A dynamics-driven approach to precision machines design for micro-manufacturing and its implementation perspectives

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Abstract

Precision machines are essential elements in fabricating high quality micro products or micro features and directly affect the machining accuracy, repeatability and efficiency. There are a number of literatures on the design of industrial machine elements and a couple of precision machines commercially available. However, few researchers have systematically addressed the design of precision machines from the dynamics point of view. In this paper, the design issues of precision machines are presented with particular emphasis on the dynamics aspects as the major factors affecting the performance of the precision machines and machining processes. This paper begins with a brief review of the design principles of precision machines with emphasis on machining dynamics. Then design processes of precision machines are discussed, and followed by a practical modelling and simulation approaches. Two case studies are provided including the design and analysis of a fast tool servo system and a 5-axis bench-top micro-milling machine respectively. The design and analysis used in the two case studies are formulated based on the design methodology and guidelines.

Key words: precision machines, micro-manufacturing, machining dynamics, design, modeling

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1. INTRODUCTION

Precision machines are essential in modern industry and directly affect machining accuracy, repeatability, productivity and efficiency. Generally, design of a precision machine mainly includes design of its key elements in the light of the applications and machining processes. There are a number of literatures on the design of industrial machine elements [1-5] and a couple of precision machines commercially available. However, few researchers have systematically addressed the design of precision machines from the dynamics point of view. While it is difficult to explicitly cover the complete design details of a precision machine in journal publication. Therefore, in this paper, emphasis is placed on the mechanical and structural design of precision machines, relevant general design methodology and usage of engineering tools driven by dynamics. Furthermore, the paper focuses on the integrated approach for modelling and simulation of the machine and machining processing dynamics and thus achieving optimal design of the machine and enhancing its performance in the dynamic machining processes.

Recently, new demands in the fabrication of miniature/micro products and micro features have appeared, such as the manufacture of microstructures and components with 3D complex shapes or free-form surfaces. Although many efforts have been put into developing IC-based fabrication method, mechanical ultraprecision machining has its unique advantage in the fabrication of real 3D miniaturized structures and free-form surfaces. Therefore precision machine design method and its machining dynamics should be researched to meet the requirement of fabrication of micro products.

This paper begins with discussing design principles of precision machine tools, including the machine configuration and performance evaluations, followed by discussion of tool-workpiece loops and vibrations issues. The principles and methodology presented is a refined formulation driven by the machine and machining dynamics, which illustrates the dynamic and practical needs of modern machine design with the aid of powerful design and analysis tools. The machine design methodology covers a dynamics-driven design process, design modelling and simulation enhancement, and well formulated design guidelines. Finally, two case studies are provided on design of a fast tool servo system and a 5-axis bench-top milling machine tool, which help to evaluate and validate the methodology and approach developed based on the industrial cases.

2. PRECISION MACHINE TOOL CONSTITUTIONS

A typical precision machine consists of five major sub-systems. They are mechanical structure, spindle and drive system, tooling and fixture system, control and sensor system, and measurement and inspection system. These sub-systems are essential and directly contribute to machine tool performance. Figure 1 highlights the machine tool constitution and key evaluation criteria for the machine tool's performance. Because of varied machining purposes and different machine configurations, Figure 1 can not be very comprehensive, but rather than provide a thorough summary for understanding the machine tool constitution and its performance evaluation related to machining dynamics in particular.

2.1. Mechanical structure

Mechanical structure normally comprises of stationary and moving mechanical bodies. The stationary bodies include machine base, column and spindle housing, etc. They usually carry moving bodies, such as worktables, slides and carriages. The structural design is critical since the mechanical structure not only provides the support and accommodation for all the machine’s components but also contributes to dynamics performance possessed in a machine tool. To achieve high stiffness, damping and thermal stability, two major design issues are involved in mechanical structure design, i.e. the material selection and configuration.

The material selection for a machine tool structure is one of the essential factors in determining final machine performance, with many criteria being considered, such as temporal stability, specific stiffness, homogeneity, easiness of manufacturing and cost, etc [6].

Although there are a number of structural materials available, up to now only a few materials have been chosen to build machine tool structures. Cast iron has widely been used for many years due to inexpensiveness and good damping characteristics to minimize the influence of dynamics loads and transients. There are still many cast iron applications in precision machine tools albeit its high initial cost of fabricating patterns and molds and poor environment of operating foundries [7]. Granite is another popular material used to build precision machine base and slideways because of its low thermal expansion and damping capacity. The drawback of granite is that it can absorb moisture so it should be used in dry environment. For this reason many machine tool builders seal the granite with epoxy resin. The need for higher material damping and light weight in ultra-precision machining, combined with long-term dimensional and geometrical stability, leads to the development and usage of polymer concrete for machine tool structural elements in spite of the low strength [8].

The symmetry and closed loop structural configuration are widely used in precision machine tool design. Among various configurations ‘T’ configuration is popularly used for most of the precision turning and grinding machines. A tetrahedron structure proposed by the NPL in England has been applied in an internally damped space frame with all the loads carried in a closed loop. The design generates a very high stiffness coupled with exceptional dynamics stiffness [9], albeit its complexity and cost are increased in manufacturing and assembly. Another novel pyramidal space frame structure was adapted by Loadpoint for a special grinding machine [10]. This design offers very high static loop stiffness and high dynamic loop stiffness for damping.

2.2. Spindle and feed drive system

Spindle is a key element of the precision machine tool because the spindle motion error will have significant effects on the surface quality and accuracy of machined components. The most often used spindles in precision machine tools are aerostatic spindles and hydrostatic spindles. They both have high motion accuracy and capable of high rotational speed. An aerostatic spindle has lower stiffness than an oil hydrostatic spindle. Aerostatic spindles are widely used in machine tools with medium and small loading capacity while hydrostatic spindles are often applied in large heavy-load precision machine tools.

Accurate linear motions are generated by the use of slideways. Similarly, aerostatic slideways and hydrostatic slideways have been frequently applied in precision machine design and is replacing contacting surface type slideways.

On the drive side, the electric AC motor and DC brushless motor for high speed spindles are frequently built into the spindle so as to reduce the inertia and friction produced by the motor spindle shaft coupling as well as the dynamic. DC and AC linear motor drives can perform a long stroke direct drive and thus eliminate the need for conversion mechanisms such as lead screws, belt drives, and rack and pinions, with potentially better performance in terms of stiffness, acceleration, speed, smoothness of motion, accuracy and repeatability, etc [11]. Friction drives are very predictable and reproducible due to a prescribed level of preload at the statically determinate wheel contacts, thereby superior in machining optically smooth surfaces [12]. But there are some practical considerations that restrict the application of friction drives in machine tools. One such limitation is referred to as the thermal capacity. Therefore, it is difficult for friction drive to achieve a high speed operation.

