error	81	78	69
	Synchronous	38	39	32
	Asynchronous	60	62	64

We can notice that since the measurement lasts longer when the motor is not powered, the asynchronous error on this measurement in larger. However the residual synchronous error is reduced.

3.c Differences between Icepap with and without FIR filter

The Icelab controller provides specialized hardware features to make a FIR filters. An FIR filter has a number of useful properties which sometimes makes it preferable to an infinite impulse response (IIR) filter. FIR filters can easily be designed to be linear phase (where the phase response of the filter is a linear function of frequency) by making the coefficient sequence symmetric. We used here an 8 order FIR filter with a symmetric sequence: using this filter in the Icelab controller allows us to smooth the positioning steps sent by the Icepap, thus to remove the mechanical noise due to the abrupt steps signal. Here bellow we compare the results with and without a FIR filter.

Axis/Plane	Component	Measure 1c (nm) • 10 turns • 60 RPM • **ICEPAP+FIR**	Measure 2c (nm) • 10 turns • 60 RPM • **ICEPAP**
X axis	Radial	387	427
	Residual Synchronous	158	158
	Asynchronous	295	335
Y axis	Radial	242	290
	Residual Synchronous	160	174
	Asynchronous	110	178
XY plane	Sensitive direction	352	417
X2 axis	Radial	335	367
	Residual Synchronous	110	107
	Asynchronous	259	338
Y2 axis	Radial	320	365
	Residual Synchronous	81	88
	Asynchronous	279	316
X2Y2 plane	Sensitive direction	364	394
Z axis	Axial Error	78	94
	Synchronous	39	38
	Asynchronous	62	83

As we can see, the results are better with a FIR filter but mostly for the asynchronous error. It means that the system is less prone to vibratory states caused by the command signal.

3.d Leuven Air Bearing results

For more details, the entire technical report from LAB can be found at:
R:\home\PDMU\PEL\Measurement_library\ID31\Spindle_ID31\LAB_Measurement_error_motion
The table below compares the PEL best results using Icepap with a filter to the LAB results using Icelab.

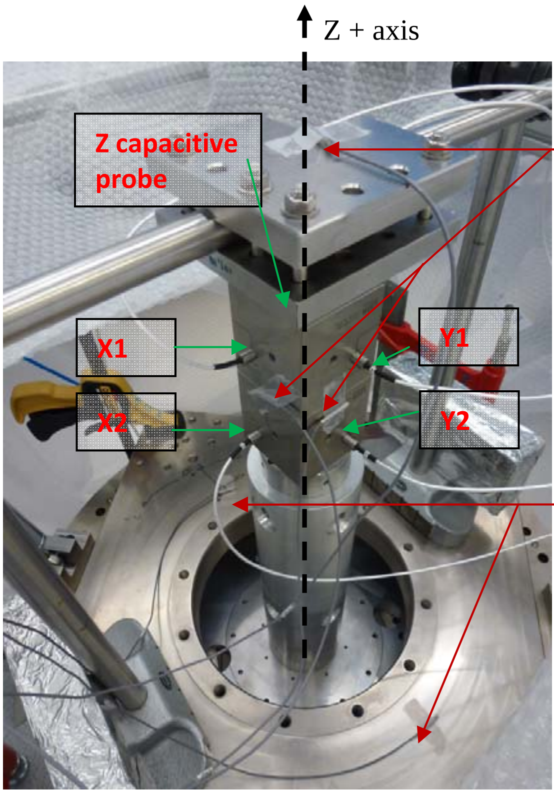
Axis/Plane	Component	PEL measure (nm) • 10 turns • 60 RPM • **ICEPAP+FIR**	LAB measures (nm) • 10 turns • 60 RPM • **ICELAB (USB)** **At 355mm**
X2 axis	Radial	335	
	Residual Synchronous	110	72
	Asynchronous	259	NA
Y2 axis	Radial	320	
	Residual Synchronous	81	76
	Asynchronous	279	NA
Z axis	Axial Error	78	
	Synchronous	39	36
	Asynchronous	62	NA

In this table, we can see that the results obtained in both laboratories seems to be close. It means that the system is compliant with the Icepap control method using these settings.

Axis/Plane	**Component**	**PEL measure (nm)** • 10 turns • 60 RPM • **No motor**	**LAB measures (nm)** • 10 turns • 60 RPM • **No motor at 555mm**
X2 axis	Radial	451	
	Residual Synchronous	148	73
	Asynchronous	324	NA
Y2 axis	Radial	247	
	Residual Synchronous	143	96
	Asynchronous	139	NA
Z axis	Axial Error	69	
	Synchronous	32	25
	Asynchronous	64	NA

Nevertheless, the results without the motor performed in both laboratories shows a difference. To perform this measurement at the PEL, we launched the rotation at 60 RPM to then cut off the power. The spindle continues to rotate but the speed decreases quite fast. Perhaps the method used is not the same than LAB since we didn't try to maintain the speed by hand.

4-Stability

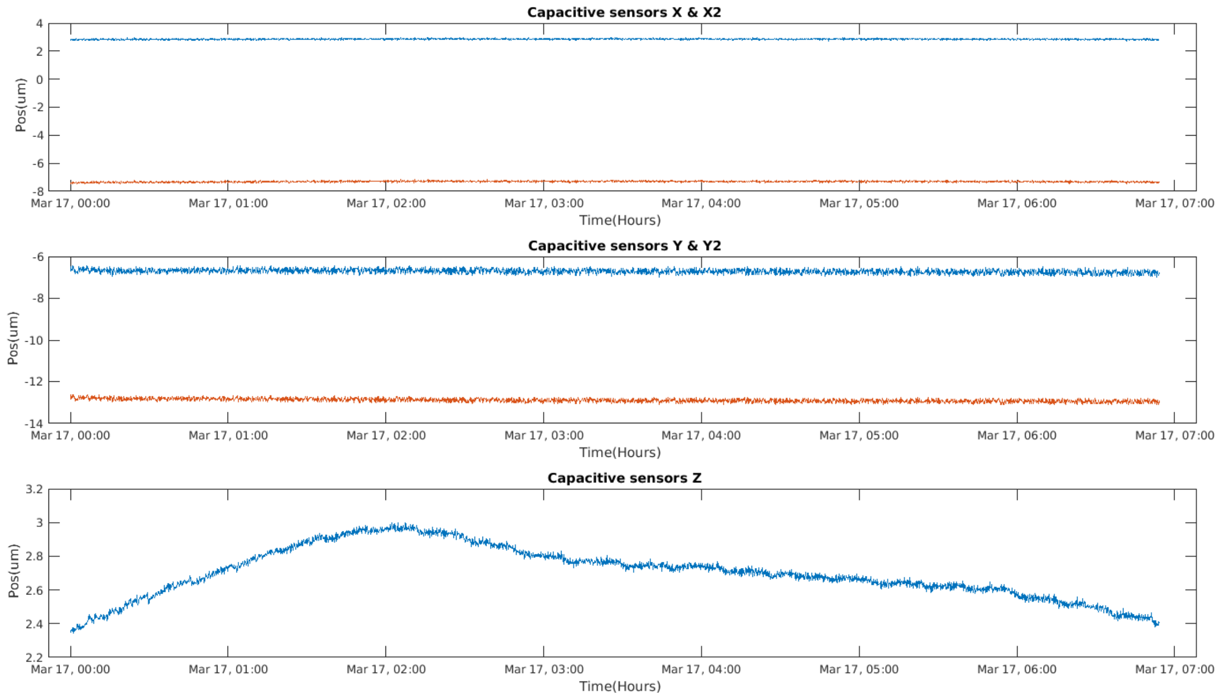


Temperature sensor 1, 2 & 3 (Cage temperature)

