Precision Engineering 37 (2013) 721–737

Contents lists available at SciVerse ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Investigation of the influence of the main error sources on the capacitive displacement measurements with cylindrical artefacts

Hichem Nouira[a,*], Alain Vissiere[b,c], Mohamed Damak[b,c], Jean-Marie David[c]

[a] *Laboratoire Commun de Métrologie (LNE-CNAM), Laboratoire National de Métrologie et d'Essais (LNE), 1 Rue Gaston Boissier, 75015 Paris, France*
[b] *GEOMNIA: Advanced 3D Engineering and Software Solutions, 165 Avenue de Bretagne, EuraTechnologies, 59000 Lille, France*
[c] *Ecole des Arts et Metiers ParisTech de Lille, 8 Boulevard Louis XIV, 59046 Lille, France*

ARTICLE INFO

Article history:
Received 5 October 2010
Received in revised form 8 February 2013
Accepted 11 February 2013
Available online 21 February 2013

Keywords:
Displacement capacitive sensors
Error sources
Dimensional and mechanical metrology
Theoretical modelling
Uncertainty evaluation

ABSTRACT

Capacitive displacement sensors are usually used with flat-targets in dimensional metrology applications, which require measurements with nanometer-level uncertainties. The use of capacitive sensors has recently expanded to cover the measurement of cylindrical artefacts (roundness, straightness and cylindricity). The error produced by the curved shape leads to the increase of the nonlinearity, since the sensing range between the targets and the sensitive part shrinks. This phenomenon cannot be ignored for applications requiring a nanometer-level uncertainties.

In the context of LNE's (French National Metrology Institute NMI) on-going development of a machine for form measurement with an uncertainty of a few nanometres (<5 nm) using capacitive sensors, an experiment has been developed to characterize the behaviour of two commercial capacitive sensors. The experiment enabled the evaluation of the major error sources (axial and radial error motions as well as the deviation/tilt of the capacitive sensors) which influence capacitive displacement measurements. The research was completed with a flat-target and cylindrical artefacts whose diameter values varied between 50 and 200 mm. For radial error motion, both experimental and theoretical results were compared and were found to agree within 2 nm, especially when the radial error motions were small (<50 μm). Finally, the polynomial fitting methods using terms up to 4 and 6 resulted in a deviation between measured displacements and fit of 0.005%FS (FS: Full Scale corresponds to the working range of 90 μm).

1. Introduction

Capacitors are widely used to measure displacement down to fractions of nanometres. Within the field of precision engineering, capacitive sensors are used to assess small motions, dynamic behaviour of structure or vibration, surface friction and control of thin film thickness, to measure positioning error [1,2] and to calibrate workpieces, for instance their cylindricity, roundness [3,4] and sphericity. The advantage of the sensor lies in its capacitance, which is very easy to calculate using a parallel-plate capacitor [5]. Capacitors' high sensitivity is obtained using transformer ratio bridges, relatively high ac-supply voltages and short integration times.

Many capacitive sensor designs are presented in scientific publications and are developed to carry out specific measurements such as the evaluation of the displacement of a precision active magnetic bearing spindle [6], which is achieved using a capacitive sensor containing eight-segment cylindrical capacitive sensors. However, the standard commercial capacitive sensor includes only one sensing electrode and one guard ring enclosed in a ground sensor body. The sensor is positioned perpendicularly with the appropriate stand-off distance from the artefact, and can be made of conductive or non-conductive materials.

Usually the target is a flat surface with much larger characteristic dimensions than the sensitive surface. This condition follows the edge effect reduction of the sensor, and significantly minimizes the linear residual. Nevertheless, many applications and studies in workpiece metrology [7–10], on line machine tool control [11] and the ultra-high-precision measurement of spindle error motion, require cylindrical or spherical artefacts [12–15].

Due to increasing interest in capacitive sensors in the mechanical metrology area, several studies based on the finite elements modelling of the capacitance have been proposed, especially when using non-parallel flat or non-flat targets [16–18]. Vallance et al. have proposed an experiment to investigate how displacement measurements taken with capacitive sensors targeting spherical surfaces can cause four detrimental effects, in particular when the capacitive sensor is calibrated with a flat target [13].

This article mainly focuses on the evaluation of the principal error sources that influence the capacitive displacement

---

* Corresponding author. Tel.: +33 1 40433763.
E-mail address: hichem.nouira@lne.fr (H. Nouira).

