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Macro-micro Combined Motion Strategy for Turning-milling Complex CNC Machine Tool: An Overview

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Abstract

This paper acts as a review on the developments aiming at improving macro micro motion platforms performance criteria's; high acceleration, Ultra-precision positioning and large stroke. A hybrid two way methodology is opted combining experimental data and literature on the improvement advances towards the macro micro stage. An Ultra-precision macro micro motion platform CXKG25-I machine tool is assessed and compensated for motion errors using start of the art laser interferometer detection.

Keywords

Macro Micro Motion Platform; Laser Interferometer; Error Compensation; Piezoelectric (PZT) Ceramic Actuator.

1. Introduction

The growth and spread of the precision manufacturing of micro-electronics elements to machine small Ultra-precision components for circuit boards [1], has created a massive applicability challenge and redundancy to conventional high speed and long stroke positioning macro-scale precision processing servo system CNC machine tools. The gap has come in due to the difficulty and incapability of servo system in achieving nano level precision and accuracy in machining ultra-high accuracy and precision workpiece due to low motion resolution in addition to tool path tracking and contour errors [2]. On the other hand the advances in micron-scale positioning technologies under the machining science and technology fields has given an opportunity to close this gap by coupling fine and course motion actuators [3].

The precision manufacturing industry demands machine tools achieve these three criterions; high speed and acceleration long stroke and Ultra-precision positioning resolution for nanometer accuracy levels [4].

2. Purpose

The purpose is in twofold; introduce the Macro-micro motion platform and explore the improvements in:

1. High acceleration and speed
2. Large stroke
3. Ultra-precision positioning resolution

3. Methodology

To successfully achieve this review, this hybrid methodology to combine lab findings and literature to review the attainability of the performance criteria's of the Macro-micro motion platforms.

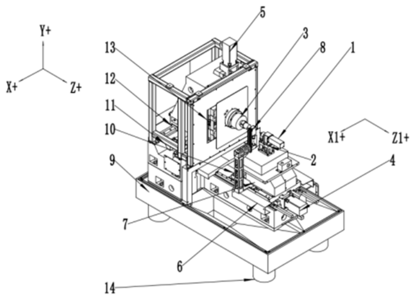
1. Identify and select smart material for micro motion platform
2. CXKG25-I Error detection, modelling and compensation

3. Review current research work on the macro micro combined technology to validate methods 1 and 3.

4. CXKG25-I Turn-milling Complex Machine Tool

Figure 1. CXKG25-I Macro-micro Motion Complex Machine Tool

The CXKG25-I is 5-axis high precision Macro-micro dual drive complex milling-turning combined machine tool. The internal components are visually presented and named in Figure , followed by the CAD pictorial view and topological structure in Figure and Figure respectively.



Milling spindle (2) Micro stage (3)Workpiece spindle (4)Z-axis macro motion servo motor (5)Y-axis macro motion servo motor (6)Z-axis grating device (7)B-axis rotary stage (8)online detector(9)Base frame (10)online detector holder (11)X-axis macro motion servo motor line (12) X-axis grating device (13)Y-axis grating device (14)flotation isolator.

Figure 2. Machine components nomenclature

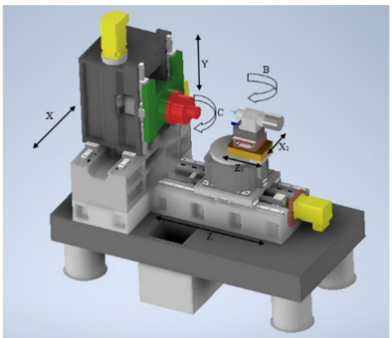


Figure 3. CAD pictorial model view of the Ultra-precision Macro-micro-Complex machine tool with labelled degrees of freedom

CXKG 25-I, positioning variables are categorized;

Macro motion stage movement control variables include;

- X-axis slide rail
- Z-axis column rail
- Y-axis slide rail
- B-axis turntable

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- C-axis Spindle

Micro motion stage movement variable include;

