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Design of an ultra-high precision machine for form measurement

Saint-Clair T. Toguem^{a,b*}, Alain Vissière^a, Mohamed Damak^c, Charyar Mehdi-Souzani^b, Nabil Anwer^b and Hichem Nouria^a^a *Laboratoire Commun de Métrologie (LNE-CNAM), Laboratoire National de Métrologie et d'Essais (LNE), 1 Rue Gaston Boissier, 75015 Paris, France*^b *LURPA, ENS Paris-Saclay, Univ. Paris-Sud, Université Paris 13, Sorbonne Paris Cité, Université Paris-Saclay, 94235 Cachan, France*^c *GEOMNIA: Advanced 3D Engineering and Software Solutions, 165 Avenue de Bretagne, EuraTechnologies, 59000 Lille, France** Corresponding author. E-mail address: saint-clair.toguemtagne@lne.fr**Abstract**

Companies are steadily developing more complex and small scale products to be more competitive. This leads to an increasing demand for high precision machines for the measurement and characterization of products. Moreover, to improve the characterization through traceability chain, national and international laboratories are regularly increasing the accuracy level of the calibration of standards. This is done through the development of ultra-high precision measuring machines. The LNE (French National Metrology Institute) is developing a new machine for cylindrical and spherical form measurement with a nanometric level of accuracy. The Dissociated Metrology Technique (DMT) has been applied in order to achieve the targeted level of accuracy. This paper aims at providing details on the design process starting from the design requirement to the final system. The design method as well as the used design concepts is described. The developed machine is also presented and its current limitations are discussed.

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Keywords: Design guidelines; Precision machine; DMT

1. Introduction

As predicted by Taniguchi [1, 2] (Fig. 1), McKeown [3] and Evans [4], there is a significant increasing need for ultra-accurate measuring and manufacturing machines. Nowadays the development of microscale devices with sub-nanoscale level of accuracy raises the issue of quality control. Thus national laboratories need to improve and develop new ultra-high precision measuring systems to help the development and the qualification of measurement standards.

A new ultra-high precision machine is being developed by the LNE (French National Metrology Institute) for the measurement of cylindrical and circular forms. The main purpose of this machine is to measure the cylindricity of cylinders and pistons for pressure standards with a measurement accuracy below 20 nm [5].

To reach this objective, numerous original concepts of precision engineering have been applied during the design process. One of them is the Dissociated Metrology Technique (DMT). It has been applied to get rid of unpredictable error sources which represent a significant cause of the limitations of current systems.

With the aim to provide details on the design method and design concepts used for the new machine, the present work starts with a general description of precision design issues, principles and concepts. The machine under development is also described and its current limitations highlighted. Calibration and data processing challenges are finally tackled.

The remainder of this paper is as follows: section 2 summarizes the general concepts in precision design for metrology, section 3 presents the design methodology and section 4 describes the new ultra-high precision measuring system.

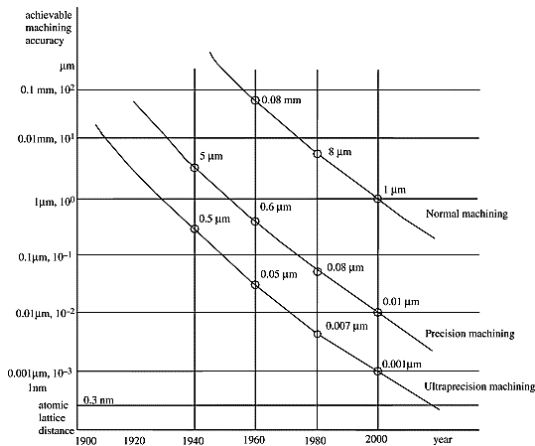


Fig. 1. Taniguchi graph [6]

2. General concepts in design for precision

Precision engineering regroups three main disciplines: design for precision, metrology and precision manufacturing [7]. The main concern here is the field of design for precision. It aims at enhancing and developing new design concepts, techniques and principles by thoroughly identifying precision design issues.

