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Development of Integrated Design System for Structural Design of Machine Tools

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Abstract: The design process of machine tools is regarded as a sequential, discrete and inefficient process, as it requires various kinds of design tools and many working hours. This paper describes an integrated design system, embedding a design methodology that can support systematically the structural design and analysis of machine tools. The system is a knowledge-based design system and has three machine-tool-specific functional modules, including: configuration design and analysis, structural element design, and structural analysis support module. A machine configuration appropriate for design requirements is selected using the configuration design and analysis module. The arrangement of ribs for each structural part is then decided in the structural element design module. The structural analysis support module converts the design result into script file which is used to evaluate the designed structure by utilizing FEA software "ANSYS." The system is applied to the design of a tapping machine, and shows that the machine structure can be designed quickly and conveniently with minimum dependency on the capability of a design engineer.

Keywords: Integrated Design System, Machine Tools, Structural Design, Structural Analysis, Knowledge–based Design System

45.1 Introduction

The machine tools dominate over the quality of machine elements and, consequently, affect the development of other machinery. The design technology of a machine tool requires complicated and diversified design knowledge. Also, it evolves over a long period by accumulating designers' experiences and knowledge, rather than by revolutionary advances in a short period.

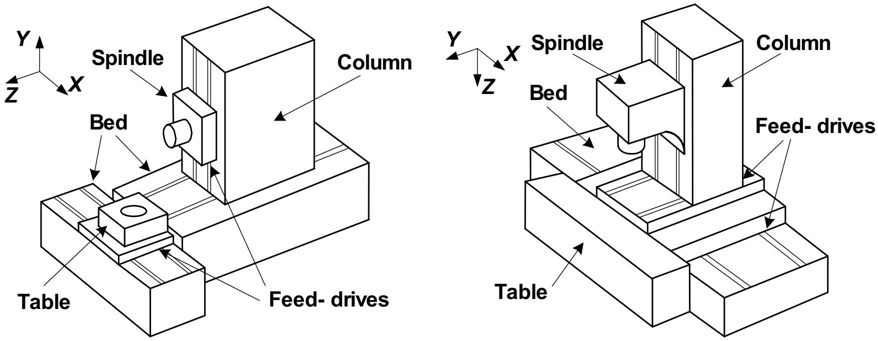
The machine tools are required to have properties of high speed and accuracy. To realize these requirements, light weight and high stiffness of structural parts, such as bed and column, are essential along with the quality function of each unit part [6, 7]. CAE analysis is indispensable to estimate the structural stability and dynamic behaviour of a machine tool. Much research to integrate design and analysis has been carried out actively [3, 7, 8, 9], and commercial CAD/CAE systems such as I-DEAS, and Pro/E have been developed. However, these are general-purpose systems, and thus exclusive functions for machine tool design are feeble. Also, in order to get reasonable results from CAE analysis, a design engineer must establish proper finite element model and boundary conditions, and therefore it is very difficult for a design engineer to use CAE functions without any help of CAE engineers.

In this research, an integrated design system, ICAD/TM, has been developed by applying a knowledge-based system [1, 2, 4, 5], by which a design engineer can design and analyze structural parts of a machining centre easily and quickly with no help from CAE experts. The system has three functional modules - the configuration design and analysis; the structural element design; and the structural analysis support module. The function of the configuration design and analysis module is to select the appropriate machine configuration and decide key outer dimensions. The selection is carried out by knowledge inference. The structural element design module is to design the internal structure of bed and column with the arrangement of ribs for reinforcement. The function of the structural analysis support module is to generate a finite element model including boundary conditions of the designed machine structure for ANSYS software with a simple interactive procedure. The system enables a designer to evaluate the alternatives swiftly and to select an optimum design in the early stage of development due to its simplified process of integrating design and analysis.