2.3. Tooling and fixture system

Fixture system and tooling are the essential parts of the machining system. They also play significant roles in the machine tool design, because they are at the end of the machine tool-machining loop. The deformation of tooling and fixture system both in static and dynamic circumstances will entirely be copied to the workpiece surface and hence influence the workpiece form and dimensional accuracy as well as its surface texture and topography.

In contrast to the machine tool dynamics, the dynamics of tooling and fixture could change significantly, depending on the location of the cutting tool with respect to the workpiece, owing to its localized structure and geometry of the workpiece [13]. In the precision machine tool design, it is very important if designers can take this varying dynamics into account in spite of the possible difficulty, because this will be helpful to accurately evaluate the machine dynamics and errors budget. In practice, the dynamics change by the location of the cutting tool with respect to the workpiece can be dealt with by putting a larger safe bandwidth of the machine tool, and the speed of spindle can be limited as designed to decrease this dynamic change.

2.4. Control system

Computer numerical control (CNC) was introduced into the machine tools industry in early 1970's and since then many companies started to develop their own control systems for machine tools. The control sub-system includes motors, amplifiers, switches and the controlled sequence and time. High speed multi-axis CNC controllers are essential for efficient control of, not only servo drives in high precision position loop synchronism for contouring, but also thermal and geometrical error compensation, optimized tool setting and direct entry of the equation of shapes [14].

From the dynamics viewpoint, stiffness in control system indicates the capability to hold a position when dynamic forces try to move it. Therefore, a proper design of control system and its algorithms can lead to a high servo-stiffness and hence improve machining precision through the machine tools.

2.5. Metrology and inspection system

Metrology and inspection systems are the basis for qualifying assurance of precision machining and enabling the technology to be widely applied in industry. On the other hand, higher level accuracy assurance in metrology and inspection system is also a drive for precision machines towards higher precision requested for future engineering industry. Fast and accurate positioning of the cutting tools towards the workpiece surface and monitoring of the tool conditions visually by the operator should be integrated into the inspection system especially for on-line operation purposes.

2.6. Machine tool performance evaluation

The overall objective of the design of machine tool sub-systems discussed above is to achieve required machine performances. The performances are evaluated normally in the following aspects:

- Accuracy
- Kinematics
- Static performances
- Dynamics performances
- Strength performances
- Thermal performances
- Noise
- Vibration

These machine performances are collectively reflected on the tool-workpiece loop in terms of stiffness, thermal stability, static and dynamics as shown in Figure 1. The following sections will focus on the tool-workpiece loops, in relation with the machine dynamics in particular.

Figure 1. Machine tool constitutions and performance

3. TOOL-WORKPIECE LOOPS AND MACHINE TOOL VIBRATION

Precision machine tools are highly dynamic systems in order to sustain the required accuracy, productivity and repeatability. The precision of a machine is affected by the positioning accuracy of the cutting tool respect to the workpiece surfaces and their relative structural and dynamics loop precisions, which are fundamental and essential for the machine design.

From a machining viewpoint, the main function of a machine tool is to accurately and repeatedly control the point of contact between the cutting tool and the uncut material - the ‘machining interface’. This interface is normally better defined as tool-workpiece loops. Figure 2 shows a typical machine tool-workpiece loop. The position loop - the relative position between the workpiece and the cutting tools which directly contributes to the precision of a machine tool and directly lead to the machining errors.

On the other hand, deformations introduced by stiffness and thermal loop are two important aspects in tool-workpiece loops. The stiffness loop in a machine tool is a sophisticated system. The stiffness loop of the machine includes the cutting tool, the tool holder, the slideways and stages used to move the tool or the workpiece, the spindle holding the workpiece or the tool, fixtures, and internal vibration, and other dynamic effects. The physical quantities in the stiffness loop are force and displacement. During machining, the cutting forces at the machining point will be transmitted to the machine tool via the stiffness loop and return to the original point thus closing the loop. Influences outside of the structural loop, which still influence the loop and cause errors, include floor vibration, temperature changes, and cutting fluids. Thermal dynamic loop is similar to the stiffness loop and contains all the joints and structure elements that position the cutting tool and workpiece.

Figure 2. Machine tool loops and dynamics of machine tools

Machine tool vibrations play an important role in determining structural deformations and dynamic performance. Furthermore, excessive vibrations accelerate tool wear and chipping, cause poor surface, and damage to the machine tool component. As shown in Figure 2, it is useful to identify vibrations types in machine tools during the design stage and then control the vibrations from the machine tool design side.

4. METHODOLOGY AND IMPLEMENTATION PROSPECTIVE

4.1. Design processes for the precision machine

As illustrated in Figure 3 the design of a precision machine tool requires some basic steps: customers requirements and system functional requirements, conceptual design, analysis and simulation, experimental analysis, detailed design, design follow up, albeit the full design process is always iterative, parallel, nonlinear, multidisciplinary and open-ended to any innovative and rational ideas and improvements. The functional requirements of a precision machine may address the considerations in geometric, kinematics, dynamics, power requirement, materials, sensor and control, safety, ergonomics, production, assembly, quality control, transport, maintenances, cost and schedule, etc [1]. In this stage assessment of the state-of-the-art technology is needed to make the design more competitive and the cost economically. The final specifications will be determined after several specification iterations. The resultant conceptual design is important for the innovation of the precision machine design.

Figure 3. The precision machine design procedures

Brainstorming is a method most often thought of for generating conceptual design. In this stage, selection of key components in precision has to be considered. These key components include machine structure and materials, main spindle and slides, feed drive, control units, inspection unit, tool and fixtures etc. The advantages and disadvantages of these components should be compared and evaluated with respect to system functional requirements and other factors such as cost. Some of these key components in precision machines have been briefly reviewed in the previous section. Several design schemes may be proposed in this stage, which are followed by analysis and simulation processes and experimental analysis processes. From the dynamics point of view, the vibration should be avoided during this stage right first time, by the use of various integrated analysis and testing disciplines, from the component level to the final assembly.

Analysis and simulation include key component modelling, system modelling, static analysis and dynamic analysis etc. Analysis and simulation method that has been widely used is finite element analysis. The analysis results, together with errors budget and cost estimation, will be used to check the conformance to the machine's specifications. The analysis results also help to identify some weakest parts in machine tool structure and then provide data for structural modification hence speeding up the decision-making process.

Experimental dynamic analysis in precision machine involves in the selection of testing methods, frequency response function analysis, modal updating and comparisons with simulation results, etc. Through experimental dynamic analysis, some important dynamic characteristics of key machine components or even assembly such as modes and shapes, natural frequencies and damping ratio, will be obtained. Experimental analysis results can also be used to structural modification and verification of simulation model.

