Proc. of the 35th International MATADOR Conference, July 2007, Taiwan, pp. 297-300.

The Structure Design of a Micro Precision CMM with Abbé Principle

K.C. Fan[1,5], C.L. Liu[2], P. T. Wu[3], Y. C. Chen[4] and W. L. Wang[5]

[1]National Taiwan University, Taiwan, 10627, fan@ntu.edu.tw
[2]National Taiwan University, Taiwan, 10627, clliu@ntu.edu.tw
[3]National Taiwan University, Taiwan, 10627, r93522638@ntu.edu.tw
[4]National Taiwan University, Taiwan, 10627, d92522028@ntu.edu.tw
[5]Hefei University of Technology, Heifei, China, 230009, w_weili@163.com

Abstract. This paper presents the design considerations of a micro precision CMM. The structure of this CMM consists of the bridge, the Z-spindle and the XY stage. A novel bridge designed in a pagoda shape will be proposed and analyzed to prove its superior stiffness with force balanced condition. A high precision spindle design with counterweight and thermal error suppression are considered. The design of novel a coplanar XY-stage that observes the law of Abbé Principle is particularly proposed. Constructing these three structural modules the developed small CMM could meet the Abbé principle and provide high geometrical accuracy of the structure. Designed CMM has measurement lengths in X: 25mm, Y: 25mm and Z: 10mm. Driven by the ultrasonic nanomotor and fed back by the hologram scale, each axis can achieve 1nm resolution.

Keywords: Micro-CMM, Abbé Principle, Co-planarXY stage, Pagoda brideg, Structural design.

1.1 Introduction

Coordinate Measuring Machine (CMM) is a versatile instrument for three-dimensional measurement of almost all kinds of workpieces. It is widely used in industry for precision measurement with general axial resolution from 0.1 to1μm, accuracy from 1 to 5μm, range from cm to meter, and the contact probe diameter from 0.5mm to 5mm. Except those ultra-high precision CMMs that equip with laser interferometer as position sensor, common CMMs are based on the readings of linear scales that are offset from the probe moving axis. In other words, its structural design has inherent Abbé errors [1]. The Abbé principle is called the first principle in metrology by scholars. Since Professor Abbé first proposed this principle in 1890, it has been referenced by machine tool and measuring instrument societies to the accuracy design of the structures. The definition of Abbé principle is: in displacement measurement the reference should be in line with the displacement to be measured or on its extension. In Bryan's generalized interpretation, if the Abbé principle is not possible in the system design, either the slideway that transfer the displacement must be free of angular motion or the angular motion data must be obtained to compensate the Abbé error by software. Following the Abbé principle, Bryan principle extended the concept to straightness measurement [1] and Zhang extended to other geometrical measurements [2].

Nowadays, many existing machine tools and coordinate measuring machings (CMM) still cannot comply with Abbé principle, except some special cases such as the "Ultimat" CMM by Lawrence Livermore Lab. [3], the Nanomeasuring machine (NMM) by TU Ilmenau [4], etc.

Many meso to micro scaled parts have been able to be produced by new manufacturing technologies in recent years, such as MEMS, LIGA, micro machining, etc. The required dimensions are in the range of mm to μm, resolution needed is from 1μm to 10 nanometers, and accuracy demanded is from several micrometers down to about 50 nanometers. To face the inspection demand of these micro parts, the conventional CMM is no longer available to meet the requirements. The development of small CMMs has become an interesting topic in recent years. Collaborative research between National Taiwan University and Hefei University of Technology started the micro/nano-CMM project since 2001. Miniaturizing the CMM structure with nano-motion and nano-scale techniques has been developed in sequence, but the Abbé principle was partially implemented [5, 6].

This paper presents the design considerations of a novel micro precision CMM that has force-balanced structure to yield high stiffness and conforms to the Abbé principle in 3D space. Designed CMM has measurement lengths in X: 25mm, Y: 25mm and Z: 10mm. Driven by the ultrasonic nanomotor and fed back by the hologram scale, each axis can achieve 1nm resolution. The bridge design and the Co-planar XY stage design are described in the following.