0141-6359/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.precisioneng.2013.02.005

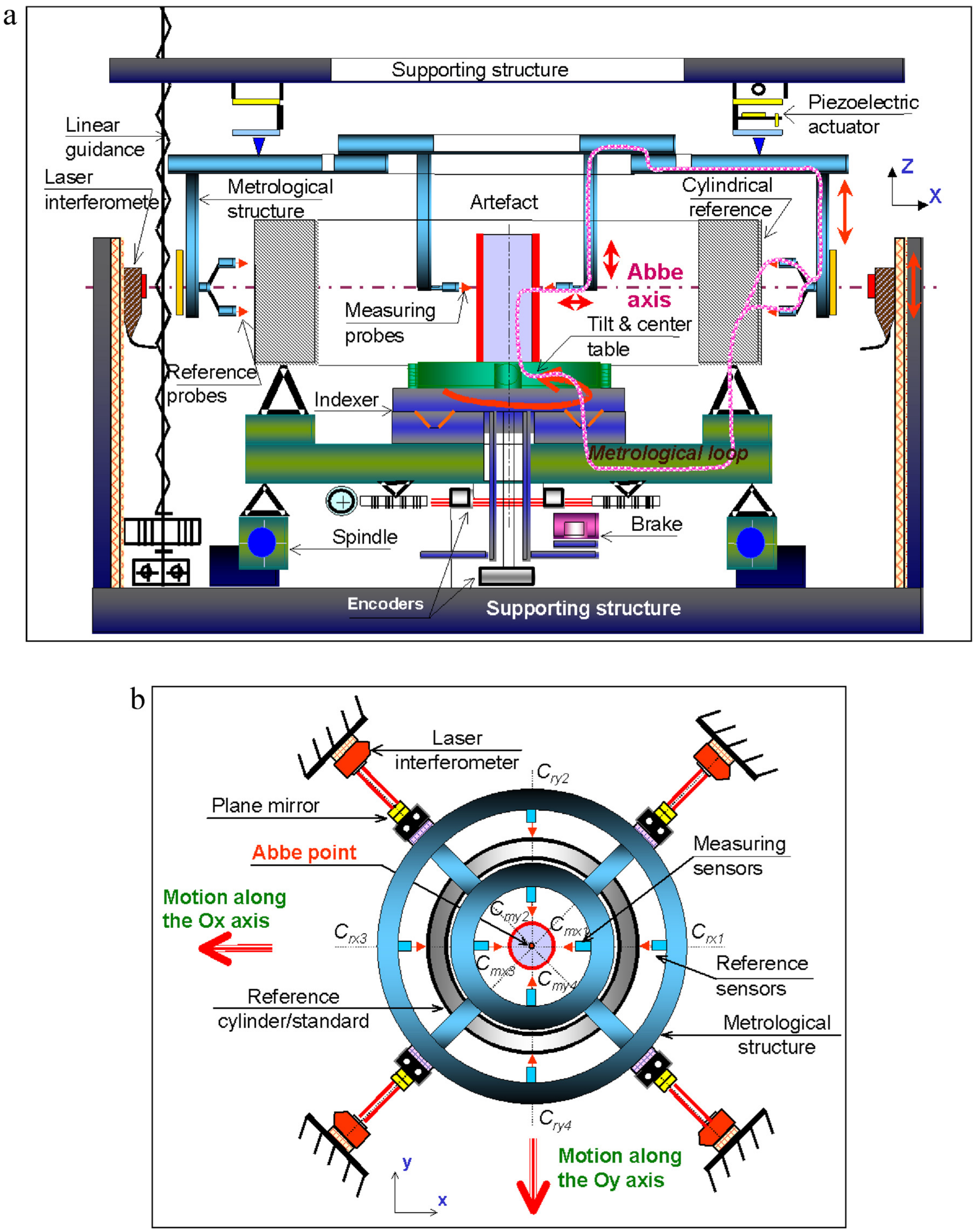

Fig. 1. Architecture of the ultra high-precision geometry measurement machine. (a) Sketch of the high-accuracy geometry measurement machine. (b) Schematic of the in situ calibration structure.

measurements. The purpose of this research lies in the on-going development of the new machine dedicated to the roundness, straightness and cylindricity measurements of cylindrical or spherical targets with an accuracy of 10 nm for the entire measured volume. The new machine contains at least 8 capacitive sensors distributed symmetrically to sense the reference cylinder, as detailed by Vissiere et al. [19,20]. Therefore, this study focuses on the characterization of two capacitive sensors with different electrode diameters in order to choose the suitable capacitive sensor dimension for the requested application of sensing the reference cylinder in real time.

Subsequently, the error sources that influence the capacitive measurements will be identified and investigated experimentally. The linear residuals and the sensitivity of both capacitive sensors in relation to the axial and radial motions as well as the *y*-inclination are evaluated when they are focused on cylindrical artefacts of diameters ranging between 50 and 200 mm and on a flat surface. For radial motion, a comparison between the results given by the