- X1-intching axis
- Z1-itching axis

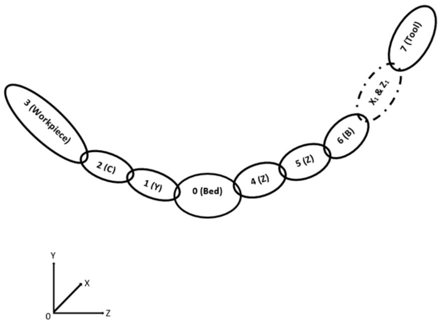

Figure 4. Topological structure

The CXKG 25-I is made up of the Macro-micro dual drive positioning platform which consist of macro servo drive motion stage and the micro feed motion stage.

The machine tool X and Z axes controls tool motion relative to the workpiece, the micro stage directly holds the tool and extends the main X and Z axes via the micro feed motion X1 and Z1 inching axis on the inching platform.

5. Research for Attaining Ultra-precision Positioning Resolution

5.1. Micro Motion Technologies

The smart materials have been the innovation back bone for micro motion devices. The electric to strain characteristics of the smart materials determines the stroke and force magnitude of the micro device [5]. This devices fall under the shape changing actuators i.e. PZT, magnetostrictive, thermal actuators, ultrasonic etc. [3].

Ideal motion platform for Ultra-precision machining are to achieve the following benchmarks [3];

Table 1. Benchmarks the platform should meet

Acceleration	> **10g**
Speed	> 1m/s
Positioning resolution	$\geq 10nm$

A piezoelectric macro micro platforms conforms to the benchmark values

Common Micro motion smart materials

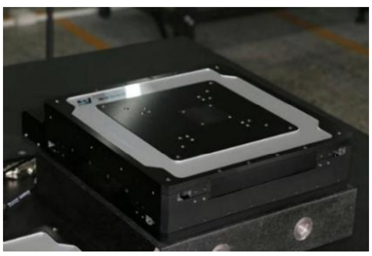

Figure 5. 2D Piezoelectric ceramic actuator

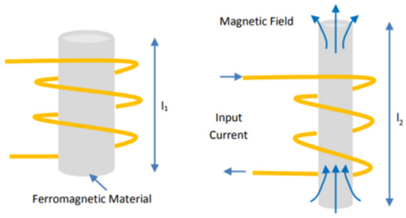

Figure 6. Magnetostrictive (joule) effect [6]

Figure 7. U-521 / M-663 Ultrasonic Linear Motor [7]

Ouyang P.et al. outlined the four categories of micro motion systems based on the motion ranges; (i) $< 1\mu m$ (ii) $1 \sim 100\mu m$ (iii) $100\mu m \sim 1nm$ (iv) $> 1nm$ .The piezoelectric ceramic smart material has the ability to attain all motion ranges when incorporated in the macro micro motion platform [3].
The selection of the piezoelectric smart material allows for the attainability of an Ultra-precision positioning resolution of nanometer.

5.2. Macro Micro Motion Platform Structural Configuration Principle

The hardware set up configuration is of a serial configuration machine bed to tool too workpiece.

The macro motion actuator produces both linear and rotary motion. For rotary motion a servo system is used while linear motion actuators like voice coil motors while the micro motion actuator utilizes the Ultra-precision linear motion actuators [8]. PZT is widely used across different industries compared to the counterpart giant magnetostrictive actuator GMA due to its high precision, small size, rapid response and massive output force.

The macro micro motion stage is commonly applied in three motion configuration;

Table 2. Macro-macro motion realization configuration [8]

	Macro Motion	Micro Motion	Example
1	Rotary	Linear	Servo motor + PZT
2	Rotary	Rotary	Servo motor + PZT
3	Linear	Linear	VCM + PZT

5.3. Piezoelectric Macro-micro Motion Platforms

The piezoelectric actuator is both sensors and actuators, for a sensor they produce electric signal when mechanically stress, the opposite produce a mechanical strain harnessed for micro motion actuators. A variety of the piezoelectric material based Macro-micro motion actuator are developed. Figure 8, Figure 9 and Figure 10 are examples of the PZT based Macro-micro stage platforms