1.2 The Pagoda Bridge Design

Rectangular type of the bridge is always employed in the precision CMM structure for mounting the Z-ram and probe. The deformation at the center of the bridge is very critical because of the concentrated load from the spindle and the generated driving force, which will react to the bridge. Although its static deflection caused by the total weight of the bridge itself and the ram does not influence the measuring accuracy, the generated driving force, evenif comparatively small, will induce dynamic deformation of the bridge up to submicron level. In order to meet the high precision requirement in nanometer measurement, the stiffness of the bridge has to be redesigned.

Figure 1.1 shows two types of bridge: rectangular shape and circular shape. Assuming they have the same width (2R), height (R), thickness, and carring the same ram load (P), from the structural analysis the maximum staticx deflection at the bridge center will be:

For rectangular bridge: $\delta_{y\max 1} = 0.55\dfrac{PR^3}{EI}$

For circular bridge: $\delta_{y\max 2} = 0.24\dfrac{PR^3}{EI}$

It is apparent that the circular shaped bridge has better stiffness.

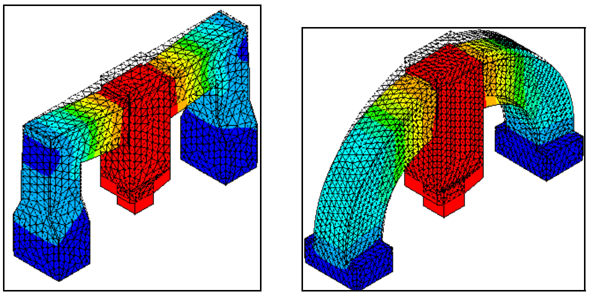

Figure 1.1. (a) Rectangular bridge, (b) Circular bridge

Again, if we consider the bridge is designed in an arch shape of the same dimension, as shown in Figure 1.2 (a), it must be even stiffer than the circular bridge as most of the bridge and tunnel in civil construction is with similar shape. Moreover, the arch shape can further be optimized for the minimum deflection design with respect to the parameters of radius R and angles of α and β, as shown in Fig. 1.2 (b). The objective function can be formulated by:

$$\begin{cases} Min \quad f(X) \\ X = [x_1, x_2, x_3] = [\alpha, \beta, R] \\ s.t. \quad 0^\circ \le \alpha \le 45^\circ \\ \quad 55^\circ \le \beta \le 90^\circ \\ \quad R_{\min} \le R \le R_{\max} \\ \quad 0 < \max(\sigma) \le 25Mpa \end{cases}$$

f(X) denotes the calculated deflection at the bridge center with design variables (R, α, β) and certain given dimension and stress constraints. The analysis can be done by finite element analysis in association with optimization technique. Figure 1.3 (a) shows the optimized arch shape.

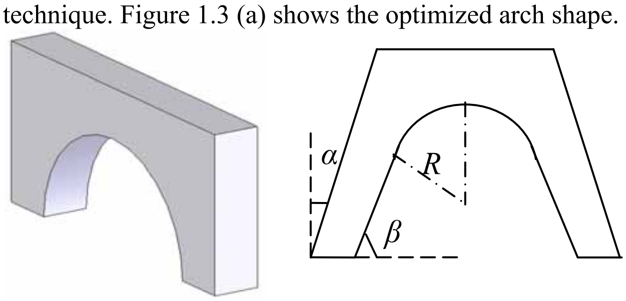

Figure 1.2. (a) Arch bridge, (b) Optimized arch bridge

From the above analysis it is seen that the conventional rectangular bridge is not the best design. The tapered arch bridge should possess the highest stiffness in the CMM structure. Moreover, the best CMM structure should be force balanced in all directions. The tapered arch shape provides force balance only in one plane. Therefore, this study proposes the pagoda bridge that is symmetrically constructed from the optimized tapered arch shape. This pagoda bridge has force-balanced structure in all directions, as shown in Fig. 1.3 (b).