Temperature sensor 4 & 5 (Top plate temperature)

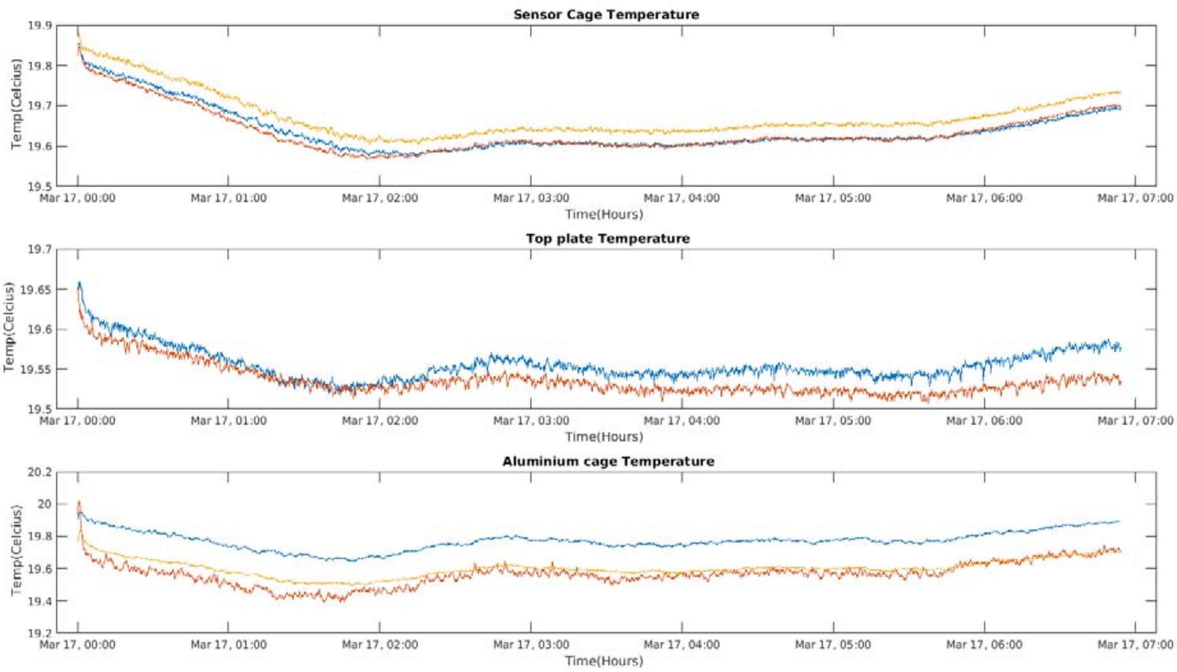
Photo: Full setup, clamped and equipped with 8 temperature sensors (3 not visible here, placed outside the aluminium cage) and 5 capacitive probes.

For this measurement, we choose to monitor the temperature at 8 different points and to compare the drifts relating to capacitive probe signals over an entire night (12 hours), after we had cut the motor power and leaved the lab.
Here below the capacitive sensors measurement, we notice that only the Z axis is concerned by the change of temperature:

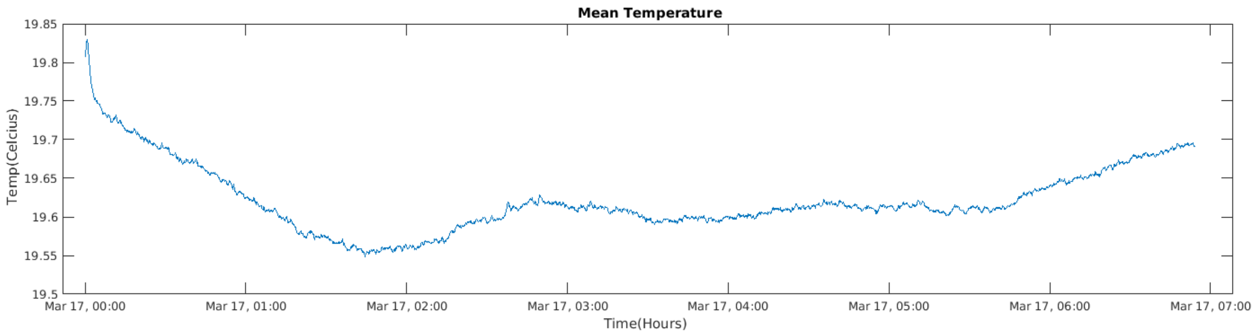


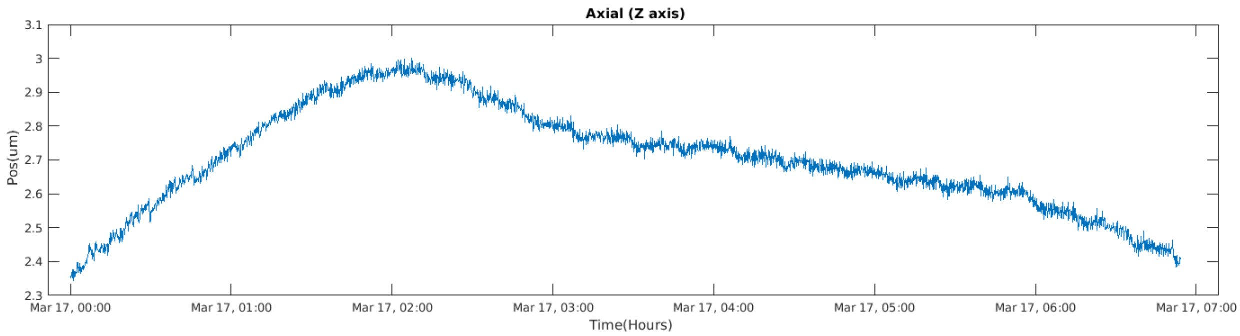
Graph: Capacitive sensor measurement over a night.

As we can see, there is no thermal effect on the radial plane (X&Y), but only on the axial axis (Z)



Graph: Temperature measurement over a night.





In consequence we can directly compare the mean temperature to the Z axis.
We notice that the expansion phenomenon occurs on the Z axis in the same way than the temperature, at a sign difference. It is explained by the different thermal expansion coefficient between the aluminium (on which is fixed the Master Ball) and the steel (on which is fixed the Z capacitive probe).

II) <u>Measurement of the MIM & repeatability</u>

<u>1-Measurement conditions</u>

The measurements of the rotating positioning system have been done at the PEL under the following conditions:

- The measurements are performed at the PEL in a controlled temperature room, 20 ±0.2°C
- The sense of the rotation is the same as used at LAB (clockwise in top view, from +X toward +Y).
- 1 encoder step (0.58µrad) repeated 10 times.

In order to verify the minimal incremental motion and the repeatability of the spindle, we used a laser interferometer system from Agilent and the internal encoder Renishaw.