2.1. Main issues in design for precision

Schellekens [7] outlined the main difficulties encountered by precision engineers to enhance the repeatability of developed ultra-high precision machines. An appropriate choice of manufacturing processes and techniques can considerably enhance the geometric accuracy of machine's components and thus avoid misalignments occurring during the assembly. These assembly errors can significantly affect the accuracy of the machine. Microscopic defects (surface integrity including surface texture) can also have a negative impact on the machine's accuracy. This aspect, generally ignored by the designers has been investigated by Knapp [8] who shows that the hysteresis at the interface of components contributes to displacement errors in mechanical linkages. Besides, machine's components are subject to deformation due to dynamics phenomenon. Dynamics effects are caused by components' stiffness and moment of inertia as a result of mass distribution. Component's deformations lead to kinematics displacement errors. The later also depends on the accuracy of actuators used, the geometrical accuracy and the kinematic suitability of the linkages between components involved in the displacement.

Another important issue in design for precision is thermo-mechanical deformations caused by a variation in temperature. Thermal disturbances critically depend on components' materials [9]. This can be illustrated by the bimetallic effect that occurs when a bimetal is subject to a thermal gradient. Also, heterogeneous dilation of components can cause unpredictable deformations. Furthermore, many authors agree on the influence of machine's structure on the effects of thermal deformations [5, 10-12]. Asymmetric structures can also lead to asymmetric dilatations.

The previously detailed error sources apply to precision manufacturing as well as ultra-high precision metrology. Their effects can be anticipated and reduced if they are accurately identified. The understanding of this deterministic property of error sources coupled with designer experiences has led to the establishment of a set of design principles and guidelines.

2.2. Precision design principles (PDP)

Precision designers generally agree on a set of design principles as a result of decades of investigation. The only challenge is to creatively apply them according to specific design objectives [7]. However, different formulations are presented in the literature. By summarizing the PDP declined by McKeown [12, 14], Loewen [15], Pollard [16], Teague and Evans [17, 18] during decades, Schellekens [7] listed a set of seven PDP: the rules of Abbe and Bryan, kinematic design, structural loop, drive offset, force compensation, symmetry and repeatability principle. The author also suggested a predictive design approach. It consists in the establishment of the uncertainty budget early in the conceptual design stage. This approach provides an insight on the machine's overall accuracy and thus validates the adopted solutions. Designers have to perform a kinematic, thermo-mechanical, static, and dynamics and control system analysis prior to the detailed design of subsystems and components. This approach has been used by Chen [19] to propose an integrated tool used for the design of ultra-high precision machine tool.

Another formulation of PDP is given by Hale [20]. The first principle is the determinism principle based on the assumption of the deterministic property of error sources. The second is alignment principle. First proposed by Abbe [21] and generalized by Bryan [22], it states that "the measured distance must always be a straight line extension of the graduations on the reference scale". It is also known as the first principle of precision machine design and dimensional metrology. This explains why the design of many machines such as the ultra-precision CMM (Coordinate Measuring Machine) developed by Ruijl [23] are mainly based on the application of the Abbe principle.

The symmetry principle recommends symmetrical designs since they can be simpler to analyze, build and they may allow more accurate measuring and manufacturing methods [20]. Teague [18] recommends incorporating symmetry to all the properties of the machine. This involves the geometry, mass, forces and thermal sources repartition to avoid asymmetric thermal distribution that can cause distortion of components. Symmetric structures like tetrahedral structures increase the stability of the machine [24].

The separation of systematic errors principle states that it is possible to identify and separate some errors through specific experimentations. This can also be performed using either measurement standards with known defects or computational methods such as reversal, multistep and multi-probes separation techniques. Another technique standing for volumetric error mapping is the recording of positional and

angular errors of a machine throughout its working volume [7].