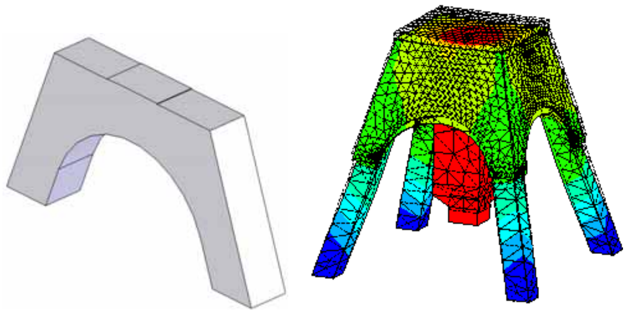

Figure 1.3. (a) Optimized arch bridge, (b) Pagoda bridge

In order to compare the stiffness of different bridge shapes for the required micro-CMM, we design the same width of 220mm, height of 110mm, thickness of 60mm, supporting pad of 70mm×100mm×40mm, and under the same ram weight of 29.4N. The bridge material is granite with density 2660 (Kg/m^3), Young's modulus 60 GPa and Poisson's ratio 0.3. From FEM analysis by AnSYS 7.0 software the center deflection of each type of bridge is compared in table 1.1. It can be seen that the pagoda bridge has the best stiffness among all and the force balance structure. The dynamic driving force generated from the actuator (such as the motor) will superimpose on the bridge due to its reaction force. Although this driving force is small comparing with the static load, it will inevitably generate dynamic deformation of the bridge. For instance, one Newton force will incur 12.3nm deflection at the rectangular bridge center and 3.9nm at the pagoda bridge center. This will cause the same amount of measuring error of the micro-CMM. The pagoda bridge certainly has the minimum influence.

Table 1.1. Comparison of Stiffness

Bridge type	Deflection due to self-weight	Deflection due to self- weight and ram load
Rectangular	0.156μm	0.362μm
Circular	0.102μm	0.174μm
Arch	0.090μm	0.154μm
Optimum arch	0.060μm	0.131μm
Pagoda	0.060μm	0.115μm

1.3 Abbé Principle in 3D Coordinate

The famous Abbé Principle only indicates the rule in 1D motion. For a CMM, it is in 3D coordinate. This study thus proposes the extended Abbé Principle for a 3-coordinate motion machine:

(1) Each merasuring axis should be in line with its corresponding motion axis, and

(2) All three measuring axes should interset at the functional point of the machine.

This concept can be realized by Figure 1.4, where the intersecting point of three measuring axes will be the cutting point for a machine tool or the measuring point for a CMM. Obviously, all the current configurations of side-mounted linear scales in the machine tool and CMM designs have inherent Abbé errors. This is why the volumetric error analysis by 21 geometrical error terms is so important for the error compensation. Since for all the vertical types of 3-coordinate machines the vertical ram has its measuring axis in line with its motion axis, the only condition to meet with the 3D Abbé Principle relies on the XY plane motion.

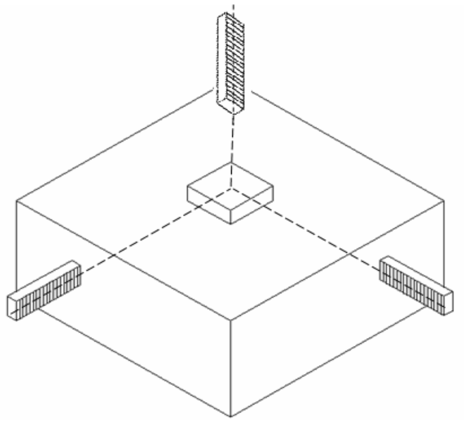

Figure 1.4. Abbé principle for 3D coordinate

1.4 The Co-planar XY Stage

Conventional XY stage is normally stacked up by two linear stages. Not only the position-dependent cross-talk between the axes cannot be avoided, the Abbé error of the lower stage is large due to the large Abbé offset.