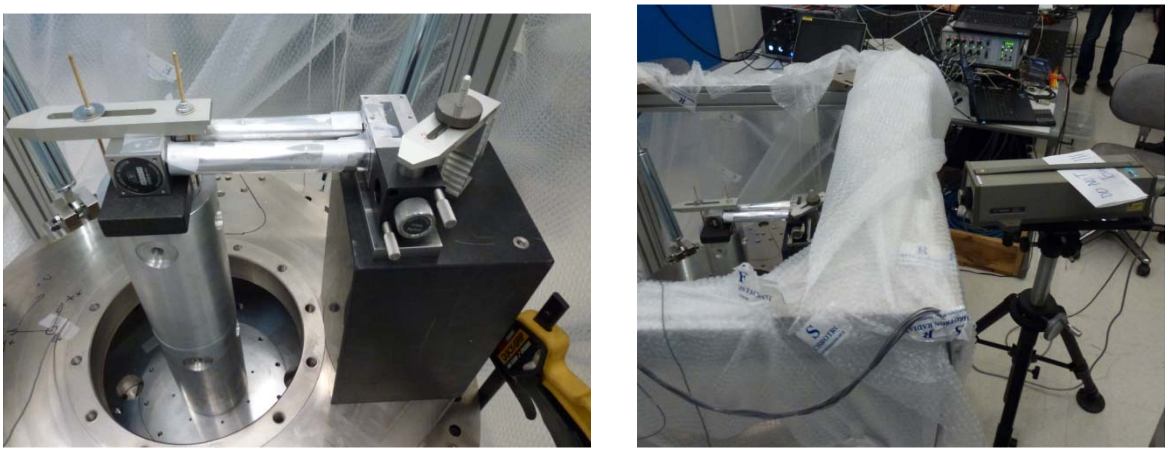


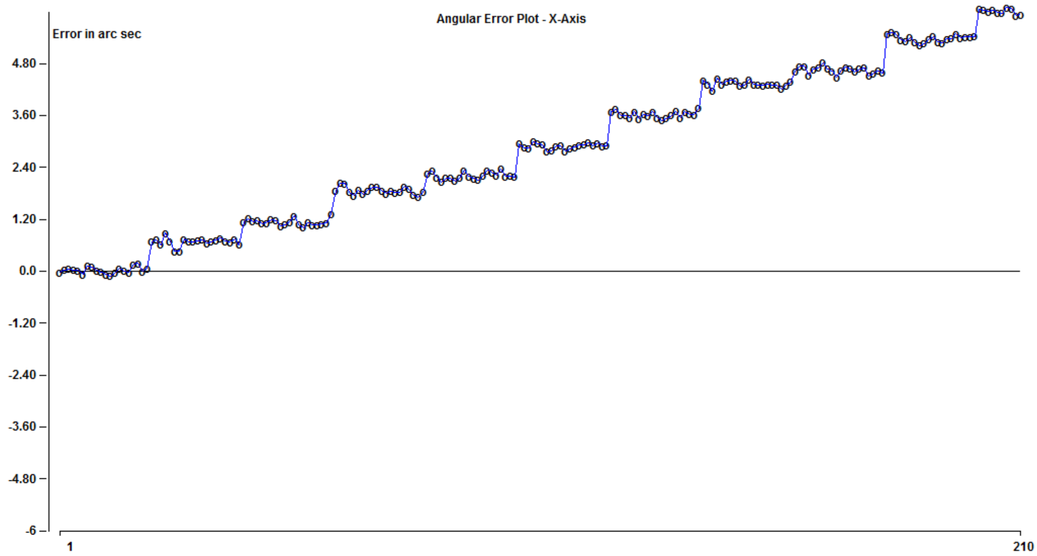
Photo: The MIM spindle test bench at the PEL using the interferometric system.

2-MIM Results

Measure	Conditions	Results
Mes 1	PEL Interferometer 1 sec averaging	3.0 µrad
Mes 2	PEL Renishaw encoder No averaging	±3 encoder steps = 3.5 µrad
Mes 3	PEL Renishaw encoder Averaging on 20 samples (0.1s)	0.6 µrad
Mes 4	LAB Capacitive probe Averaging	0.6 µrad

Graph: Synthesis of the MIM measurements.

The first measurement was performed with the interferometer at the sample height, 402 mm from the rotor surface, the results are shown below:



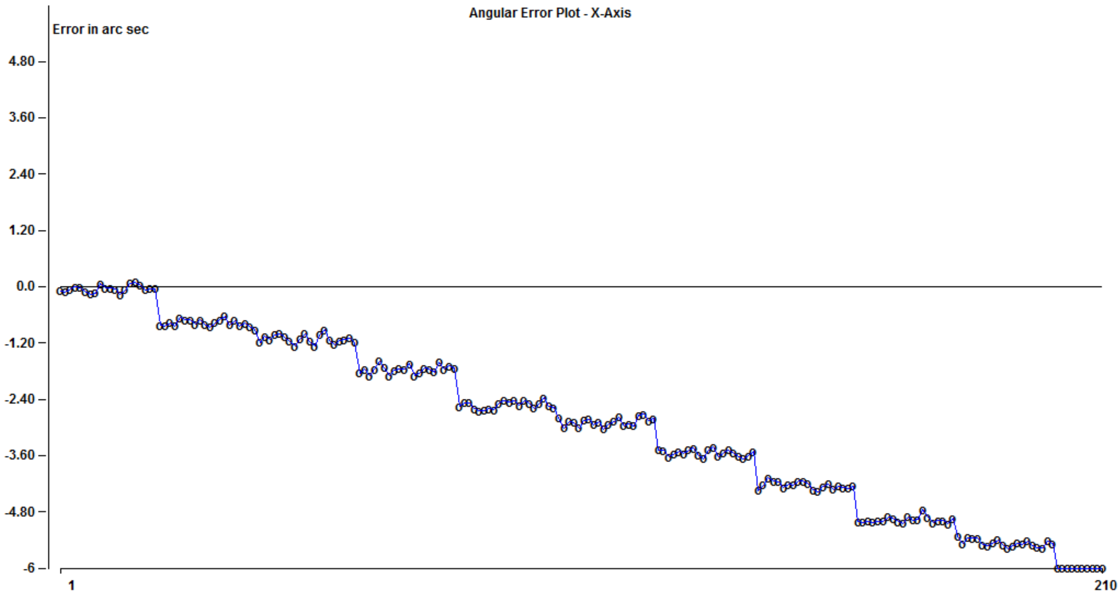
Numerical Analysis: ISO 230-2 1997 2.0σ
Raw Accuracy:↑ 6.20as.

Machine Name: spindle LAB ID31
Acquisition date: 23/03/2017 15:34:42
Current date: 28/04/2017 13:07:39
File Name: respos_3urad_01.ang
Operator: HPvdK, LR
Location: PEL
Serial No: na
Comments:
MIM measurement of the ID31 spindle from LAB, at a hight of 402 mm from the rotor surface. Forward direction.
Averaging: 1 sec. V: 1 rot/ min. 10 increments of 0.6 sec

Environment Data: Metric

	Start	End
Air T	20.0	20.0
Air P	760.73	760.73
Air H	50.0	50.0
MT1 T		
MT2 T		
MT3 T		

Graph: Mes1->Positive MIM using the interferometric system.



Numerical Analysis: ISO 230-2 1997 2.0σ
Raw Accuracy:↑ 6.38as.