For the material selection principle, Ashby [25-26] suggested a set of guidelines and a well-known chart regrouping material according to their properties. These are still used by many precision designers such as Markus Lotz et al [27]. There is also the exact-constraint design principle deriving from kinematic design and based on a set of statements described by Hale [20] and the thermal management principles where the well-known methods to deal with thermo-mechanical effects on the machine can be summarized as follows:

- Use of symmetric structures to obtain symmetric temperature distribution and reduce distortions
- Use of low-expansion materials
- Control machine's environment
- Compute and compensate errors and deviations

The separation of the metrology loop and the structural loop principle has recently been investigated by David as the Dissociated Metrology Technique (DMT) [28-29] and applied in the design of a precision angular system. This principle previously known as the usage of a metrology frame, had already been implemented by many authors like Bryan and Donaldson in the design of ultraprecision diamond turning machines [30-31]. It is based on the definition of a structural loop and metrology frame. The structural loop can be defined as an assembly chain of machine components. The metrology loop is a conceptual chain linking one machine's element (e.g. the probe) to another (e.g. the part). It helps identifying critical components affecting the relative position of the linked elements. Any uncontrolled variation in any of these components can lead to measuring errors. Furthermore, Lahousse and David [28] discussed the two architectures for high precision machines: serial and parallel architectures. Serial architectures are widely used for the design of measuring machines. The components or subsystems are stacked one with another with one degree of freedom linkages. This architecture needs specific materials to increase their rigidity. Parallel architectures are cost-effective with reduced weight and higher stiffness. They are also suitable for a symmetric design. These architectures have been long investigated by authors like Stewart [32]. It has been demonstrated that they are suitable for symmetric design though they lead to a reduced working volume.

3. LNE Design Method

The following design method has been improved during the previous two decades at the LNE through various projects [12, 28]. The purpose is to provide a general design framework for precision engineering with a focus on specific concepts for high precision measuring machines for revolute forms.

The proposed design method is divided into two main steps. The first is the definition of the system's architecture. It characterizes the stage of conceptual design and leads to the definition of the working principles of the machine. The

validation of the machine architecture and working principles is done after the determination of the uncertainty budget. This is obtained by performing a predictive analysis of the mechanical system (kinematic, thermal, static and dynamic analysis) and the control system. This first step ends with the identification of all the subsystems of the machine. In the second step, the global design objective is detailed into sub-objectives and allocated to each subsystem of the machine. Finally, the final design of subsystems is performed (Fig. 3).

3.1. System's architecture definition

The architecture of a system can be seen as component's arrangement in the machine and the kinematic links at their interfaces. Regardless of the design objective, a critical analysis of existing systems needs to be performed prior to the definition of the machine's architecture. The aim is to analyze and to associate their architecture and calibration techniques of existing systems with their performances.

Conventional machines for cylindricity measurement are usually based on two working principles. The first consists in a fixed probe and a rotating part during the measurement of circular profiles (Fig. 2). The cylindrical profile is obtained by measuring several circular profiles at different heights. The measurements are affected by spindle errors of rotation and probe's positioning errors. Machines with rotating spindles are widely used for form measurement. The second working principle is based on machines with rotating probes. Here the part is fixed and the probe rotates around the cylindrical surface of the part [33-34].

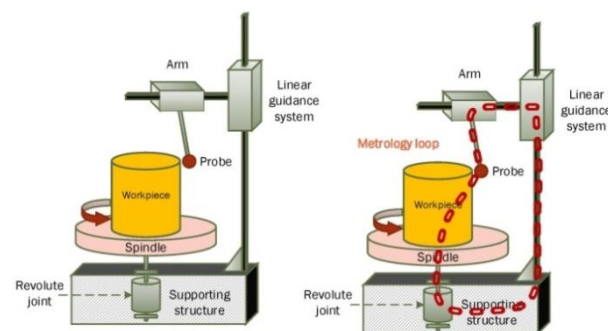


Fig. 2. Architecture of conventional measuring machines for revolute parts; (left) working principle; (right) Metrology loop