45.2 Integrated Design of Machine Tool Structure

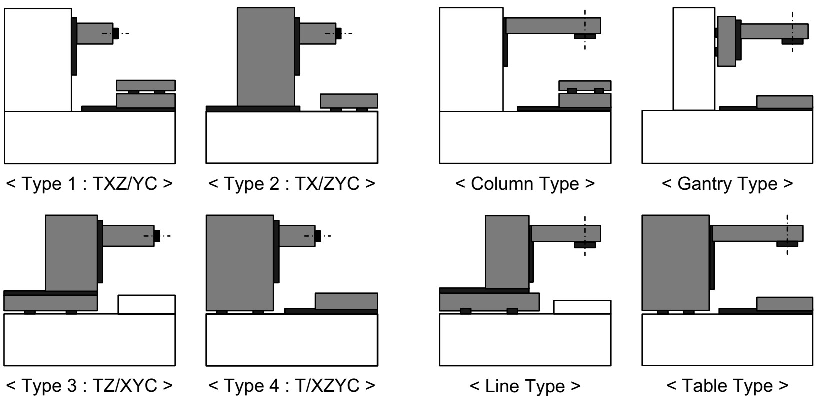
The Machining Center and the Design Process

Generally, a machining centre for the representative machine tool is composed of several unit parts, such as a supporting unit including bed and column, a main spindle, a feed-drive unit for positioning, and accessory parts including the magazine, tool changer and controller. The main spindle unit is attached on the column, and the workpiece table and column are put on the bed as shown in Figure 45.1. The machining centres are roughly classified into horizontal and vertical styles of machines according to the direction of the spindle axis, and various detail types are possible according to the feeding direction of the column and whether or not the column is fed. The spindle direction of the horizontal machine tool is horizontal, and chip removal is easy since most cutting chips are dropped right under the cutting tool. On the other hand, the vertical machine tool has a vertical spindle, and moving the cutting-tool to a machining position and loading/unloading of the workpiece are easy. Eight types of machine tools - four horizontal and four vertical types as shown in Figures 45.2(a) and 45.2(b) - can be designed and evaluated by using the developed system.



(a) Horizontal machine tools (b) Vertical machine tools

Figure 45.1 Typical configuration of machine tools



(a) Types of horizontal machine tools (b) Types of vertical machine tools

Figure 45.2 Types of machine tools

Usually, the design of a machining centre starts with the selection of the appropriate style and type based on customer requirements or goal specifications, and then basic configuration of the machine tool and principal dimensions of structural parts are decided and evaluated by static a and dynamic analysis program. Following this, each unit part of the machine tool is designed and evaluated based on the acceptable configuration of machine tool. Once the design of each unit part has been completed, analysis of the machine configuration is carried out once more in order to ensure the static and dynamic stability. In this paper, the design of the spindle and feed drive unit are excluded, and the part related to the design and analysis of the machine structure only is described.

Integrated Design of Machine Structure

Figure 45.3 shows the process of design of the basic structure and supporting elements of the machining centres by using ICAD/TM. The developed system has the functions for configuration design, modal analysis on machine configuration, rib design, and interfacing for FEA. These tightly interfaced function modules enable a coherent flow of information during the process of design and analysis.

The basic machine structure is designed based on design knowledge in accordance with the process defined in the configuration design module. The modal analysis module, which is the dedicated analysis program, is used to assess dynamic characteristics of the structure. If the structure is judged to be inappropriate, the location, size, and type of elements are rearranged interactively according to the result of the assessment. The design change is repeated until the structure is configured satisfactorily. Then, the ribs are allocated inside the structural elements, like bed and column, using the rib design module. Upon completion of the rib design, the finite element model is generated by the module for model interface. The model is fed to ANSYS where the structural analysis by the finite element method is carried out. If the designed machine is considered to be structurally inappropriate, the design process is reactivated so that the goal specification is satisfied by changing configuration or inside structure. The integrated design system is intended to design and analyze the machine configuration and the structural elements following the consistent flow during the early stage of machine tool design.