A novel co-planar Abbé free XY stage is thus proposed in this study. The moving table slides along a common base plane which is precision ground to less than 1μm flatness and isolated from the base plate of the stage. This is the essence of co-plane motion. Two push-pull bars move the table in X and Y directions via two linear slides respectively, as shown in Figure 1.5 (a). Each bar is driven by an ultrasonic motor through a linear slide, which is supported by a heavy block fixed to the base. A hologram grating scale is then mounted on the top of the bar along the axial direction. The motion of the bar can be detected by an optical reader mounted on the base plate. Figure 1.5 (b) shows the entire configuration of the developed Co-planar stage. The stroke of each axis is 25mm. Since it has been proved the minimum step of the motor and the resolution of the optical reader (called Linear Diffraction Grating Interferometer, LDGI) can all reach to 1nm [5, 6], the designed co-planar stage can have 25mm stroke and 1nm resolution in each axis. Moreover, the intersection of two scales' axis is right to the functional point of the XY stage, it observes the law of Abbé principle in 2D space. An additional feature of this design is the hollow common base plane that allows a sensor to be embedded in to measure the straightness error of the moving table at the functional point, as shown in Figure 1.6. This agrees with the Bryan principle [1]. In addition, the squareness of X and Y motions can be assured by the smooth motion of two linear slides.

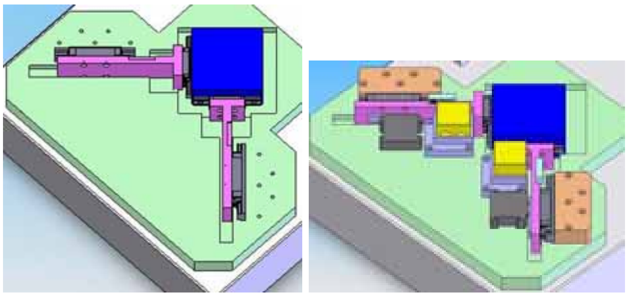

Figure 1.5. (a) Push-pull co-planar motion mechanism, (b) Adding supporting block, ultrasonic motor, hologram scale and the optical reader

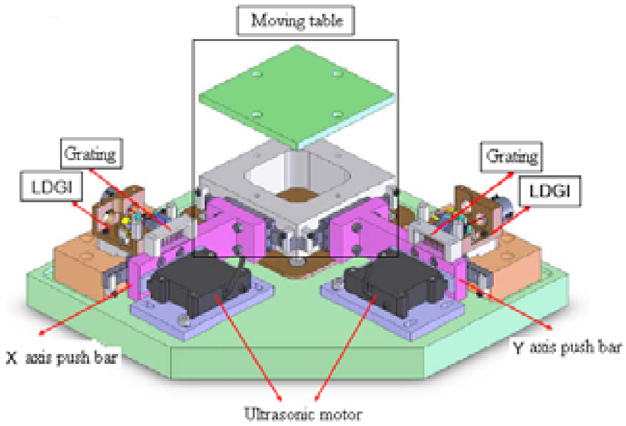

Figure 1.6. Complete structure of the co-planar XY stage

1.5 The Ram Design

Due to the symmetrical geometry of the pagoda bridge, the ram is mounted in the center of the bridge through the top plate, and with the geometry as symmetry as possible. Figure 1.7 shows the structure of the ram of which the moving part is driven by the same ultrasonic motor from one side and a LDGI (displacement sensor) is equipped on the other side to balance the weight. A hologram grating scale is mounted on the moving part in line with the ram axis. The other two sides of the moving block are mounted on two linear slides, respectively. The end of the ram can chuck a high speed spindle for machining purpose, or a probe for measurement purpose. A coaxial counterweight is also designed to balance the driving force.