Emphasis should also be placed on the type of errors, their causes and the impact on the machine's accuracy during the critical analysis. Machine's dimensional errors can be classified into two main categories. The first is systematic errors. It represents errors with a predictable variation [35]. They can be anticipated using mechanical and digital compensation techniques. Mechanical compensation techniques consist in modifying the size and form of components based on the errors to compensate. However, they can be difficult to implement with errors depending on more than two parameters [12]. Digital compensation techniques are based on tables of pre-processed data used to adjust the measurements. The second category of dimensional

errors is random errors. It stands for unpredictable errors. These errors can be caused by thermal dilatation of components, external and internal vibration sources and displacement errors of machines. It is practically difficult to deal with random errors (see section 2). However, new developments in metrology and computational systems offer the possibility to compensate random errors through online metrology by measuring and adjusting deviations directly when it occurs. This is demanding and not always cost-effective.

Another alternative to get rid of both systematic and random errors is the DMT (Dissociated Metrology Technique). It mainly consists in separating the metrology frame from the supporting frame (see section 2). This prevents the metrology frame from disturbances generated by the supporting frame (such as vibrations and thermal disturbances). The dissociation is made through isostatic linkages between the two structures. Mechanical linkages between components of the metrology loop are replaced by probes. With these types of linkages called metrological linkages [28], unwanted displacements between components can be accurately identified and their effects compensated. The accuracy increases with the number of probes used for the linkage. One limitation of the DMT is the cost related to the increase of the number of components to realize a linkage. However, by reducing the number of redundant probes, it is possible to optimize the DMT application [12]. The choice of probes used in metrological linkages for the measurement of components' location is one important issue with the application of the DMT [12]. The displacements of components must remain in a suitable range to avoid measurement uncertainties. Thermal disturbances as well as the presence of other probes can also bias the measurements and affect probes' accuracy. Intermediate test benches can be suitable to validate a single conceptual design choice. However, for the global architecture of the machine, the convenient validation approach is the predictive establishment of the uncertainty budget.

Once the architecture is defined, it is possible to precisely separate the machine into interacting sub-systems. This modular approach is appropriate for ultra-high precision measuring machines because of their complexity. It provides an overview and simplifies the analysis of the interaction of the system's components.

3.2. Subsystems definition

Subsystems can be defined from the system's architecture through a decomposition process. This can be done either by dividing the design objective into sub-objectives or by grouping components performing the same function. One of the main common practices in complex systems' decomposition is Functional based decomposition [36]. Here components are grouped based on their performed function. This enables the identification of the components of the metrology loop. These components are critical and need to be considered separately during the design process. There are several attempts to define guidelines for system's

decomposition based on functional analysis. One is the Functional Basis model (FB model) of Otto and Wood [37]. It uses the flow of material, energy and information to model the design objective (or the overall function) as interdependent functions. This approach enables the consideration of digital chain and data processing source of errors right from the design stage. It is suitable for high-precision measuring machine where only energy and information flows are usually considered during the design stage. Information flows from probes to the calculator and inversely while energy goes from actuator to probes or artifacts.

