A new Spindle Error Motion Separation Technique with sub-nanometre uncertainty

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Abstract

In this paper, a new spindle error motion separation technique, with sub-nanometre uncertainty, is proposed and validated experimentally, based on an elaborated error analysis of three most used spindle error motion separation techniques.

1 Introduction

The radial error motion of an ultra-precision aerostatic rotary table is usually characterised with the use of a lapped spherical artifact. However, the form error of such an artifact (~ 25 nm) is of the same order of magnitude as the error motion of an ultra-precision aerostatic rotary table. As a result, the artifact form error cannot be ignored and must be separated from the error motion of the ultra-precision rotary table, using a spindle error motion separation technique. Three most commonly used methods are: Donaldson reversal, Grejda reversal and the multiprobe technique [1]. However, the operations required to perform these methods, will influence the accuracy and repeatability of these techniques and consequently the measurement uncertainty. In this work, typical errors introduced while performing a spindle error motion measurement, are analytically stipulated in order to quantify the measurement uncertainty of the aforementioned methods and to indentify the root cause that impedes sub-nanometre accuracy and repeatability.

2 Error budget and Monte-Carlo analysis

In order to quantify the root cause of inaccuracy and measurement uncertainty of the three spindle error motion separation techniques, we performed an error budget and Monte-Carlo analysis. To this end, real data of respectively the radial and axial error motion of an aerostatic rotary table and the form error of a lapped spherical artifact are used. To do this, firstly, the key contributors to measurement uncertainty are observed closely. Secondly, the maximal inaccuracy of each of these components is defined. Last, a theoretical expression is derived for each error component, in order to calculate the resultant error. This data is summarised in Table 1.

Table1: Summary of the measurement uncertainty and errors introduced while performing a spindle error motion separation technique.

Error component		Unit	Donaldson		Grejda		Multiprobe	
			Max. inaccuracy	Resulting error [nm]	Max. inaccuracy	Resulting error [nm]	Max. inaccuracy	Resulting error [nm]
Artifact	Indexation	deg	0.1	0.1	0.1	0.1	n/a	n/a
	Misalignment (eccentricity)	µm	10	2	10	2	1	0.1
Sensor	Indexation	deg	0.1	0.1	n/a	n/a	0.1	0.06
	Tilt error	deg	0.05	0.003	n/a	n/a	0.05	0.005
	Alignment	deg	0.02	0.001	0.02	0.001	0.02	0.002
Indexation Table	Indexation	min	n/a	n/a	0.5	0.05	n/a	n/a
Uncertainty		nm	0.6		0.6		0.02	

It is clear from the table above that the multiprobe technique has the lowest measurement uncertainty. The Donaldson and Grejda reversal techniques, on the other hand, have a significantly higher uncertainty. This is due to the fact that the artifact must be indexed by 180° between two measurements which can lead to a large misalignment (eccentricity). It is important to note that not all errors were included during the analysis like instrument and DAQ errors but it was only restricted to the typical errors which are directly related to the three reversal techniques.

3 Principle

Based on the results and conclusions of Table 1, a new spindle error motion separation technique is developed, which combines the advantages of the multiprobe and Grejda reversal techniques. The principle of the multiprobe technique is adjusted so that only a single displacement indicator and artifact is used, which are never moved at any time during the analysis. The error motion is measured three consecutive times under three different orientations by rotating the whole setup using an indexation table. This bypasses accurately indexing of the artifact and sensor(s) during testing, as well as the effects of varying sensor sensitivities if multiple sensors are used. The measurement setup is depicted in Figure 1.

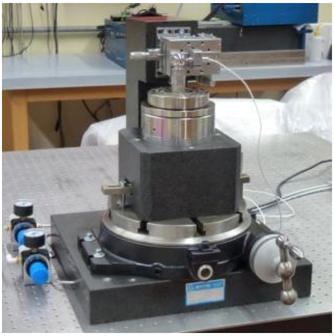

Figure 1: Measurement setup

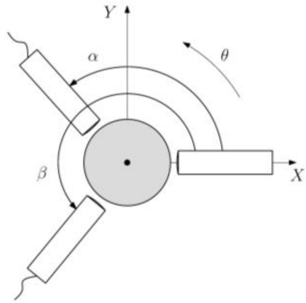

Figure 2: Definition of the measurement angles

4 Optimization of the measurement angles

The key idea of the multiprobe technique is a mathematical manipulation that eliminates the contribution of the spindle error motion. The performance of this method is dependent upon accurate knowledge of the measurement angles α and β, which are indicated in Figure 2. Moreover, poorly chosen measurement angles can lead to incorrectly computed Fourier coefficients of the error motion [2]. This is overcome by an optimization of the measurement angles, maximizing the lowest value of the harmonic sensitivity function for the first fifty harmonics. Figure 3 shows this result. A low value (black) of the harmonic sensitivity function depicts a region where certain harmonics will be suppressed during separation. Such combinations of α and β must therefore be avoided. One of the optimal measurement angles is **α = 106.875°** and **β = 275.625°**, as indicated in Figure 3.

5 Experimental results

The spindle error motion separation technique proposed here is validated in our lab. The first experiment examines the repeatability of the measurement principle without removing the artifact form error. The second experiment, on the other hand, analyses the repeatability of the proposed error motion separation technique. Both experiments were done while measuring the synchronous radial error motion at 60 rpm [3]. The results, listed in Table 2, prove the sub-nanometre measurement uncertainty of the measurement principle proposed in this work. The difference between the experimental results and the outcome of the analysis can be attributed to the fact that not all errors were included during the analysis as already stated.

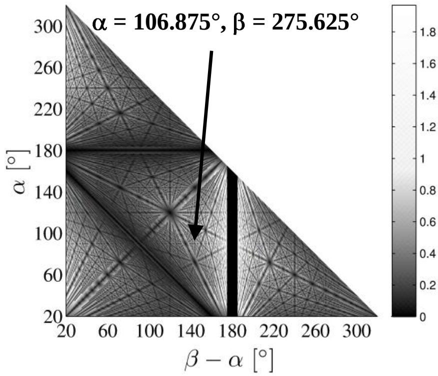

Figure 3: Optimization of the measurement angles.

Table 2: Experimental results for the multiprobe technique.

Test	Experiment 1	Experiment 2
1	37.8 nm	14.2 nm
2	38.0 nm	14.7 nm
3	38.0 nm	14.8 nm
4	38.0 nm	15.1 nm
5	37.9 nm	15.2 nm
σ	**0.09 nm**	**0.4 nm**

6 Conclusion

In this paper, we have proposed and validated a new spindle error motion separation technique with sub-nanometre uncertainty, by identifying and overcoming the uncertainty components of three commonly used spindle error motion separation techniques. The principle is based on the multiprobe technique using a single displacement indicator and artifact by placing the whole setup on an indexation table. Moreover, the optimal measurement angles of the multiprobe technique are determined.

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