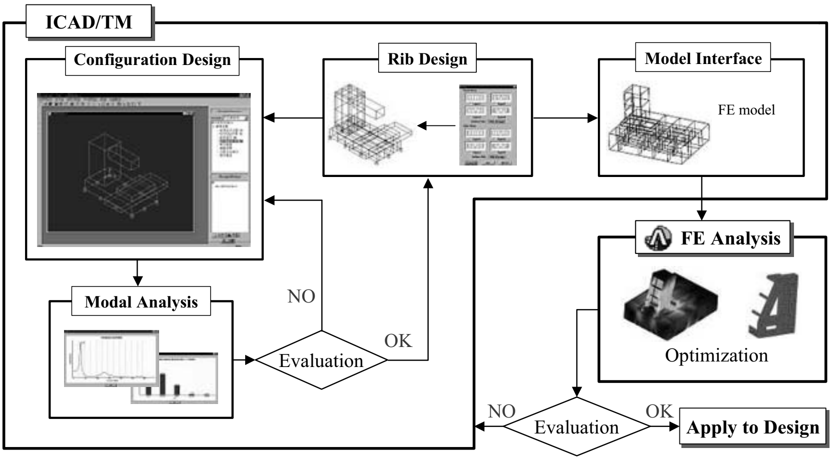


Figure 45.3 Integrated design and analysis flow of the system

45.3 Structural Design and Analysis of Machining Centers

Design of Machine Configuration

The goal of the design of machine configuration is to set up an appropriate machine structure for goal specifications with a decision for the machine type, and the sizes, positions, approximate weight, and materials of the structural components, as well as a structural evaluation of the machine structure. Through the interview with experts on machine tool design, the design process for the machine configuration has been analyzed and modelled using a structural analysis and design tool, called IDEF0 [10]. The design process embedded in the system is composed of several steps such as machine type selection, configuration design, and configuration analysis, and is managed by a design manager according to the sequence of steps to determine whether or not the design is changed.

In the machine type selection step, an appropriate type of machine for the customer requirement is selected first, based on the characteristics of each type of machine, and then the specific machine type is selected by inferring design knowledge on the required machine properties such as stiffness, cutting capability, occupying space and manufacturing cost, *etc.*.

The configuration design step is the process in which the sizes and positions of the structural component parts are determined, as well as the strokes of the feed mechanism. Usually all the dimensions of the machine configuration are determined in accordance with the size of the workpiece table. Therefore, the size of the workpiece table is decided first based on the size and weight of the workpiece and working load. Then the sizes and positions of the each structural component part are calculated in proportion to the size of the workpiece table by inferring the design knowledge such as stroke-decision formulae, size-decision formulae, and position-decision formulae. A suitable bed type is selected, based on the overall size of the machine and workpiece table, working load, and weight of the workpiece. Since the accessory components like tool magazine, tool changer, and controller box affect the dynamic behaviour of the machine tool, those sizes and positions are determined as well. In order to evaluate the machine configuration with structural analysis, the material properties and weight of each component part, as well as joining methods among component parts, are determined in the configuration design step.

The configuration analysis step estimates the dynamic behaviour of the determined machine configuration with a modal analysis that is embedded in the system. Once the machine configuration is evaluated as not suitable, the design engineer can change the machine configuration with re-execution of the design steps or modification of the sizes and positions of the components.

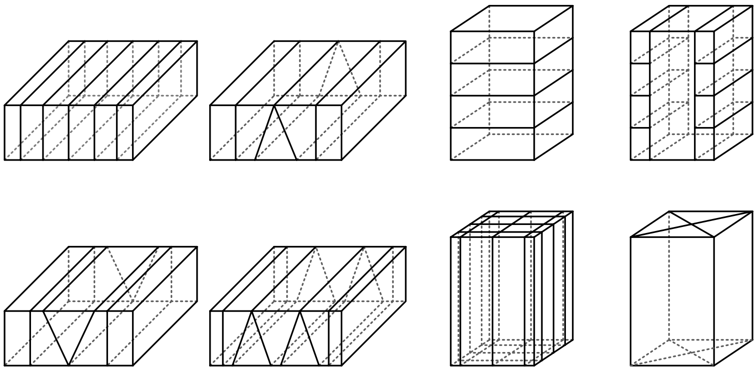
Design of Structural Elements

Design of structural elements such as bed and column is an important process as the assembled structure greatly influences the machining accuracy and stiffness. Bed and column are basically shell structures with ribs inside for reinforcement.

The shape and location of the ribs are decided by the designer's intention to make the structure stiff while keeping it light.