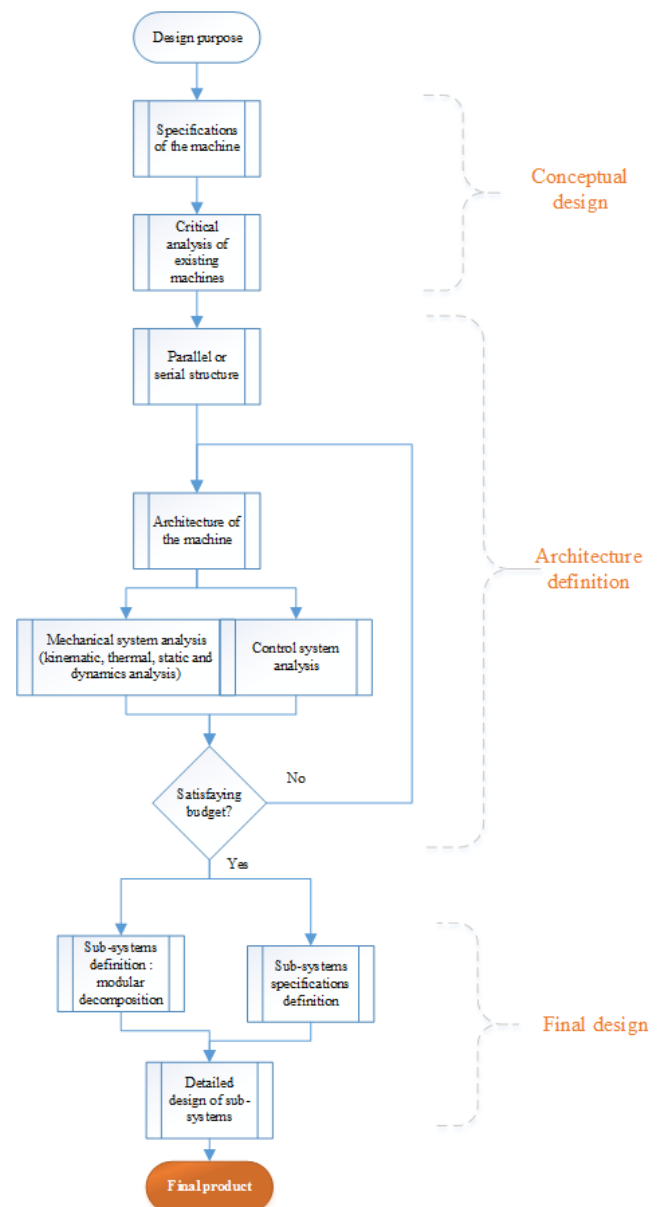


Fig. 3. Proposed design flowchart

4. New machine for cylindrical form measurement with a nanometric level of accuracy

One main issue related to form metrology is the level of achievable accuracy. This is true for simple forms as well as for complex form metrology. Hence, the LNE is developing a new ultra-high geometric measuring machine for the

measurement of cylindrical forms. One objective is to measure cylindrical forms of piston-cylinder assemblies with an uncertainty below 5 nm, 10 nm and 20 nm for respectively roundness, straightness and cylindricity evaluation in a cylindrical working volume of 350 mm diameter and 150 mm height.

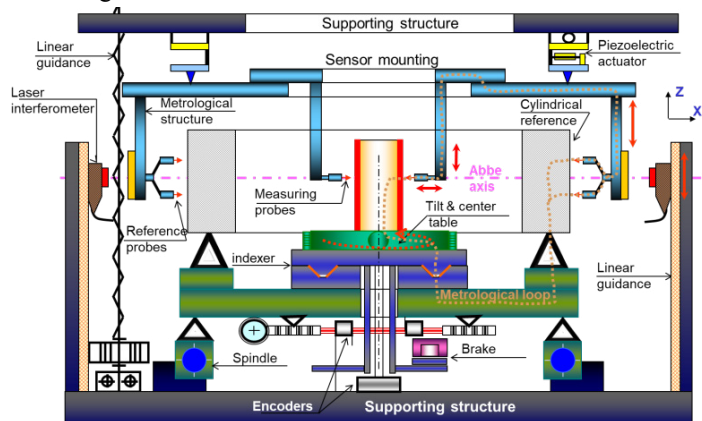


Fig. 4. Reduced architecture of the new ultra-high measuring machine developed by the LNE for cylindrical forms measurement [5, 38].

4.1. Machine's architecture

The adopted architecture shows a system made of a supporting frame carrying a high-dimension rolling spindle. The latter is isostatically linked to a table. The reference cylinder is supported by the table through an isostatic linkage. The angular indexer installed on the table enables the control of the rotation of the artifact. The tilt and center system installed on the indexer is used for the alignment of the axis of the artifact and the revolution axis with a micrometer level of accuracy (Fig. 4). A set of eight capacitive probes (reference probes) are aligned on the reference cylinder whereas four other capacitive probes (measuring probes) measure the artifact. The probes are arranged to perfectly respect the Abbe principle. They are fixed on a table that can vertically translate. This movement is controlled by a set of three optical rulers. Laser interferometers aligned along the Abbe axis are used for the calibration of the capacitive probes [5, 12, 34].