It should be stressed that the processes of structural design, structural dynamic analysis and tests are not necessary linear but interactive each other. Design of precision machines should involve structural design, analysis and experiments in an integrated engineering environment. First of all, experimental dynamic tests will be in support of dynamic simulation, since many unknowns prevail in a pure analysis and simulation process, especially when dealing with a fully assembled new design configuration. Insufficient understanding of the various simulation procedures, the characterization of new materials, or the use of different construction methods for structures, all generate unknowns and can lead to an inefficient use of simulation, and therefore more iterations. A principle role for structural dynamics tests will provide the necessary feedback data to support the design and analysis process. Data feedback can often be understood in a broad sense. It is usually unnecessary to perform the dynamic testing for the whole assembled precision machine, or it will fall into traditional trial-and-error methods. For instance, data from dynamic testing of aerostatic slideways can be feedback to finite element analysis to establish an accurate model; data from nanoindentation tests will benefit the development of simulation criteria of nano/micro machining processes modelling. The experimental database should be integrated into the overall analysis and modelling processes to help update or correct the existing analytical model such as FEA model or to build new models based on experimental data.

The need for this integration is driven by the increasing demand of high precision machines. Fortunately advances in hardware and software have been contributing to this integration. The hardware and software available for executing structural testing and analysis has evolved from standalone instruments to computer based system and usually PC-based systems. Various successful commercial CAE software available in the market have been of benefit to designers in dynamic analysis. The data acquisition card and analyzers used for data acquisition and signal processing have become flexible, powerful and customizable to user requirements.

Once conceptual design, dynamic analysis and test has been finished a design plan can be formulated for detailed design. In the detailed design stage, all subsystem including mechanical structure, spindle and feed drive systems, tooling and fixture systems, control and sensor systems, and metrology and inspection systems will be completed, and if necessary more detailed analysis and simulation need to perform based on the detailed design.

After the detailed design is completed there is still much work that needs to be done in order to make the design successful, including development of test and user support programmes, update of design and document, etc.

4.2. A simulation-based design approach

Many researchers and machine tools manufacturers have been making efforts to improve dynamic performance of precision machine tools, Due to the complexity of the machine tool structure and the machining process, however, the experimental measurement of the structural and thermal dynamic performance is difficult because of enormous cost and time consuming. Establishing and executing the machine computational models would therefore have great value in evaluating and validating improving dynamic performance of machine tools. The models can be used for:

- Quantitatively predicting and evaluating structural/thermal deformation distributions of the machine tool structure even at early design stage and thus rendering the effectively compensation method.
- Optimizing machine tool structure for the best dynamic accuracy at design stage.
- Identifying a few structural elements that significantly influence the machining accuracy.
- Verifying machine performance such as stiffness, chatter, accuracy, reliability, etc.
- Reducing the amount of experimental data required and hardware and experimental cost.

From the machine design point of view, modelling can be used to simultaneously represent the machining processes and the machine tool structure. The simulation model can therefore establish the relationship between inputs and outputs which enable the static or dynamics performance of the machine tool numerical and graphically illustrated by using the process variables of the input.

To some extent, the simulation model can bridge the gaps among the real machine, its physical model, mathematical model and its dynamic performance output. Figure 4 illustrates the general modelling and simulation approach to simulating dynamic performance of the real machine tool system. The ideal physical model is extracted from the real machine system by simplification. Simplification is necessary because of the complexity of machine tools. Some minor factors will be neglected during this stage. The mathematical model is deductively derived from basic physical principles and is established to solve the physical model. The mathematical model can be regarded as an idealization of the ideal physical model; conversely, the ideal physical model can be presented as a realization of the mathematical model. For dynamic analysis, the mathematical model is often an ordinary differential equation in space and time. In practice it is difficult to solve the equation and get the solution directly by the analytic method. Therefore, the discrete model is developed to solve the problem. The discrete model, also termed simulation model or numerical method, is the imitation of discrete value of time of a dynamic process on the basis of a model and generated from the mathematic model and this process is called discretization method. Among various methods to generate discrete models, including finite element method, boundary element method, finite difference method, finite volume method, and mesh-free method, etc, finite element method still dominates most of the engineering design and analysis. It should be noted that in some practical machine tool design and analysis processes discrete model (FEA model) may be generated without reference to mathematical model and directly from real physical model instead because it may be difficult to establish a mathematic model.

Figure 4. A general modelling and simulation approach

The design of precision machines has significantly benefited from the development of computer-based techniques to analyze the static and dynamics characteristics of machine tool. Figure 5 highlights an overview of machine tool analysis types and followed by a practical structural analysis approach using FEA.

Figure 5. Overview of machine tool analysis

5. APPLICATIONS

5.1. Design case study 1 - A piezo-actuator driven Fast Tool Servo system

The piezoelectric actuator is a kind of short stroke actuator. It is very promising for application in the rotary table drive and slideways drive because of its high motion accuracy and wide response bandwidth [11]. Currently, piezoelectrics have been applied in the design of the fine tool-positioner in order to obtain high precision motion of the cutting tool. The piezoelectric actuator combined with mechanical flexure hinges is used for positioning control of the diamond cutting tool. More recently, Fast Tool Servo (FTS) system has been introduced for diamond turning components and products with structured and non-rotationally symmetric surfaces such as laser mirrors, ophthalmic lenses molds, etc [15].

The piezo-actuator driven fast tool servo (FTS) system is designed to perform precision positioning of the tool during short stroke turning operation which has been implemented in a test turning machine tool set up at Brunel University.

The FTS is designed to perform turning operations and hold diamond tools. Static deformation of the FTS structure caused by cutting forces during rough and finish machining, must be minimized to reduce form and dimensional error of the workpiece at nanometer scales. Therefore, high stiffness, particularly in the feed direction which affects the machined surface directly is required. A high first natural frequency is required in the FTS structure so as to prevent resonance vibrations of the structure due to the cutting forces.

On the other hand, the high stiffness of the FTS structure will reduce effective stroke of the piezo actuator to some extent. For this reason a compromise is made between high stiffness and actuator stroke reduction.