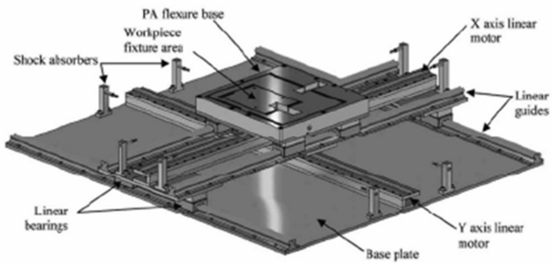

Figure 8. Two-dimensional dual-drive positioning system developed by McMaster University [9]

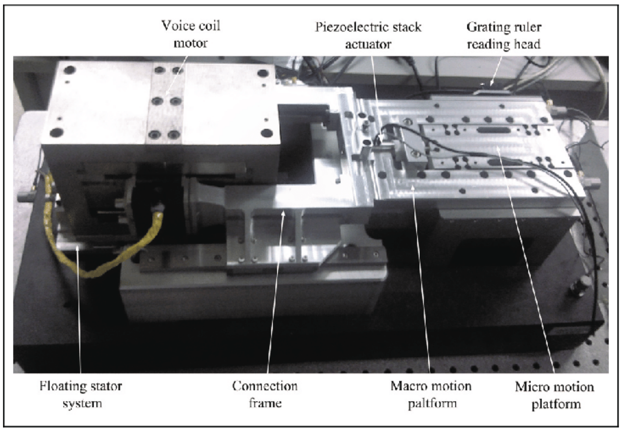

Figure 9. A Voice Coil Motor-PZT Macro-micro motion actuator [10]

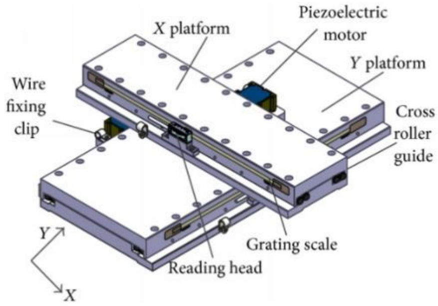

Figure 10. Long-Stroke Nano positioning Stage Driven by Piezoelectric Motor developed at Harbin Engineering University [11]

6. Research Status for Attaining High Acceleration

The macro actuators realizes high acceleration has a negative impact on the micro actuator ability to realize nano positioning accuracy [12].

For optimum performance of the macro micro motion platform, increased platform acceleration is significant. Due to static and dynamic characteristics affecting the level of acceleration several solution aiming at isolating vibrations are exploited from literature.

General approach is to optimize the Macro-micro platform hardware by analyzing the static and dynamic characteristics to attain stresses and displacement under different loads. L F Zhang. et al developed a ultra-high acceleration macro micro platform concept structural model by analyzing the static and dynamic characteristics and identifying the micro stage vibration modes using finite element method. [13]. Zhang et al used a floating stator to reduce the effect of external disturbances through having continuous stalling of force in the direction of motion [10].

Jian Gao 2018 developed a special spring PZT stage shown in Figure 11. Specialized spring PZT structure for dynamic micro-motion to counter act the dynamic vibrations hence reducing the settling time and maintaining high acceleration.

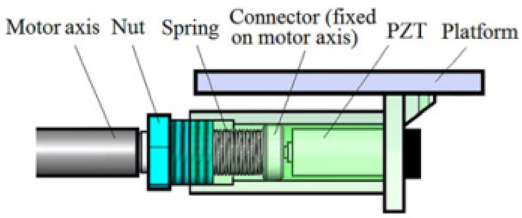

Figure 11. Specialized spring PZT structure for dynamic micro-motion [14]

7. Theoretical Analysis of Macro Micro Stage Accuracy

7.1. Laser Interferometer Error Detection and Offline Compensation Results

The inherent geometric error data was collected using the Renishaw laser interferometer error detection method for position and straightness error in the x-axis for both forward and backward stroke.