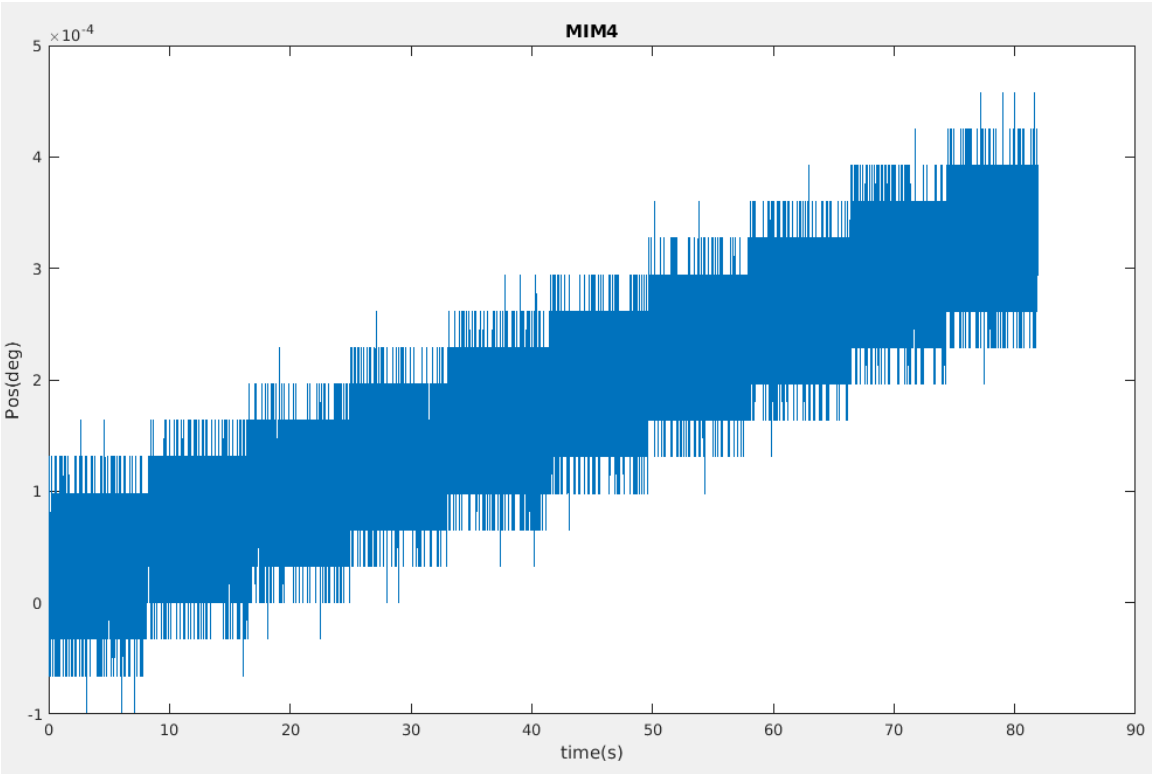
Machine Name: spindle LAB ID31
Acquisition date: 23/03/2017 15:44:34
Current date: 28/04/2017 13:07:06
File Name: resneg_3urad_01.ang
Operator: HPvdK, LR
Location: PEL
Serial No: na
Comments:
MIM measurement of the ID31 spindle from LAB, at a hight of 402 mm from the rotor surface. Backward direction.
Averaging: 1 sec. V: 1 rot/ min. 10 increments of 0.6 sec

Environment Data: Metric

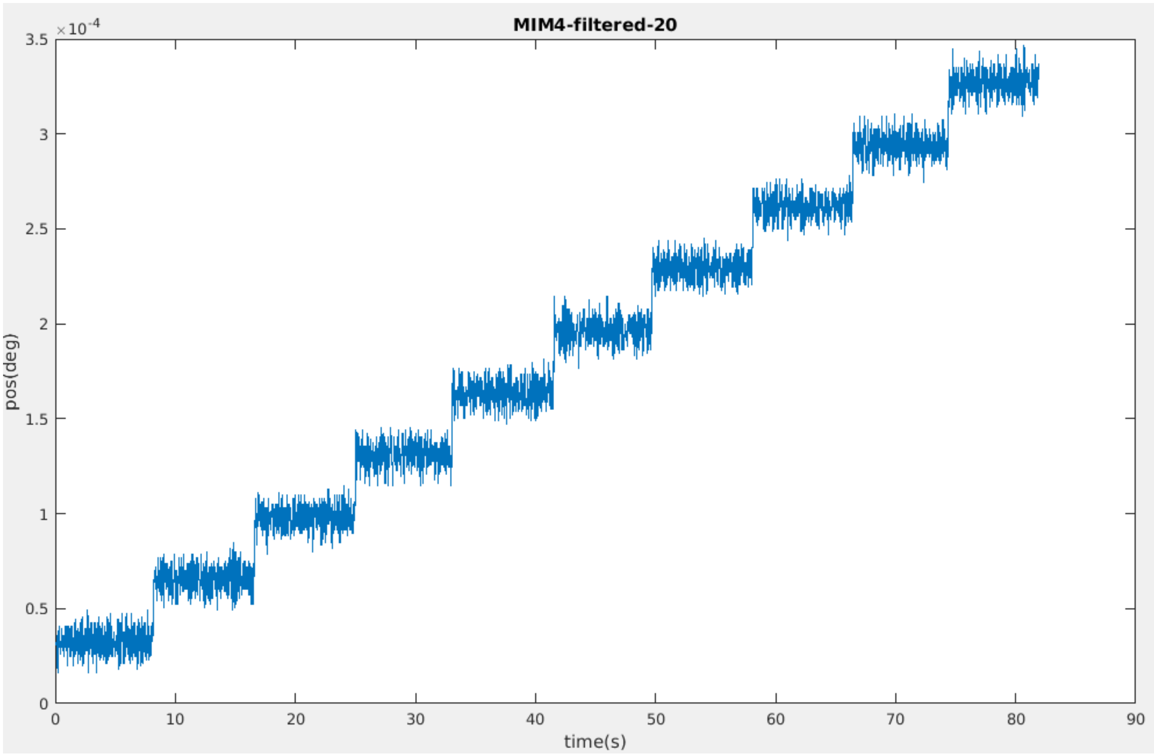
	Start	End
Air T	20.0	20.0
Air P	760.73	760.73
Air H	50.0	50.0
MT1 T		
MT2 T		
MT3 T		

Graph: Mes1->Negative MIM using the interferometric system.