Figure 6 shows the schematic of the FTS that comprises of a piezoelectric actuator (Cedrat Tech. PPA10M, PPA20M, or PPA40M), a flexure hinge, two cover plates, a tool holder, a capacitive sensor, and piezoelectric adjustment screw. The piezo actuator is housed under preload within the flexure hinge made from spring steel. Three piezo actuators, 18mm (PPA10M), 28mm (PPA20M) and 48mm (PPA40M) length respectively are used. Three different adjustment and preload screws with corresponding lengths are designed to house the three actuators in the same flexure hinge. Actuator displacement in actuated/feed direction is transmitted to the tool holder via four symmetric solid flexure hinges which have a circular hinge profile as shown in Figure 5. The tool holder is designed to be integrated with flexure hinge in a single part. The overall envelope of FTS is 90mm x 80mm x 55mm, with the tool holder extending 35mm. the design is compact and self-contained for easy of mounting on slideways and tool posts in other machine tools.

Figure 6. The schematic view of the FTS

To determine the flexure hinge dimension, both static and modal finite element analysis were conducted for the flexure, in which static stiffness and natural frequencies were obtained. In both analyses, hinge radius *r*, hinge thickness *t* and hinge length were chosen as optimization variables, and optimization FEA results were obtained based on the requirement of stiffness, natural frequencies and strokes reduction.

Optimized static stiffness of FTS is 9.7 N/μm and stroke reductions in the three cases are below the design requirement and it should be noted that stroke reduction will be a little higher if taking piezo-actuator preload effect into account. The maximum Von Mises stresses predicted by FE analysis under maximum load are 45MPa, which are well below the strength value of spring steel.

The FE modal analysis was used to predict natural modes of the flexure structure. The first three natural frequencies are 1262, 2086, and 2791 Hz. The lowest frequency mode is the translational motion along the actuated/feed direction with a natural frequency of 1262 Hz, which is above design requirement of 1000 Hz. Figure 7 shows a mirror surface with Ra<10nm and a sine-wave micro-featured surface obtained from preliminary cutting trails using this FTS.

Figure 7. The finished surfaces of Aluminum components

5.2. Design case study 2 - A 5-axis bench-top micro-milling machine tool

This case study describes the conceptual design process of a bench-top 5-axis micro-milling machine, which is currently being developed by the authors and their collaborators within the EU MASMICRO project [16].

The machine aims at manufacturing the miniature and micro components in various engineering materials, potential applications include MEMS, optical components, medical components, mechanical components and moulds etc.

After reviewing the state-of-the-art of commercially available ultra-precision machine tools, the initial specifications of the 5-axis milling machine are produced as listed in Table 1.

Table 1. Initial specifications of the 5-axis milling machine tool

Preliminary design and analysis. According to the machine specifications, the machining envelope, the bench-top required dimensions, the types of components/materials to be machined, and the overall accuracy to reach and maintain, the machine tool layout is initially designed with an open frame configuration to facilitate machining area access for fixturing and part handling. In this stage, some feasible structural configurations available are also reviewed.

The structural static and dynamics behaviours of the machine were simulated using ANSYS software in the light of the methodology described in previous sections. There are many air bearings in this machine tool configuration (multiple air bearing slideways and air bearing spindle), but it is difficult to simulate the compressed air directly. An equivalent method is proposed to simulate the air bearing, i.e. using spring elements in ANSYS to simulate the stiffness in different directions. The stiffness of the spring element is based on the stiffness data obtained from experiments. All the freedoms of the machine base were constrained throughout the analysis.

Both static and modal analyses were conducted and the first 10 natural frequencies were extracted in modal analysis using block Lanczos method. FEA results identified the important sensitive component on the machine structure, which can be seen from the mode shape of the first natural frequency (117 Hz). Due to the stack of slideways assembled on top of each other, the X slideway and the Z slideway are subject to important tilting effect, which is likely to affect the machine accuracy, as illustrated in Figure 8(a). Therefore, from the structural modification point of view, improving the stiffness of the slideway is the most effective method. A harmonic analysis then was performed to quantitatively predict dynamic stiffness of the machine structure and verify whether or not the designs will successfully overcome resonance and harmful effects of forced vibrations. In this analysis, the machine tool structure was excited by a serial of harmonic forces (Fsinωt) acting between workpiece and cutting tool. A frequency range from 0 to 500 Hz with a solution at 20 Hz intervals was chosen to give an adequate response curve. Only vertical direction (y direction) displacements were discussed here. As shown in figure 9, the maximum dynamic compliance of about 1.8 μm/N (y direction) occurring at 300Hz, which corresponds to a dynamic stiffness of 0.55N/μm.

Figure 8. FEA results on a 5-axis micro-milling machine
Figure 9. Harmonic response on a 5-axis micro-milling machine

Redesign and reanalysis. Following the information gained from the sensitivity analysis based on preliminary FEA results, a gantry type of machine configuration was proposed. This gantry type of machine configuration will enable a much better overall machine stiffness, in both statics and dynamics mode and overcome the problems identified in the original machine design. In order to improve the overall stiffness of the machine tool, machine structure material was changed from polymer concrete to granite. Modal analysis is conducted for the new configuration in which horizontal slideway was neglected so as to increase computational speed because there is no tilting slideway. Figure 8(b) shows the first natural frequency and its vibration shape. The first natural frequency is increased to 134 Hz from 117 Hz in preliminary design, and the following natural frequencies are also improved. The same harmonic response analysis was conducted and its results on y direction was shown in figure 9. it can be seen that the maximum dynamic compliance was reduced from 1.8 μm/N to 1.6 μm/N, which corresponding to a dynamic stiffness of 0.625N/μm. The final gantry 5-axis micro milling machine configuration is shown in Figure 10.

Figure 10. The final gantry 5-axis micro milling machine configuration

6. CONCLUSIONS

The demands for fabrication of micro-products hold a high potential of growth, which in turn requires the development of the high performance precision machine tools. It was estimated that eighty percent of the final cost and quality of a machine tool are determined during the design stages. This paper presents the general approach to the design of precision machine with emphasis on the machine dynamics. The design issues including machine-cutting tool-workpiece loops are discussed in order to identify and formulate the major design factors for precision machines, and hence enhance their machining performance from the deign viewpoint. The methodology presented is by no means comprehensive. However, it is an attempt to provide a logical, practical and dynamics-driven approach to the design of precision machines. Major conclusions being drawn are:

- The principles and methodology of the precision machines design have been implemented by the method and approaches presented in this paper, i.e. a computer-based dynamics-driven design and analysis. The formulation of the dynamics-driven design method and the general approach has provided the practical and logical guidance for the precision machines design.
- Two application case studies provided have further refined the dynamics-driven design and analysis method/approach. Furthermore, they help to evaluate and validate the methodology and approach with comprehensive industrial design data and requirements.
- The design and analysis processes in the applications case studies have shown that the dynamics-driven design and analysis approach combined with experimental tests is effective and efficient in optimizing precision machines design and thus enhancing their performance.

