

Paper:

# Optimal Structure Design Methodology for Compound Multiaxis Machine Tools – II

## – Investigation of Basic Structure –

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[Received September 3, 2007; accepted October 29, 2007]

Compound multiaxis machine tools are used to machine high-value-added parts through integrating milling and turning. Compound machine tools are generally structured based on a conventional NC lathe by incorporating Y axis and automatic tool changer (ATC) components for milling. Due to complexity of the structure and functional versatility required for a compound machine tool, accuracy, productivity, and return on investment (ROI) must be improved over conventional NC lathes and machining centers. In the sections that follow, we discuss design methodology for compound multiaxis machine tools, focusing on the design of an optimal basic structure for high accuracy and high productivity. We propose a box in box structure, a movable column-Y axis, and a boring machine structure. We analyzed static rigidity, dynamic features, and movement accuracy of machine structures theoretically using FEM for three proposed structures. We found that the box in box structure is suitable for compound multiaxis machine tools to achieve high accuracy and high productivity.

**Keywords:** compound machine tool, structural design, box-in-box, rigidity, vibration

## 1. Introduction

Compound multiaxis machine tools are used to machine high-value-added parts through integrating milling and turning on a single platform. The compound multiaxis machine tools conduct machining operations on an inclined plane, gear machining, grinding, and many other type of intricate machining by combining the functionality of an NC lathe and a 5-axis machining center. A compound machine tool is structured based on a conventional NC lathe, incorporating Y axis and ATC compo-

nents for milling. Due to the complexity of the structure and the functional versatility required for a compound machine tool, accuracy, productivity, and return on investment (ROI) must be improved over conventional NC lathes and machining centers.

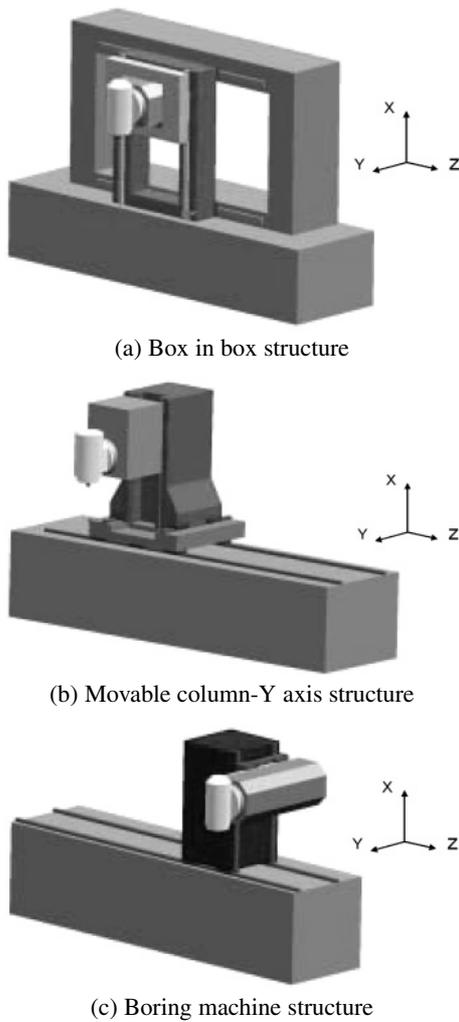
Compound machine tools achieve the same ROI as the conventional NC lathe or multiaxis lathe if the compound machine has 1.15 to 1.5 times higher productivity [1]. It is also expected that compound machine tools have the best ROI when the machine has 2 spindles and 2 tool stations. The optimal configuration of a compound machine tool is vertical with 4 tool movable axes and one rotation axis for workpiece rotation.

We propose and analyze a basic compound machine tool structure for high accuracy and high productivity. We analyzed the static rigidity, dynamic features, and movement accuracy of the structure theoretically using FEM for three structures proposed. We confirmed that the box in box structure is suitable for compound multiaxis machine tool to achieve high accuracy and high productivity [2–6].