The second measure has been done by reading the encoder head, with and without averaging the time during the acquisition:

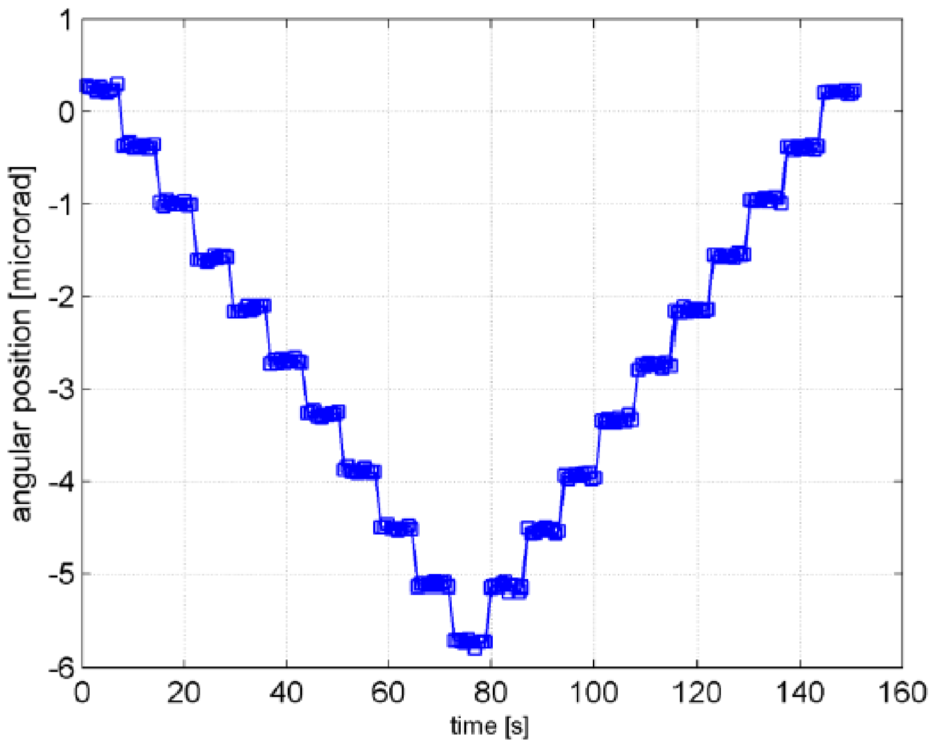


Graph: Mes2->Positive MIM using the renishaw encoder, without averaging

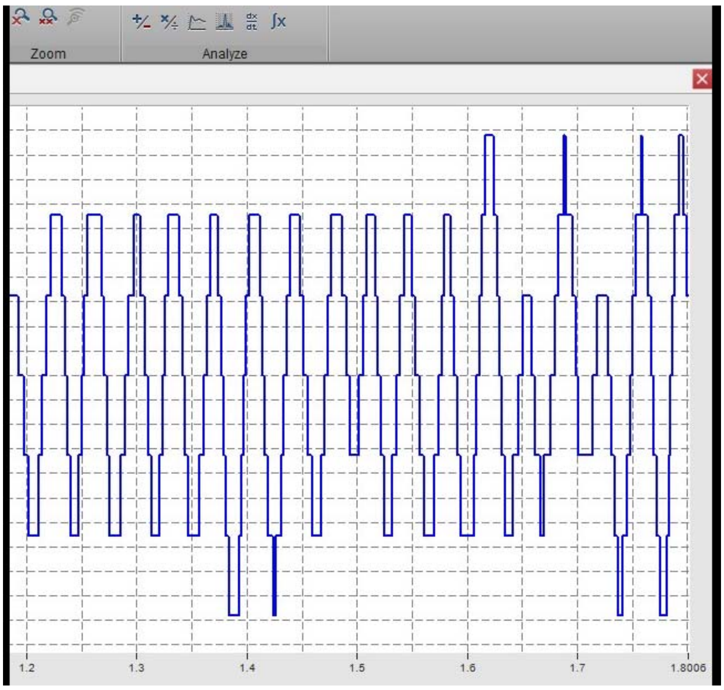


Graph: Mes3->Positive MIM using the renishaw encoder, with 0.1s averaging

Finally here below the measure performed by LAB with a capacitive probe close to the encoder:



Graph: Mes4->Bidirectional MIM using the capacitive probe, with averaging/LAB measurement

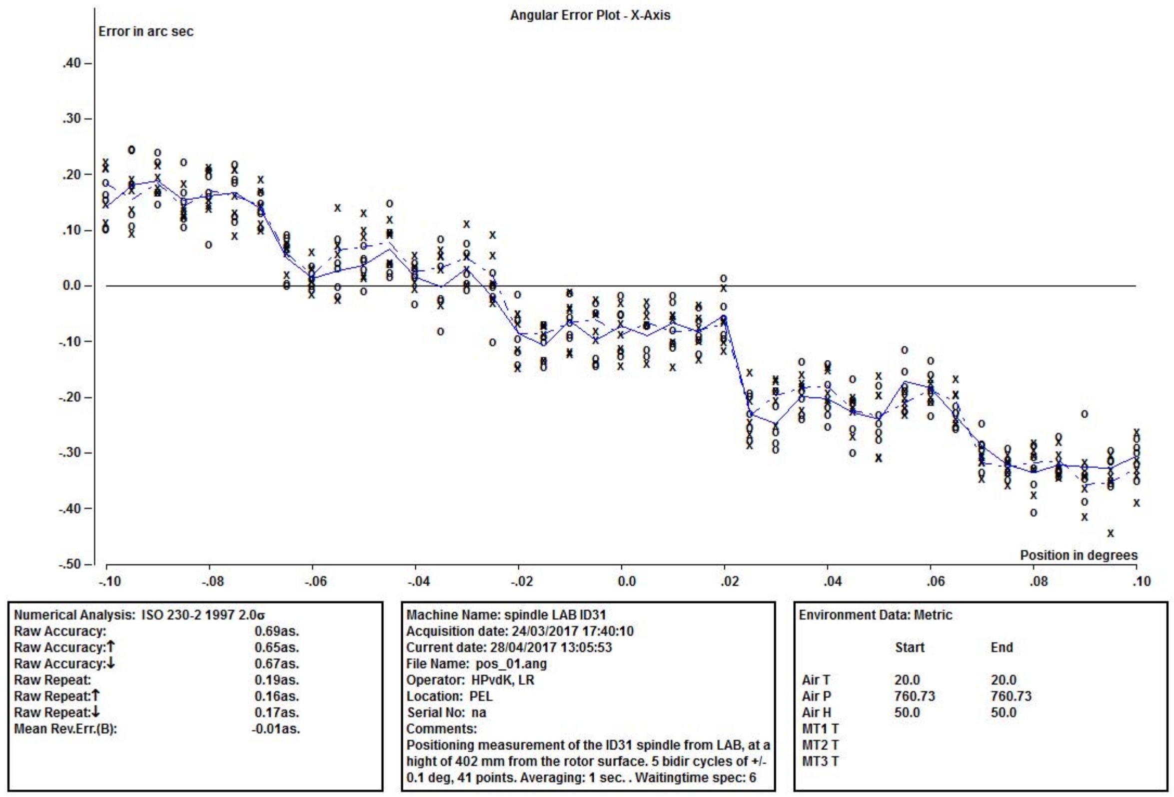


Graph: Zoom on the regulation of ±3steps.

Even if the conditions of the measures are completely different because of the kind of the sensor used and their locations, the Icelab keeps the position within the ±3 encoder steps. At each request of movement of 1 step, we can see that the position is increased by 1 step and maintained at this position within the ±3 encoder steps.

3-Repeatability Results

The positioning measurement of the spindle was performed at a height of 402 mm from the rotor surface. 5 bidirectional cycles of ±0.1 degrees on 41 points, with an averaging of 1 sec and a waiting time of 6 sec between each movement:



The results shows a good repeatability **of 0.19 as (=0.92 µrad).** Here we don't have to worry about the accuracy of 0.69 arcseconds since the position hasn't been removed from the error.

III) Bidirectional measurement

1-Measurement conditions

This measurement has been performed with the static SEA software. After the characterisation of continuous and unidirectional movement, the spindle is also characterized under bidirectional point to point movement. The spindle is first positioned at the index (0 degrees) then an angular step is made followed by a pause and then the trigger is generated to acquire the measurement point. When the spindle has done 1 turn, the direction is reversed until it reaches 0 degrees again.