ACKNOWLEDGEMENTS

This work was funded by the EU 6th Framework IP MASMICRO project (Contract No. NMP2-CT-2004-500095-2). Thanks are also extended for collaborative partners in its RTD 5 sub-group in particular.

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Table 1. Initial specifications of the 5-axis milling machine tool

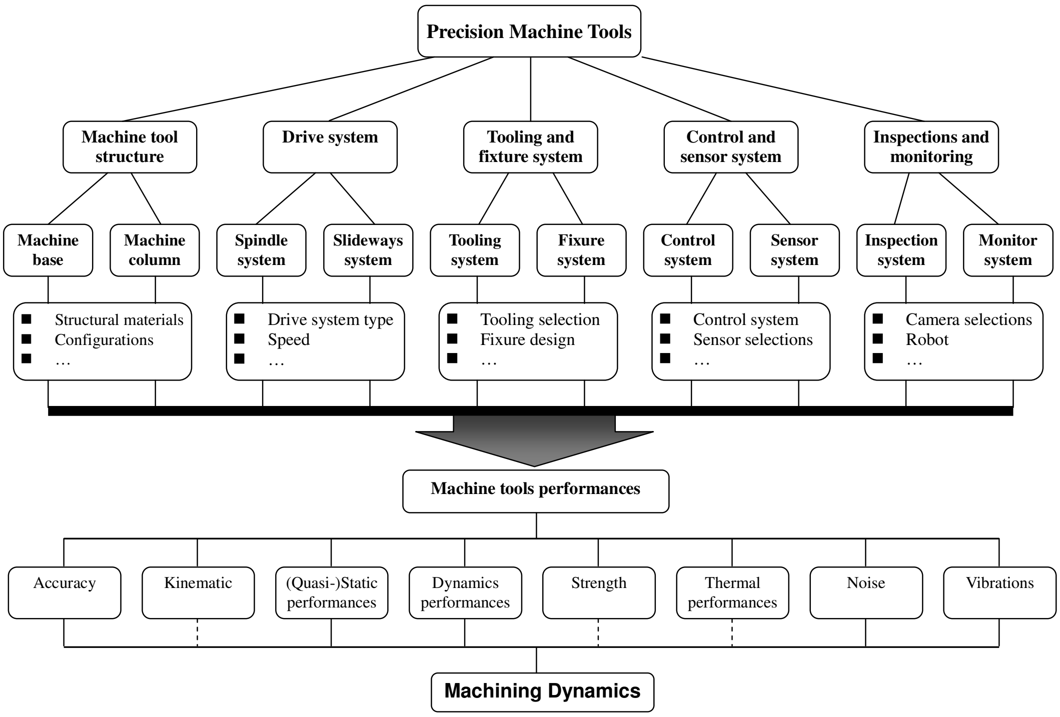


Figure 1. Machine tool constitutions and performance

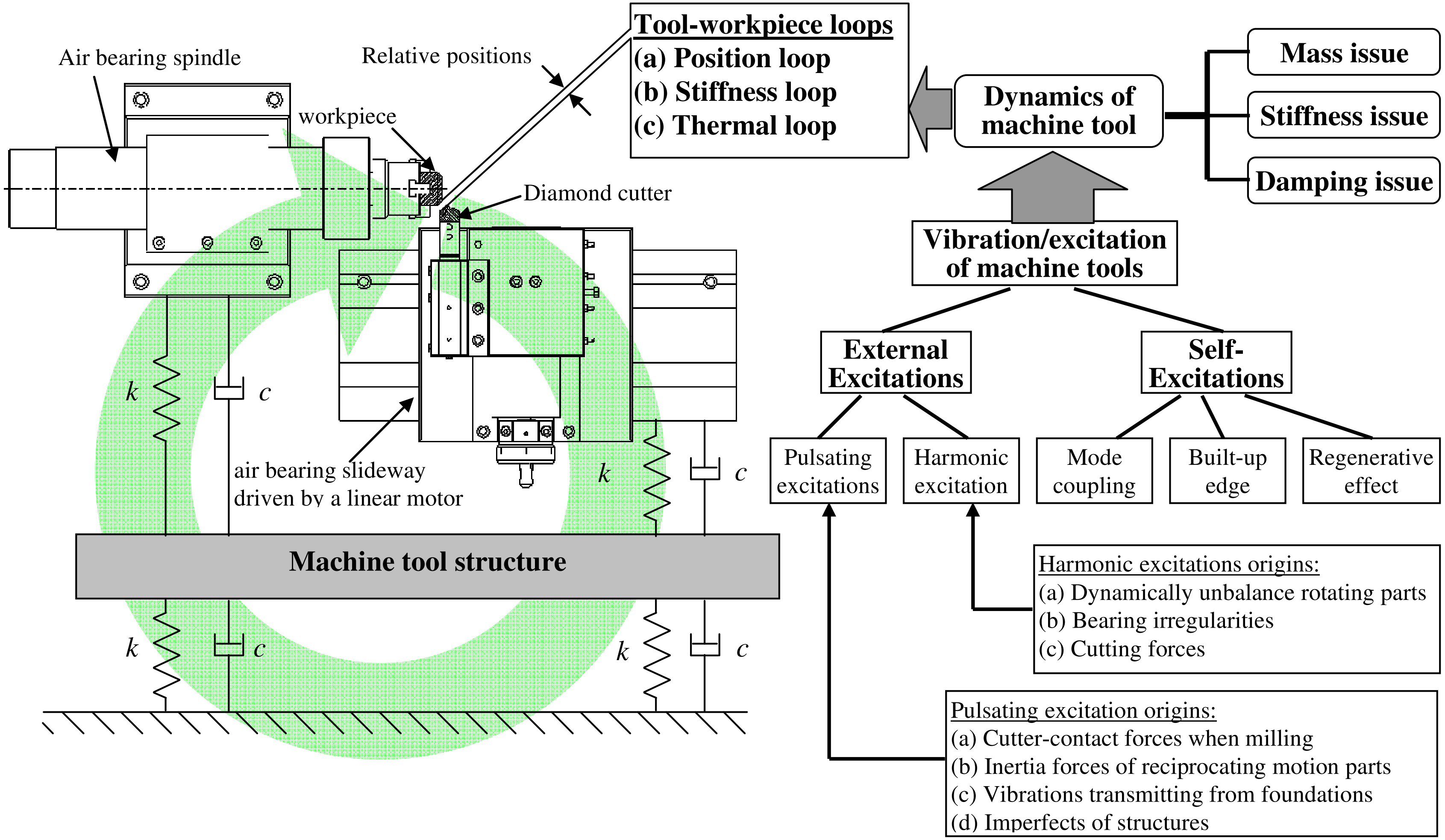


Figure 2. Machine tool loops and dynamics of machine tools

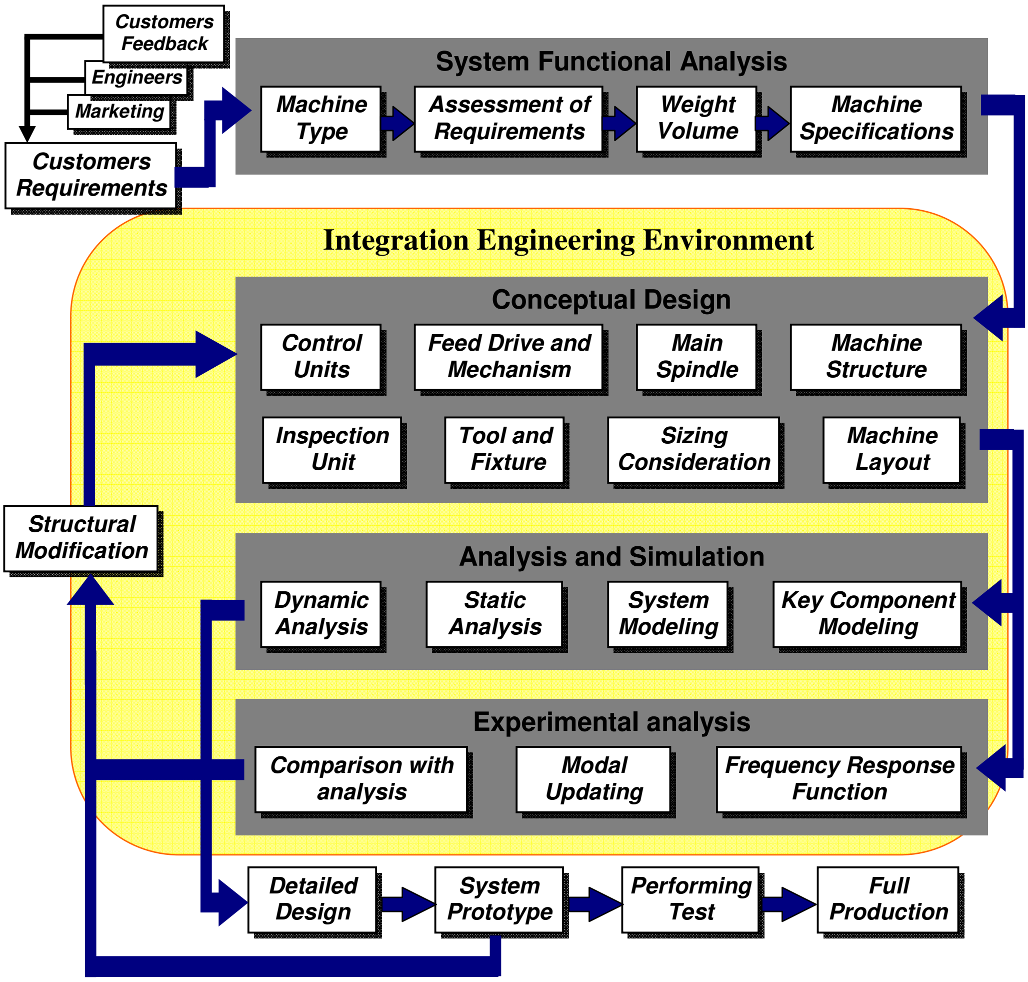