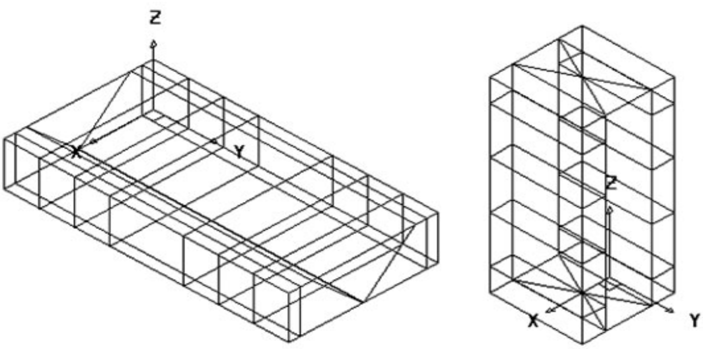
The library of basic shapes and the arrangement of ribs were set up based on the analysis of patterns of beds and columns. The design of the ribs is carried out by selecting and combining the basic patterns according to the maximum cutting force, weight of the workpiece, and size of the machine. This enables the design of various structures of ribs to be done swiftly and efficiently. There are four basic patterns of bed and column, respectively, in Figure 45.4.

The basic patterns of bed are selected for the shapes of the front view and the side view. The patterns for column are the basic shapes of the front and the top view. Considering the characteristics of column, types 1 and 2 for a shape of the front view, and types 3 and 4 for a shape of the top view are selected. Each basic pattern has the parameters for defining the location and number of ribs, which are assigned interactively during the design process.



(a) Basic rib patterns for bed (b) Basic rib patterns for column

Figure 45.4 Basic shapes and arrangement of ribs



(a) Bed design (b) Column design

Figure 45.5 Design examples of bed and column by combining basic patterns

Figure 45.5(a) shows an example of the design of bed structure by combining type 3 and type 1. In the case of Figure 45.5(b), the front of the column is shaped the same as type 2 and the top view has the pattern of type 4. In order to lighten the walls and ribs, holes can be applied at the middle of those elements. The pattern, shape, number, and location of the holes are defined by assigning values interactively to the parameters representing them.

Analysis of Machine Configuration

Analysis and evaluation of the design result are necessary in order to predict the static and dynamic characteristics of the structure. The analysis module consists of configuration analysis and support for finite element analysis.

Machine configuration can be optimized through the analysis of the vibration characteristic and energy distribution. The structure is modelled as in Figure 45.6 using four simplified elements – node, beam, spring, and support. In modal analysis, the maximum amplitude of the node where the cutting force is applied at a natural frequency up to the 10^{th} mode is predicted. Based on the modal analysis, potential and kinetic energy of each element are calculated, which show the degree of deformation and dynamic appliance.

Therefore, the configuration analysis is used to estimate the maximum dynamic deformation and the degree of displacement of each component part of the machine. Natural frequency of the structure predicted from the analysis is used to select the stable range of spindle speed so that resonance may not occur. The machine configuration is modified in order for each component to have uniform energy distribution by changing the position and size of the component, because the more a component has potential and kinetic energy, the higher the displacement and dynamic compliance of the component.

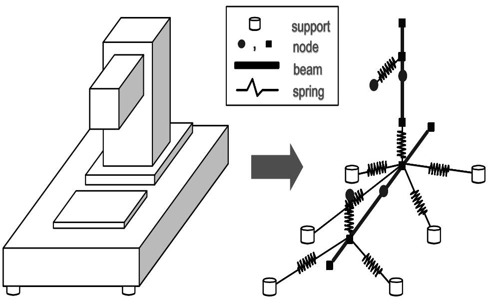


Figure 45.6 Modelling for modal analysis

Figure 45.7 Contents of the script file

Support Function for Finite Element Analysis

The function of the supporting FEA is to generate an analysis model of the structural elements for evaluation of static stability through finite element analysis. FEA is regarded as the most appropriate method to evaluate the stability and dynamic behaviour of machine structure, and many proven commercial systems are available. Therefore, it is sensible to utilize the commercial system for reliable and useful results.

However, to evaluate the structural elements through the commercial system, the assistances of FEA experts is necessary because the structural elements should be modelled interactively in the system, and the information on load, boundary condition, and method for mesh generation should be defined as well in accordance with the characteristics of structural elements. It is not easy for a designer with little experience in FEA to conduct the process of design optimization, which is the iteration of the evaluation and the modification of the design with an evaluation result.

Therefore, the function of interfacing design with analysis has been developed to support FEA on the design result. The analysis model including information relevant to the structural analysis of the designed machine tool is created as a script file for ANSYS. The interface enables less experienced engineers to carry out analysis using ANSYS by providing the script file with no special manipulation. The analysis model created by the system consists of shell elements since the machine tool is modelled as in the form of a plate structure. Analysis models for bed and column are created separately.