The conditions are the following:

- Each measurement has been performed with a low resolution (80mV/µm) capacitive sensor set from Lion Precision, composed of 3 sensors (+X, +Y, -Z) conditioned by a CPL290 and mounted on a probe nest (i.e appendix for the datasheets). The measurements are performed at the PEL in a controlled temperature room, 20 ±0.2°C
- A dual Master-Ball target was mounted on the rotor (25.4mm), used as reference surface for the measurement, and aligned at the center of the nest (i.e photo below). The master ball roundness is <20nm and it is considered negligible.
- The upper master ball is at sample high (about 555 mm height)

- No filtering on data is done.
- The first sense of the rotation is from +X toward +Y, then inverted
- The angular step size is 2 degrees.
- The data is compensated with the thermal drift

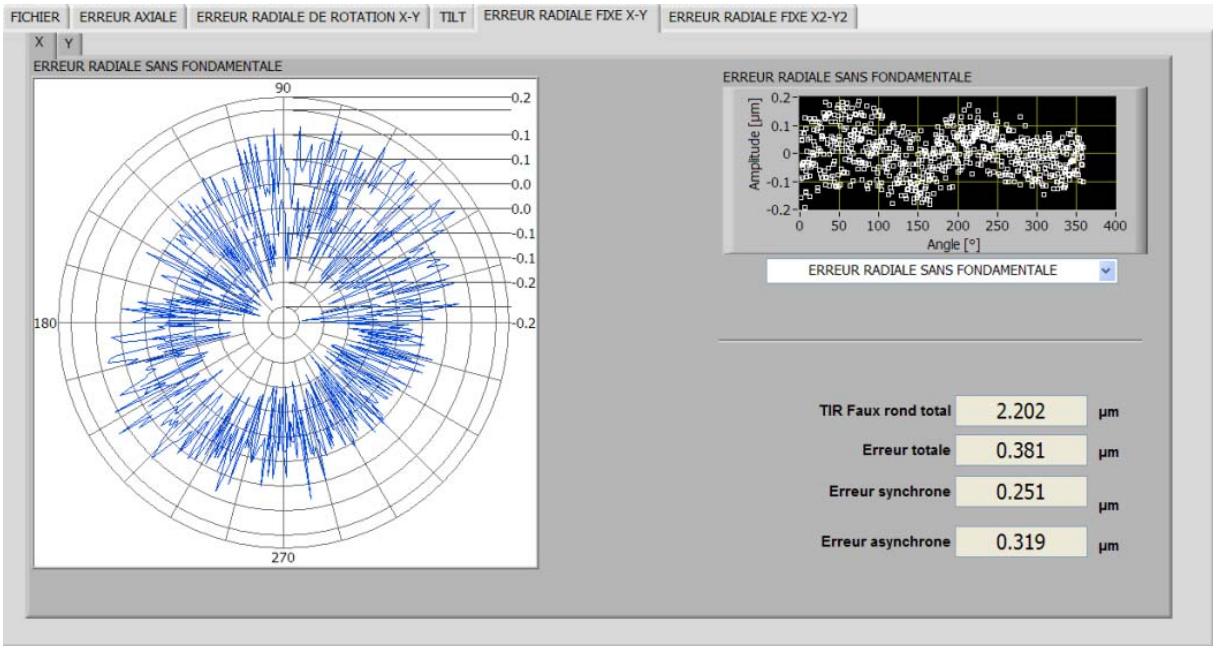
2-Bidirectional motion result.

The table here below compares the residual synchronous error found at the PEL and the ones get from LAB:

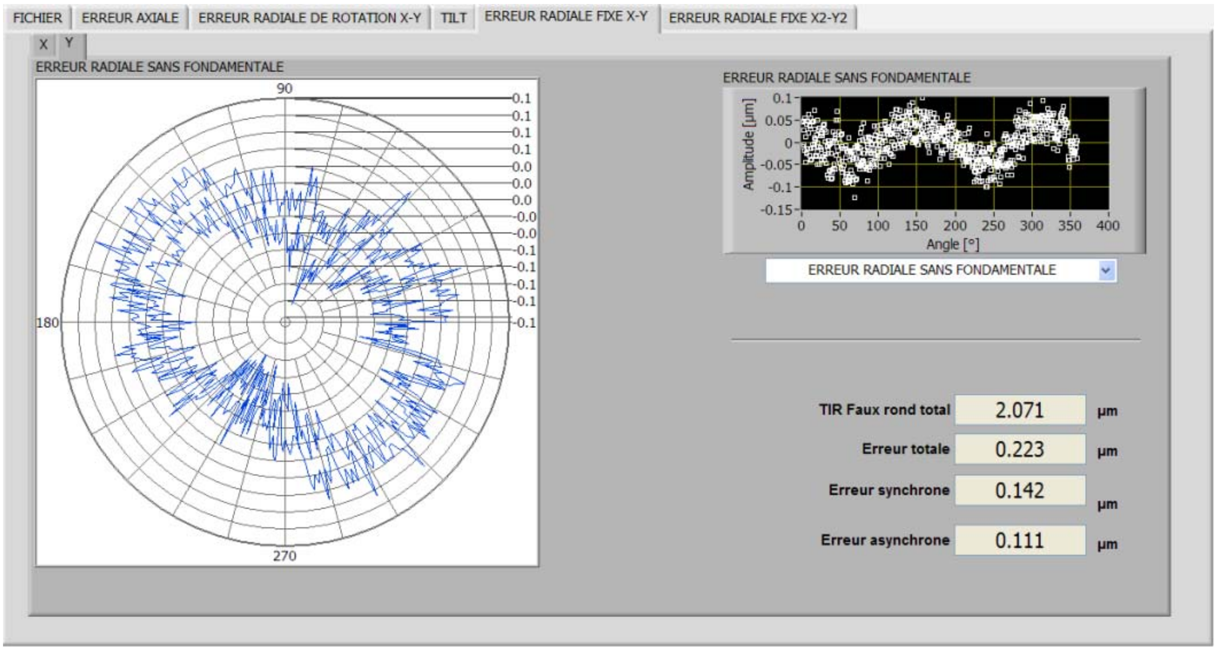
Axis\Residual synchronous error	PEL 2 degrees steps 1 cycle Linear compensation	LAB 5 degrees step 1 cycle Linear compensation	LAB 30 degrees step 1 cycle Linear compensation
+X	251 nm	145 nm	80 nm
+Y	142 nm	120 nm	95 nm
-Z	44 nm	23 nm	16 nm

We notice that the larger the step is, the smaller the synchronous error is.