4.2. Probes choice and uncertainty budget

The selected probes are non-contact probes: Laser Interferometer and capacitive probes. Capacitive probes are used to assess the topography of both the cylindrical part and the reference cylinder. They can perform areal measurements with a nanometric level of accuracy. Capacitive probes are suitable for form measurement especially because an average filter is applied on the collected data leading to the separation of form defects from surface texture (roughness and high frequency undulations) [39]. Moreover, thanks to their high resolution, repeatability and relatively small size, they are used in several high precision machines design [7, 12].

In order to validate the choice of capacitive probes, an investigation of the influence of main error sources on capacitive probes' accuracy has been performed by Nouria et

al [5]. An experimental test bench reproducing the working conditions of the capacitive probes has been developed by Vissiere et al [39]. The effects of axial and radial probes positioning errors on the measurements have been investigated. In addition, the influence of the offset of the probes caused by the eccentricity of the cylinders (artifact and reference cylinder) has also been analyzed. A numerical model of the influence of the transverse error on the measurement of capacitive probes is proposed and experimentally validated. Results show that the transverse error positioning of capacitive probes needs to be compensated in order to reach the nanometric level of accuracy. Therefore, the adopted solution of using a real-time tilt and centering table need to be completed by a numerical compensation especially in the case of important eccentricity of the cylinders (for example 30 μm transverse error for a 135 mm diameter of the cylinders).

A study has been carried out to validate the machine's architecture and evaluate the influence of both the number and the arrangement of capacitive probes on the machine's accuracy. Two configurations have been considered. One with 16 capacitive probes arranged in four crowns to measure the reference cylinder and the other with 32 capacitive probes arranged in four crowns. For each configuration, the uncertainty budget of the machine is established. It comes that, the global uncertainty of the machine decreases with the number of probes. However, one advantage of the first configuration with four probes for each crown is its suitability to fully respect the Abbe principle but also to apply the reversal based error separation techniques.

4.3. Qualification and calibration of the machine

The qualification of the machine is part of the validation process of the design choices. It involves evaluating the inputs and outputs of critical subsystems to determine the designed system's ability to fulfill the requirements. For an ultra-high precision measuring machine, the qualification process also principally refers to the characterization and the calibration of the components of the metrology loop including the measuring probes. In our case, this includes the measuring probes as well as the reference cylinder. The calibration of the reference cylinder of the new ultra-high measuring machine has been investigated [12, 34]. The application of the reversal error separation technique validates the adopted optimal probes arrangement. In addition, a multi-step based errors separation technique has been developed to evaluate the topography of the reference cylinder. It has been validated on circular forms but still need to be expanded to cylindrical forms.

Some issues related to the machine's qualification still need to be addressed. The first is the evaluation of the repeatability, stability and response of the machine to thermomechanical disturbances. There is also data processing. It involves the expansion of the methods developed in [12, 34] for the evaluation of cylindricity. There is also the development of a new multi-probe technique at a sub-nanometric level of accuracy. The aim here is to take

advantage of the probe's arrangement (four measuring probes per arrow). Furthermore, the probes calibration, the acquisition/measurement strategy and errors compensation methods are also to be developed.

5. Conclusion

The goal of this paper is to detail the concepts and the design methodology of a new high precision measuring machine. The design starts with a critical comparison of architectures, working principles, and limitations of existing systems. This leads to the choice of a suitable working principle for the machine. It also highlights the advantages of using the DMT to cope with the limitations of common errors compensation techniques.

The DMT is then applied here and the machine's architecture is iteratively built by providing original solutions to each identified error source. A functional decomposition is applied to separate the system into subsystems. A flow analysis of energy and information is performed prior to the decomposition to highlight the critical components of the metrology loop and the control system. Requirements are then set for the design of each sub-system by dividing the global objective into sub-objectives.

Future work will focus on the qualification of the machine to validate and optimize the design choices. The focus will also be placed on the development of probes' calibration protocols and sub-nanometric error separation techniques for data post processing.

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