Figure 3. The precision machine design procedures

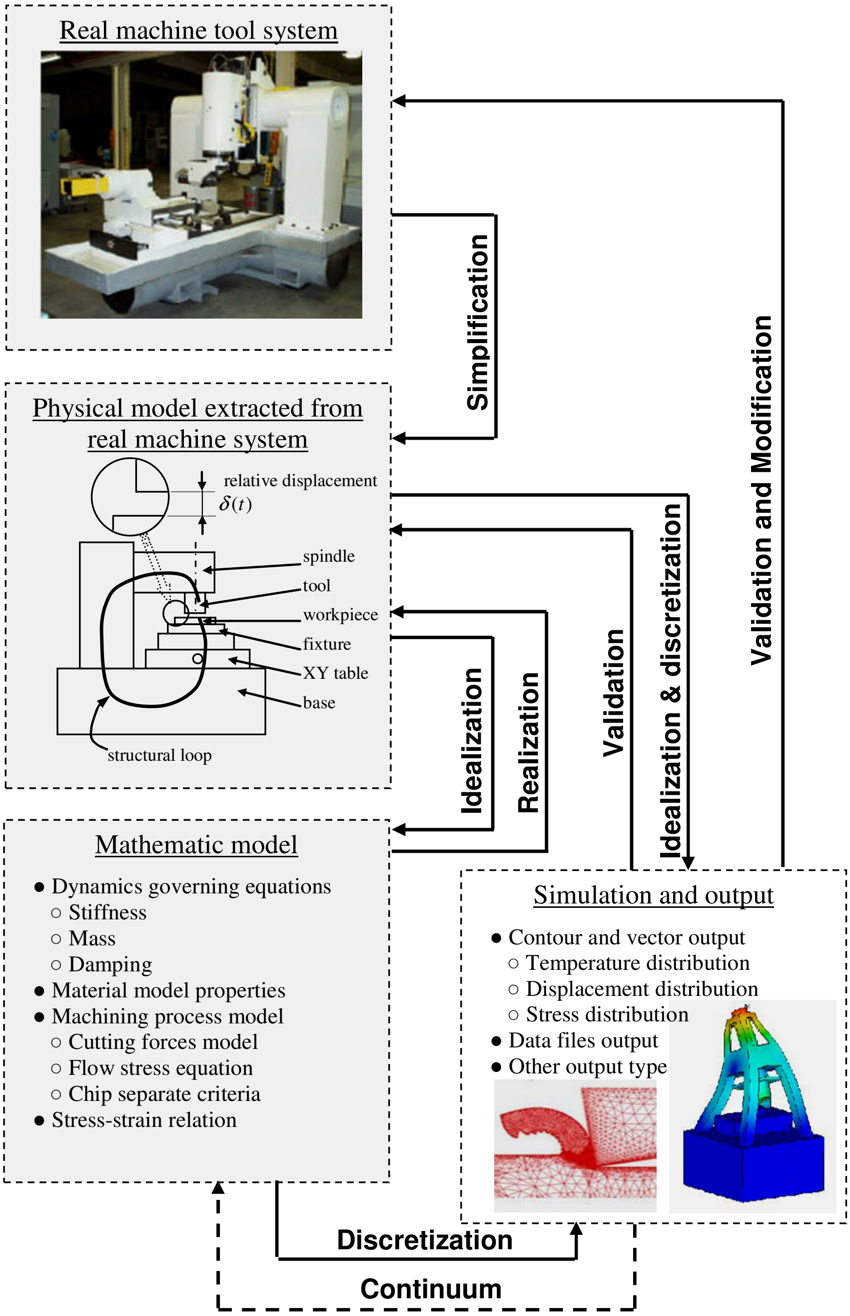


Figure 4. A general modelling and simulation approach

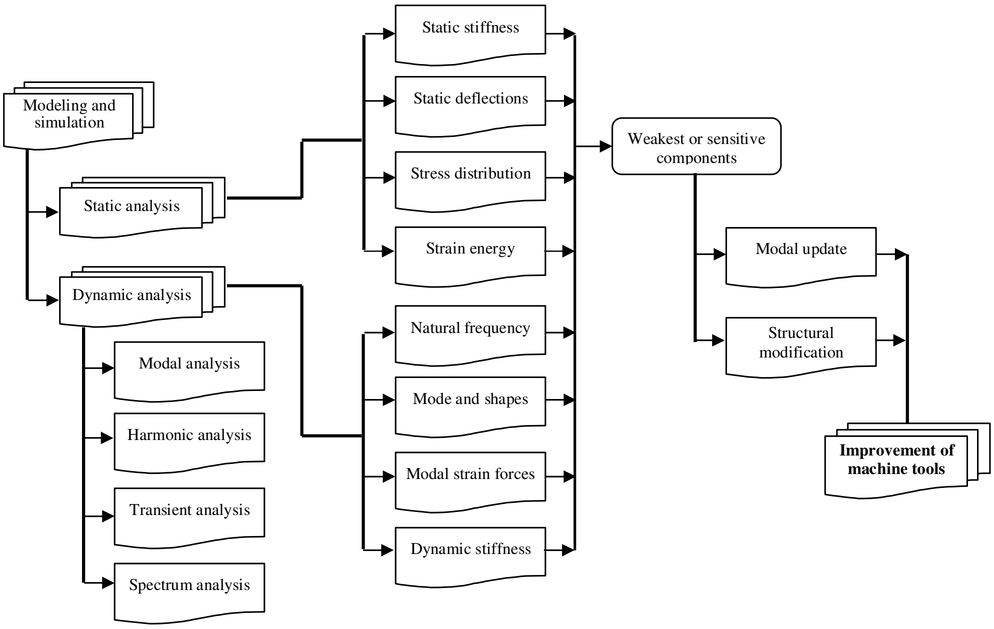


Figure 5. Overview of machine tools analysis

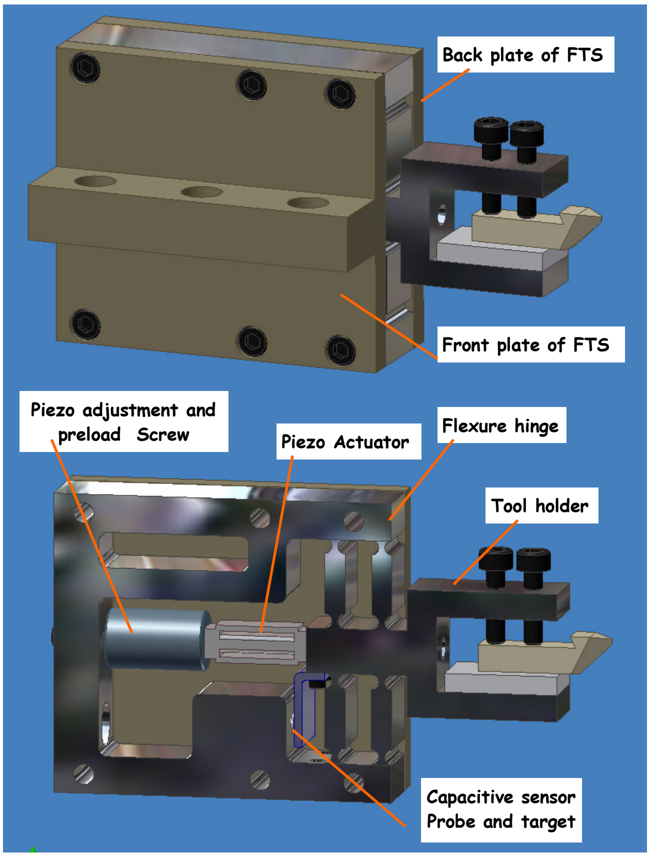
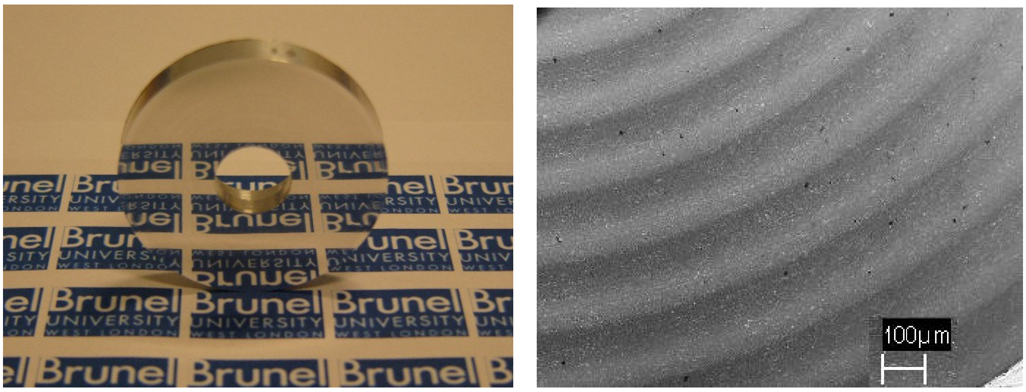