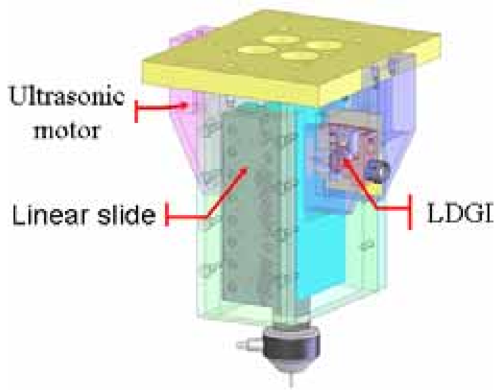

Figure 1.7. The structure of the ram

1.6 Assembly of Micro-CMM

Each of the key modules of the CMM structure has been explained on respective design concept from the precision engineering point of view. The assembly of the CMM is illustrated in Figure 1.8. It can be seen that the bridge geometry is symmetrical and the ram is in the center of the bridge. The XY stage has the co-planar feature with its centre of mass as low as possible. The extension lines of three linear scales coincide at the functional point (cutter or probe) at all commanded positions of X, Y, and Z directions. The straightness error of the moving table can be detected by an embedded sensor in line with the functional point.

The machine is under the stage of assembly and fine adjustment. The whole dimension of the machine is only about 350mm×350mm×400mm, with strokes of 25mm×25mm×10mm, and resolution to 1nm. The next step will to study the motion control of the machine so as to achieve the CNC function.

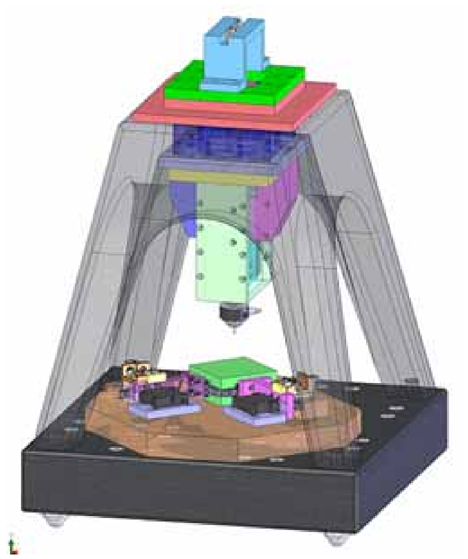

Figure 1.8. Structure of the developed micro-CMM

1.7 Conclusion

A novel micro-CMM structure has been designed with respect to the key modules, namely the pagoda bridge, the Co-planar XY stage and the ram. All are designed based on the concept of precision engineering in term of high stiffness, force balance, Abbé principle and Bryan principle. We admit that the height change of the workpiece still has Abbé offset. An estimation of the vertical Abbé error over the workspace can be calibrated in advance and compensated with feed-forward control during the measurement. As it is for the dimensional measurement and profile cutting of 3D micro parts, the actual profile height will be only a few mini-meters to micrometers. The Abbé error is deemed very small. The next step will to study the motion control of the machine so as to achieve the CNC function.

Acknowledgement

The main part of this research is sponsored by the National Science Council of Taiwan under contract number NSC-94-2212-E002-001. The bridge design is collaborated with Hefei University of Technology sponsored by the National Science Foundation of China (50420120134).

References

Bryan J. B. 1979, The Abbé Principle Revisit: An Updated Interpretation, Precision Engineering, P129-132.

Zhang G. X 1989, A Study of the Abbé Principle and Abbé Errors , Annals of CIRP, Vol.38, No.1, P525-529.

Bryan J. B. and Carter D. L. 1979, Design of a new Error-corrected Co-ordinate Measuring Machine, Precision Engineering, P125-128.

Jäger J., Manske E., et al, 2002, Nanopositioning and -Measuring Technique, 7th International Symposium on Laser Metrology, Novosibirsk, Russia, Vol. 4900, P755-762.

Fan K. C., Fei Y. T. et al, 2006, Development of a low cost Micro-CMM for 3D Micro/nano Measurements," Measurement Science & Technology, Vol. 17, P524-532.

Fan K. C., Fei Y. T. et al, 2007, Study of a Noncontact Type Micro-CMM with Arch-bridge and Nanopositioning Stage, Robotics and Computer-aided Manufacturing, Vol. 23, Issue 6, P.276-284.