## 2. Configuration of 3 Orthogonal Movable Axes

A compound machine tool normally has of X, Y, Z, B, and C axes for motion control. The C axis is horizontal to the bed to rotate long shaft-like workpieces the same with NC lathe. The X, Y, Z, and B axes are on the cutting tool side. The rotational B axis has a tilting head. To make the structure compact, the rotation radius of the B axis must be as small as possible. The B axis is located above the 3 orthogonal movable axes of X, Y, and Z.

Different approaches have been used to decide the basic machine tool structure based on the structural module concept [7–9]. We propose and discuss three basic structures extracted from basically different structures adopted



**Fig. 1.** Three basic compound machine tool structures.

for 3-axis machining centers with X, Y, and Z movement. Structures feature the following:

(1) Box in box

For the box in box structure, a small inner box is stacked above a large outer box to hold the spindle to move horizontally and vertically (**Fig. 1(a)**). The guides and drive are symmetrically arranged along the two sides with respect to the center of the small box. The advantage of this is that drive from the twin ball screws is applied to the gravity center of movable mass, minimizing Abbe's error between the cutting tool and drive. The problem is the need for twin ball screw drive and a comparatively larger structure.

(2) Movable column-Y axis

The movable column-Y axis enables the cutting tool to move horizontally along the Y axis by driving the vertical column back and forth (**Fig. 1(b)**). This is widely applied when the cutting tool must move along three linear axes of a machining center. The advantages of this structure are movable components for three axes that take cubic shapes, which have highest rigidity. The disadvantage is that Abbe's error tends to occur due to long distance between the guide and cutting tool.

**Table 1.** Same pre-conditions of three structures [11, 12].

Cutting tool spindle	
Dimension	$\phi 270 \times 500$ mm
Mass	180 kg
Structure	Typical cutting tool, tool spindle unit as well as joints of tool spindle with column are adopted to be rigid bodies.
B axis (tool spindle rotational axis)	
Dimension	$\phi 290 \times 150$ mm
Mass	150 kg
Structure	B axis unit and joint components of B axis are assumed to be rigid bodies.
Bed	
Dimension	800×800×3000 mm
Mass	3500 kg
Material	Cast iron FC300 (JIS)
Structure	Ribs and panels without partition
Other structure	
Material	Cast iron FC300 (JIS)
Structure	Ribs, panels without partition
Thickness	25 mm
Stroke	
X axis	600 mm
Y axis	250 mm
Z axis	1500 mm
Linear guide type and installation	
Equivalent to type	45mm size for X, Y and Z axis
Distance between the guide rails for X axis	500 mm
Distance between the guide rails for Y axis	700 mm
Distance between the guide rails for Z axis	1000 mm
Note	The distance between the guide rails for Y axis and that for Z axis are 500 mm and 1800 mm apart respectively for the box in box structure.

(3) Boring machine

The boring machine has a quill structure component moving along the Y axis which holds the spindle just like a boring machine (**Fig. 1(c)**). The linear guide and drive for the quill are mounted on the column. This structure is widely adopted for boring machines. The advantages are that the structure is compact and cabling is easy. The disadvantage is that the long distance between the tool and the guide may increase Abbe's error. Uneven thermal deformation is expected to be generated due to the asymmetrical structure.

To determine the model (**Fig. 1**) most suitable for the compound multi-axis machine tools, we quantitatively analyzed structures for accuracy and productivity, evaluating (1) rigidity variation with axis movement, (2) resonant frequency, (3) magnitude of moving mass, and (4) the distance between the center of gravity of the moving component and the point where drive is exerted [10]. This distance mainly determines the amount of Abbe's error.

The comparisons are made among three structural modes shown in **Fig. 1** under the same conditions in **Table 1**. For modeling and analysis, we use commercial software packages SolidEdge and I-DEAS.