Research of design an educational modular 5 axis milling machine

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Abstract. Industrial CNC machine tools are supplied as closed architecture systems. Their structure, kinematics and CNC controllers are designed to be used exclusively for their basic purpose, without any possibility of being changed. Reconfiguration is seen as the ability to add or remove modules from the machine, to be equipped with additional degrees of freedom (axes). For the concept to become a reality, it is necessary that the machine tool can be easily assembled and disassembled by an end-user and can adapt to changing projects or machining requirements. The approached of this research was to develop a 5-axis modular machine tool, with technological capabilities similar to industrial ones, at an affordable level of development costs and suitable to be used for teaching CAM techniques for future engineers.

1. Introduction
The mechanical modules, from which a reconfigurable modular machine (RMM) is created, can be assembled in a "building" manner. This allows the mechanical modules to be assembled in several configurations, offering a variation of the degrees of freedom in processing and processing functions on a single platform.[1] The primary stage in the development of an RMM is the synthesis of a library with precompiled mechanical modules, which includes only the modules needed to provide the desired machine configuration.[2] The goal is to design a modular machine tool to represent three different possible architectures of 5x machine (Table-Table, Table-head and head-Head). By modular, we mean being able to disassemble the machine tool into different parts: at first glance each degree of freedom is at least divided into one part. Some intermediate parts are needed for easy assembly.

The main requirement of a machine tool is to provide a guide for continued accurate movement under certain condition: [5] ability of the structure of the bed to resist distortion effectively due to static and dynamic loads; stability of the motion of under load; wear resistance of guides; freedom from residual stresses; leveling; resistance to vibrations; freedom from slip-stick.

2. Desktop milling machine tool concept
When designing this machine, we placed great emphasis on the versatility of the parts we created. In other words, we've made sure that as many parts as possible are reusable from one configuration to another. For this, our parts are not necessarily optimized for an assembly, but optimized to have a place in several assemblies to reduce the production cost.
The design concept is for 5 axis NC milling machine in 3 basic configuration Table-Table (fig.1.a), Table-Head (fig.1.b) and Head-Head (fig.1.c)

According to the nomenclature of machine tools, the Table-Table assembly will be designated by the code (YCAOXZ), which means that the translations according to the rotations of axis X and Z as well as the translation of axis Y are located at the table level, while the X and Z axis translations are at the machining head.

According to the nomenclature of machine tools, the Table-Head assembly will be designated by the code (XYCOZB), that is to say that the translations along the X and Y axes and the rotation along the Z axis are located at the table level, and that the translation along the Z axis and the rotation along the Y axis are at the machining head. The two rotations are done with two separate motors, an SSPM HT-62 motor for the rotation of the table, and a stepper motor (same model as for the translations) for the rotation of the head.

According to the nomenclature of machine tools, the Head-Head assembly will be designated by the code (XYOZCA), that is to say that the translations along the X and Y axes are located at the table level, and that the translation along the Z axis and the rotations along the X and Z axes are at the level of the machining head.

3. Hypothesis and simplification of milling machine tool concept
An element of originality consists in the design of numerically controlled axes of modular translation and rotation, compact, completely independent that can be assembled in different architectures specific to machines with numerical control up to 5x NC used for educational purposes.

The modules of a machine must have standard interfaces that allow a wide variety of machine tool configurations. Reconfiguring a machine by replacing modules will require disassembling the machine and reassembling it as well as calibrating, setting set-up parameters and other operations.

The main criteria of the concept are the flexibility and versatility of the machines. Still some requirements like stability of the motion under loads, resistance to vibrations, machine accuracy (squareness of the axis, repeatability, and positioning) must be accomplished even if are not to the level of industrial machine.

For linear axis, a classic kinematic chain of direct drive has been created formed by step motor, leading screw, and nuts. For the guiding, linear bearings are used. All three linear axis were made in the same manner to simplify the construction and decrease the costs.

The assembly solution of the linear axis between them for construct the XYZ architecture is very simple, based on carriage shape which ensure the perpendicularity of the axis and fit position at the same time. In figure 2 a and b are marked the alignment surfaces of the carriage and the base of the next axis. In figure 3 a simple XY axis assembly is presented. For this axis, a physical prototype was made.
The machine table has been designed in a specific shape to allow the mounting on linear axis as well on rotational C axis in any configuration. In XYOZCA configuration the table is mounted over the X linear axis and will be aligned by the green surfaces (fig. 3a and b).

For XYCOZB the table will be centered on the yellow surface and aligned on the green surface (fig. 3a and b). The Z axis carriage design tries to respect the simple form and at the same time to ensure the stiffness of the machine. In figure 4 the Z axis assembly and components are specified. On Z carriage (4.a) can be mounted directly the B axis (fig. 4b) or C and B assembly formed by B axis and C axis (fig. 4.c) without the support used in XYCOZB machine configuration.

4. Design and analysis

Due to basic configuration of the machine type on Z carriage the main spindle is mounted along with one (B) or two (C and B) rotational axis some verification and validation of the design must be done.

Finite element simulations were made for the XYCOZB configuration by take in account the possible load on the table and B axis flange in a conservative milling process (in polymers and composite material for prototyping). Some aluminum 5083 series has been used for all components with the following characteristics: Density 265 g/cm³; Modulus of Elasticity 72 GPa; Thermal Expansion 25 x10^-6 /K; Tensile Strength 270 - 345 MPa; Poisson's Ratios 0.334 used in FEM analysis.

To simulate the reaction of the XYCOZB configuration during its operation, the following conditions were imposed: an embedding on the underside of the assembly's support plate, a force of 300N imposed on the machining table, which represents the weight of the stock to be machined (the mass has been overestimated to observe the response of the assembly in extreme cases), and a force of 245N along the Z axis has been applied at the level of the machining head (overestimated again), to represent the forces imposed by the cutting process (Figure 5.a). First analysis was on a simple model design (initial design of components) (figure 5.b)

A maximum deformation of 0.67mm can be observed at the level of the machining head. This value represents a significant loss of precision during machining under the imposed conditions. For this, it was necessary to stiffen the "square" part (fig. 9) to limit the bending phenomena that can be observed in the simulation, but also to prevent any torsion that could appear. For this, the rib of the square has been enlarged to better withstand bending forces and a bar has been added to limit the effects of torsion.
5. Conclusion

An simple to build educational machine tool up to 5x, in modular architecture can be used in higher education and technical school for better understanding of CAM software capabilities.

A modular system must have several characteristics: it must be modular, convertible, it can be customized, it can be integrated, and it can be diagnosed.

All parts were machined by milling from aluminum sheets (some of them of 20 mm thickness) with a conservative cutting regime in order not to induce a remanent stress in material which over time will affect the part accuracy.

Regarding the stresses, a maximum of 46 MPa can be observed (Figure 5) at the level of the Z axis slide connection. This value can be easily supported by steel and aluminum without impairing performance or performance life of parts, no further action was taken.

The design changes made to the square have reduced the deformation of the square to 0.2mm, but the addition of a "machining head holder" part results in deformations of the order of 0.48mm. This value should not be exceeded in practice, since the forces applied for finite element analyzes are greater than those applied during machine operation (fig.7).

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