For position accuracy detection and error occurrence repeatability validation, five experiments were conducted for both positioning error and straightness error along the x-axis. A single experiment included both forward and reverse error data collection according to the national standards [15].

The 50mm stroke laser interferometer error data is presented as follows.

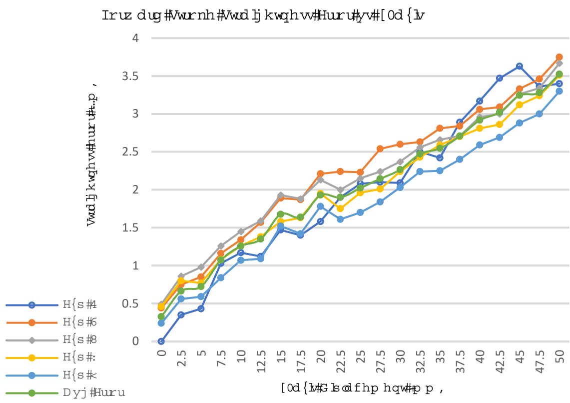

Figure 12. Laser interferometer measured forward stroke straightness error

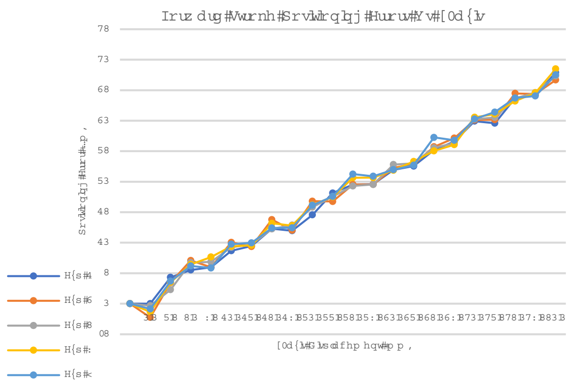

Figure 13. Laser interferometer measured forward stroke positioning error

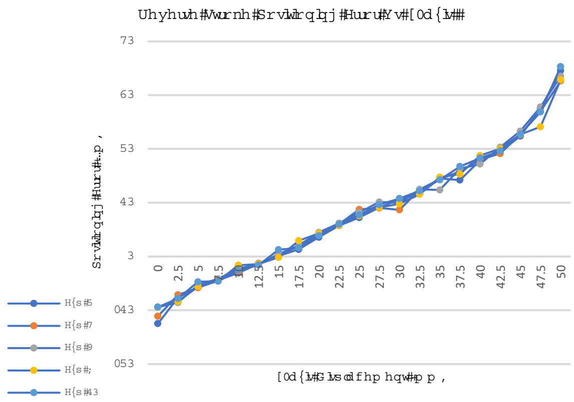

Figure 14. Laser interferometer measured reverse stroke positioning error

In Figure 12 it is noted that the average maximum forward straightness error is $3.5\mu m$ and from Figure 13 and Figure 14 for forward and backward positioning error curve the average maximal error is $35\mu m$. This error data does not meet the accuracy requirements for a submicron. As it can been seen the errors becomes nonlinearly larger as the machining route/stroke increases.

The offline database error compensation model attained maximum average straightness error reduced from $3.5\mu m$ to $0.45\mu m$ and maximum average error from $35\mu m$ to $0.006\mu m$ .Reaching the required submicron machining accuracy with a significant error reduction potential.

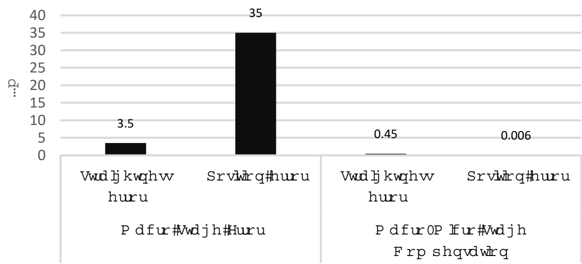

Figure 15. Table showing error values before and after compensation

8. Conclusion and Discussions

In has been shown in the literature and the presented lab data that the Macro-micro motion platform has been a success in achieving Ultra-precision positioning, ultra-high acceleration and long stroke machining.

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