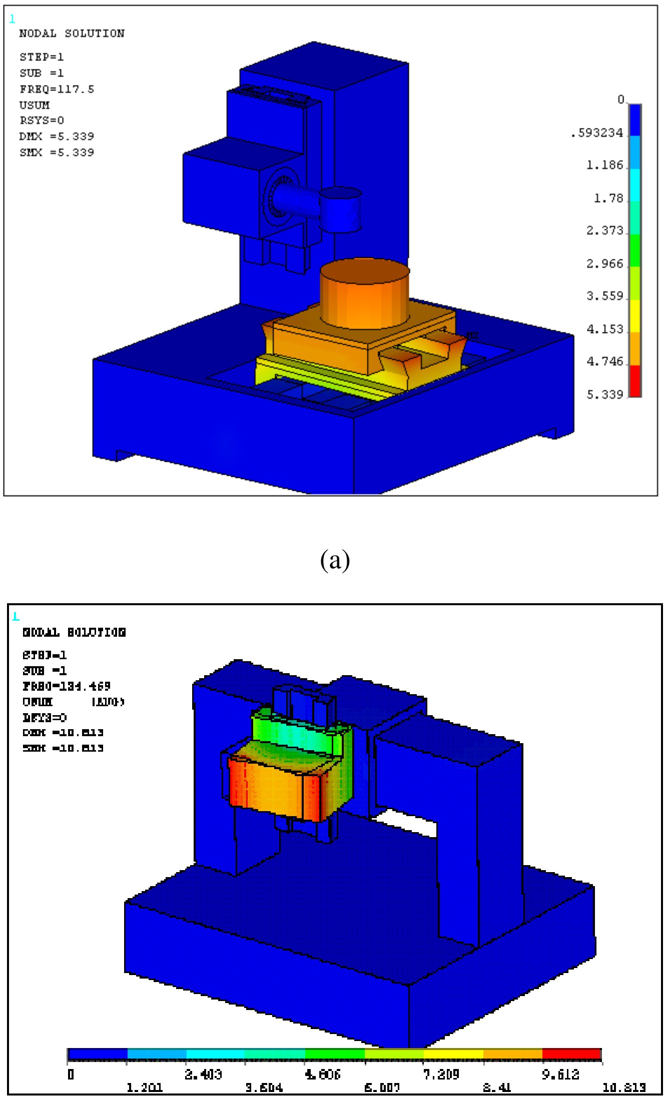
Figure 6. The schematic view of the FTS



(a) (b)

Figure 7. The finished surfaces of Aluminum components

(a) Mirror-like surface by face turning (b) Sine wave micro-featured surface cut by the FTS



(a)

(b)

Figure 8. FEA results on the 5-axis micro milling machine

(a) First natural frequency and its mode of origin configuration

(b) First natural frequency and its mode of gantry configuration

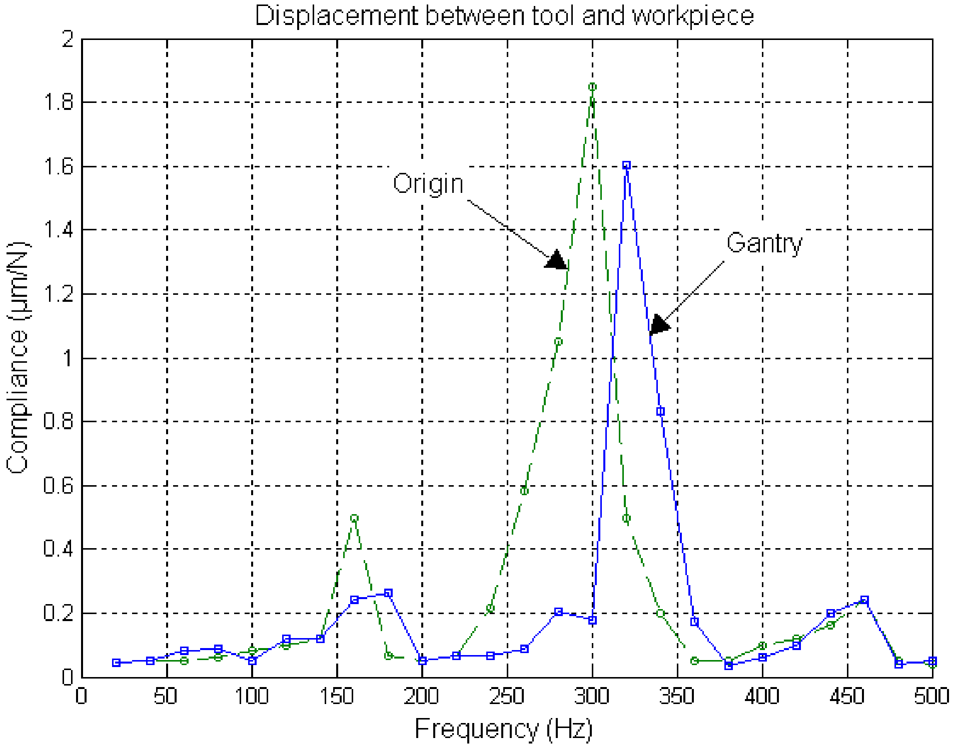


Figure 9. Harmonic response on the 5-axis micro-milling machine

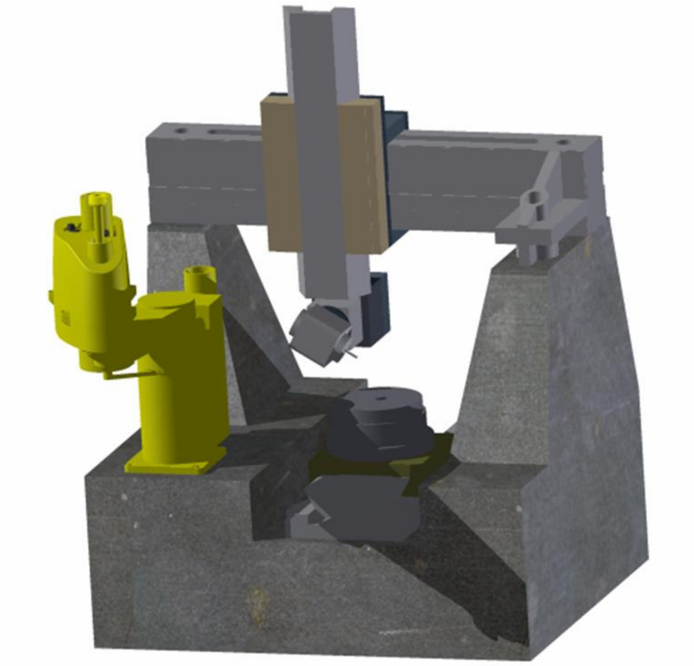


Figure 10. The final gantry 5-axis micro milling machine configuration

Table 1. Initial specifications of the 5-axis milling machine tool

Configuration	5-axis CNC micro-milling machine			
Base	Polymer Concrete			
Axes	X, Y and Z axis	B axis	C axis	Spindle
Type	Aerostatic slideway	Air bearing	Air bearing	Air bearing
Stroke	X:200mm Y:100mm Z: 50mm	360°	360°	N/A
Stiffness	>400 N/µm	N/A	N/A	50 N/µm
Motion accuracy	Straightness (µm/mm): X, Z<0.01/200, Y<1.0/250	Radial/Axial run out (µm): <1/0.5	Radial/Axial run out (µm): <0.1	≤ 10 nm
Resolution	1nm	0.000001°	0.00001°	N/A
Drive system	Linear motor	Servo motor	Servo motor	DC brushless motor
Maximum speed	N/A	N/A	N/A	300,000 rpm