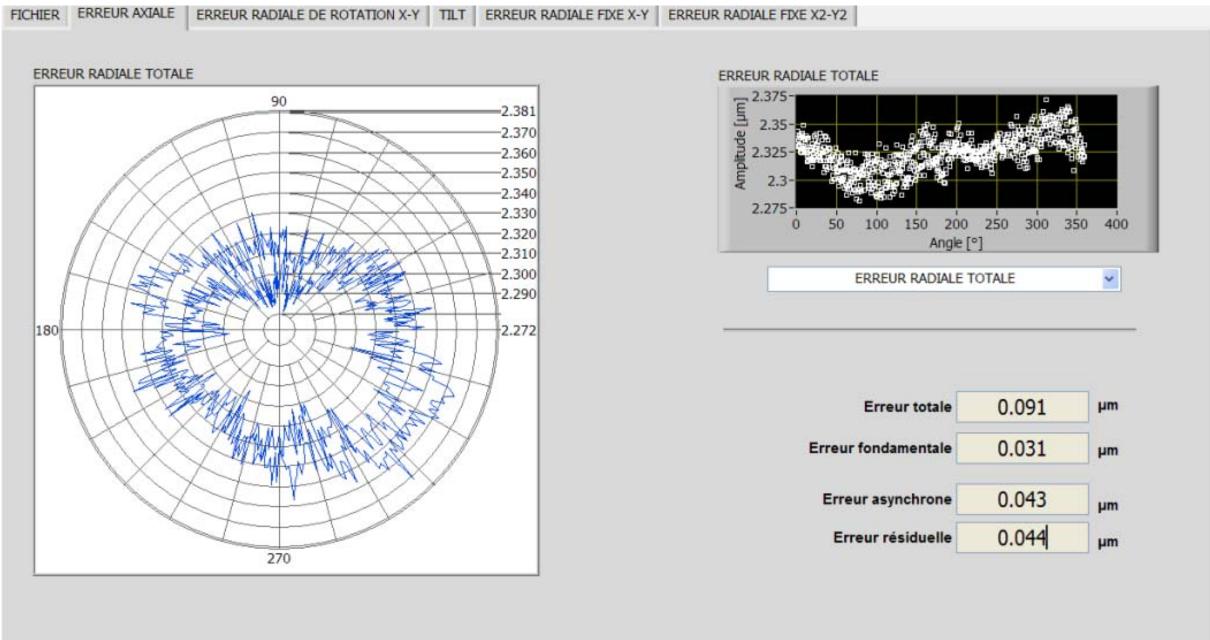
PEL results:



Graph: PEL bidirectional using the capacitive probe, +X axis, 2 degrees step size.

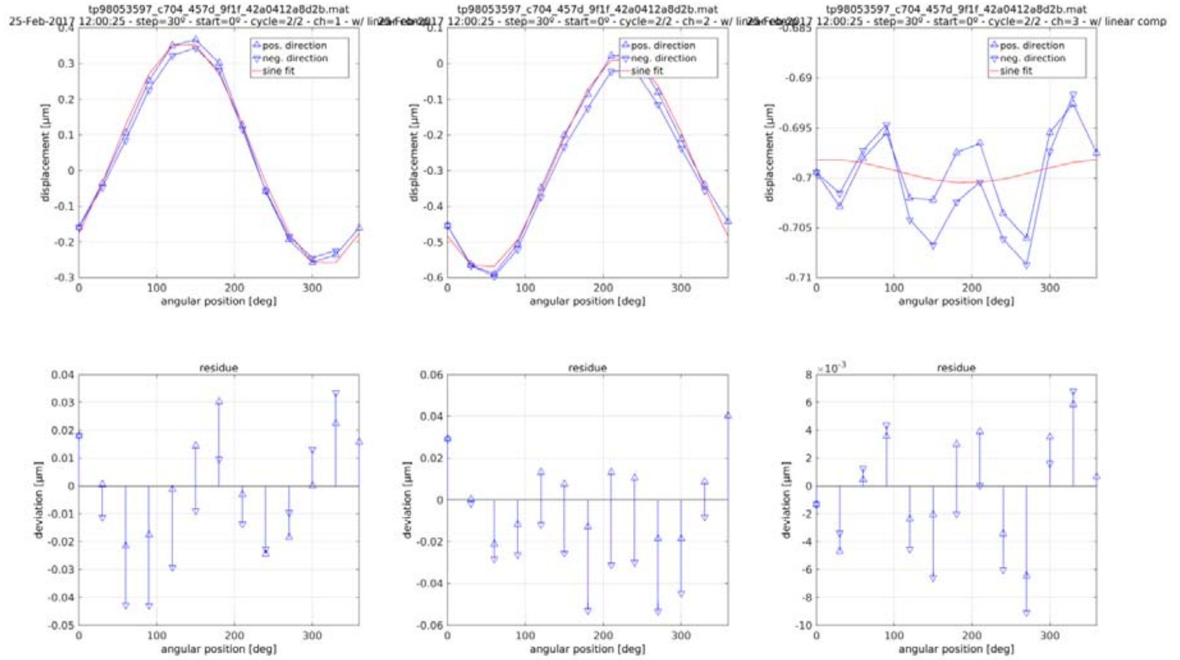


Graph: PEL bidirectional using the capacitive probe, +Y axis, 2 degrees step size.

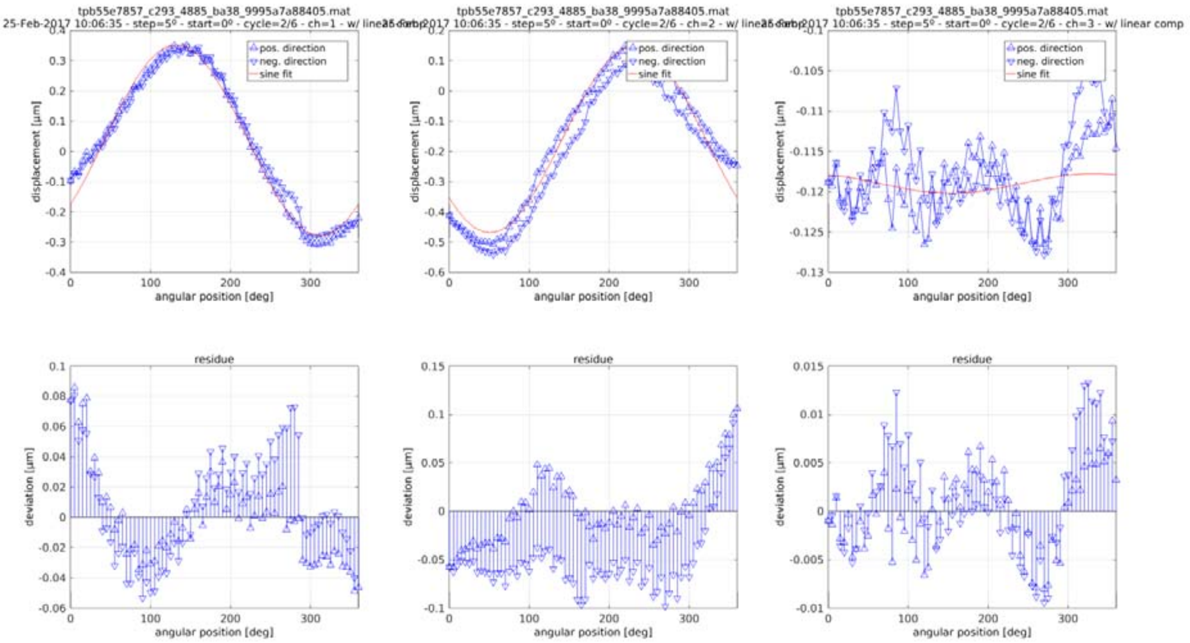


Graph: PEL bidirectional using the capacitive probe, -Z axis, 2 degrees step size.

Lab results:



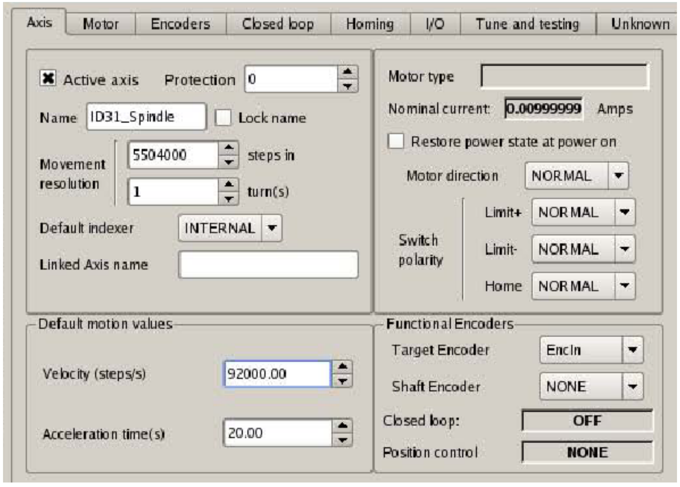
Graph: LAB bidirectional using the capacitive probe, +X (left), +Y(middle), -Z (right), 30 degrees step size.

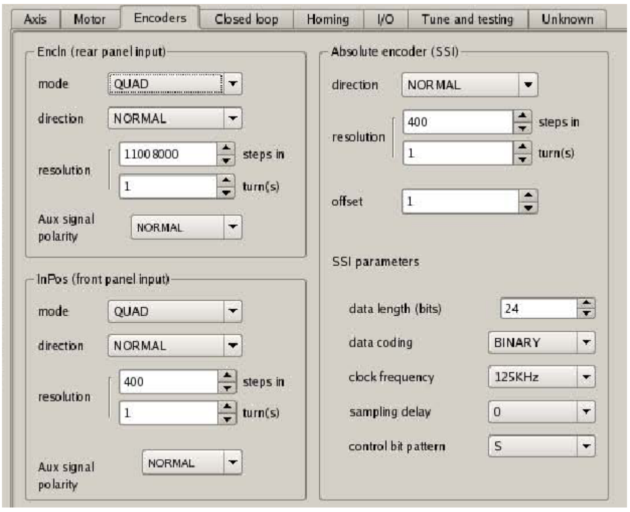


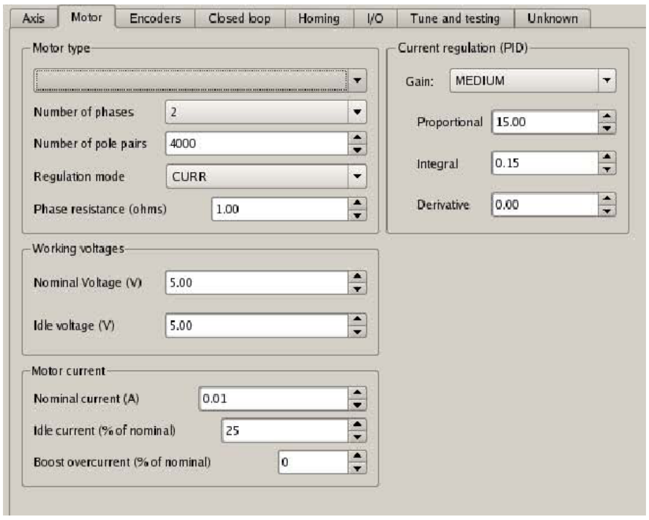
Graph: LAB bidirectional using the capacitive probe, +X (left), +Y(middle), -Z (right), 5 degrees step size.

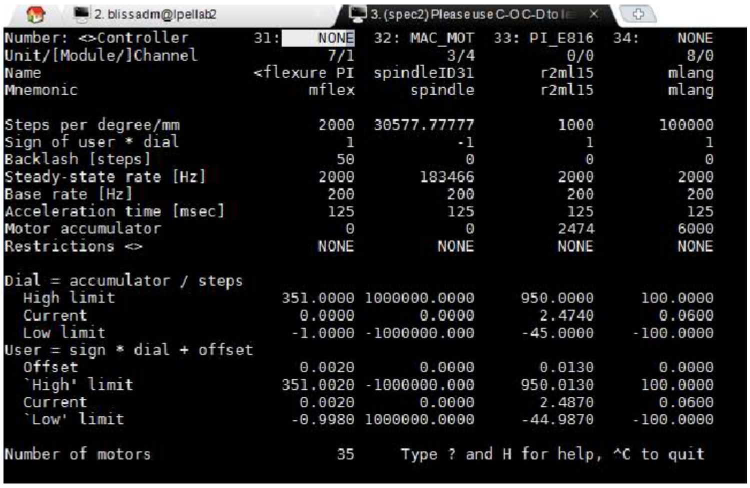
IV) Appendices

1- Motion controller configuration:









2- Specification of the capacitive probes and the CPL290

Specifications

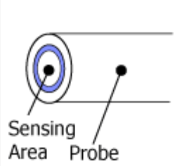
Typical specifications. Resolution and linearity depend on probe, range, and bandwidth. See Probes

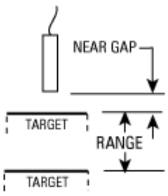
Typical Resolution	0.003% @ 15 kHz 0.0005% @ 100 Hz
Bandwidth (PCB Dip-Switch Selectable)	15 kHz, 10 kHz, 1 kHz, 100 Hz
Typical Linearity	0.2%F.S.
Maximum Drift	0.04%F.S./°C
BNC Output	±10 V, 0 ohms, 15 mA max
Rear Panel National Instruments Interface Connector Output Voltage	Differential ±10 V
Operating Temperature	4-50 °C

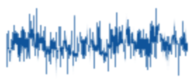
↑ *CPL290datasheet*

CPL190/CPL290 Ranges/Resolutions - Probe Dependent

1 mil = 0.001"







Integral filters included in the CPL190 and CPL290

Standard Probes Sensing Area Diameter mm	Measurement Range Range Type	Range µm mils	Near Gap µm mils	Resolution* @ Bandwidth 100 Hz nm µin	1 kHz nm µin	10 kHz nm µin	15 kHz nm µin	Linearity % F.S.	Body Style
0.5	Fine	10 0.4	20 0.8	0.06 0.003	0.1 0.004	0.4 0.016	0.6 0.024	0.25	3mm 5mm
	Standard	50 2.0	50 2.0	0.3 0.012	0.5 0.020	3.0 0.12	4.0 0.16	0.25	
	Extended	80 3.0	60 2.4	0.5 0.02	1.0 0.04	5.0 0.20	—	0.25	
0.8	Fine	25 1.0	75 3.0	0.2 0.008	0.5 0.02	1.2 0.05	1.5 0.06	0.15	3mm 5mm
	Standard	100 4.0	100 4.0	0.5 0.02	1.0 0.04	3.5 0.14	5.0 0.20	0.15	
2.0	Ultrafine	10 0.4	20 0.8	0.05 0.002	0.08 0.003	0.15 0.006	0.25 0.010	0.15	5mm 8mm
	Fine	50 2.0	75 3.0	0.20 0.008	0.30 0.010	0.60 0.024	1.0 0.040	0.15	
	Standard	250 10.0	125 5.0	0.80 0.03	1.0 0.04	4.0 0.16	6.0 0.24	0.10	
	Extended	500 20.0	125 5.0	1.5 0.06	3.0 0.12	10 0.40	15 0.60	0.15	

↑ *Capacitive sensor used: 2mm area, range standard.*