The model file includes information on shape, load, boundary condition, and generation of finite elements as shown in Figure 45.7. The shape information of the design structure is created by defining the vertices and cross points of intersection lines among the ribs as sequential key points. The areas are defined by linking the numbers assigned to the key points, and then the shape is defined using those areas. Loading information is defined through calculation of self-weight and machining force according to the type of machining centre. The boundary condition is given depending on the method for combining structural elements. Then, the commands for generating finite elements, executing analysis, and issuing results are written in the analysis model file. The structural analysis can be started by simply feeding the file to ANSYS, and the result of the analysis is available with little delay.

45.4 Implementation of the System

The architecture of the design system developed is as shown in Figure 45.8. The knowledge base established through analysis of the design process and the interview with design experts is systematically managed by the knowledge manager. The design manager controls the design process according to precedence, activates the inference engine, visualizes the design result by Parasolid modeller, and stores the result as design history. The design analyzer evaluates the dynamic characteristic of the machine configuration. The model interface generates a geometric model of the designed machine tool and the analysis model file for ANSYS.

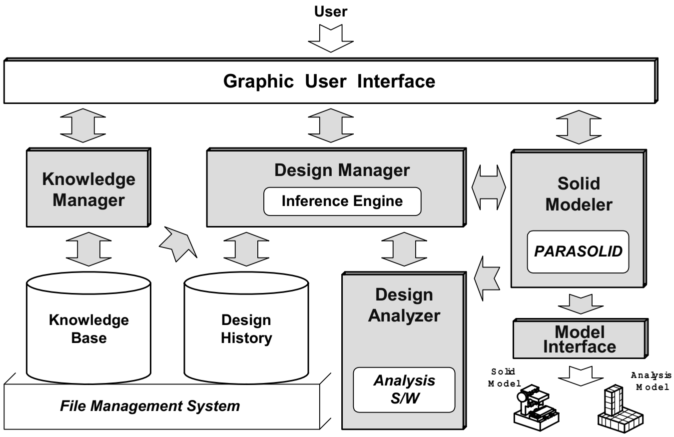


Figure 45.8 Functional architecture of the system

Figure 45.9 shows the main screen of the ICAD/TM system implemented by using Visual C++ 6.0 and Open GL. The menu for supporting functions like the management of the design project, design knowledge, and the modeller are allocated at the upper end of the screen. The area for the management of the design process and design history are on the right, and the functions for producing results through a geometric model and analysis model are on the left. The design process of each module is selected at the design management area, and the current status is shown by the icon as the design progresses. The design version and the composition part of the version can be inquired about through the history manager. A change of design is possible through reprocessing the pertinent stages. It is also possible, using the correction function of the solid modeller, but in that case, the processes following the changed part must be made invalid and the icon representing the design status must be changed interactively.

45.5 Design Instance

The system was applied to the design of the machine configuration and structural elements of a tapping machine. The design started with a selection of the type of machine. Inputting design requirements through the dialog box, the system recommends the most appropriate type of configuration. In the example of Figure 45.10, the ‘line type’ was selected when stiffness, cutting capacity, and manufacturing cost were given priority. When maximum size and weight of the workpiece, and maximum cutting force are given as 800 (mm) x 1000 (mm), 200 (kg), and 50 (kg), respectively, the table size and key outer dimensions of the machine are automatically decided by the system, as visualized in Figure 45.10. According to the modal analysis of the basic structure, maximum amplitude is expected to be 1.58 (mm) at 5Hz, as in Figure 45.11. Therefore, the designer can reduce maximum compliance, or adjust the location where the maximum compliance occurs, by changing the design based on the result of analysis.

Resonance can also be avoided, reflecting the result of the analysis, during the design of the spindle and considering the elements related to vibration. Energy distribution among the units is checked and the size and location of the unit are modified so that potential and kinetic energy are not concentrated in a certain part. The optimal structure satisfying the design requirement can be decided at the early stage of design through this analysis process.

Figure 45.12 shows the process of rib design where a basic pattern is chosen and design parameters for the arrangement of the ribs are input. Figure 45.13 shows the result of the structural elements design. In this example, type 1 is adopted as the basic pattern for both the front and side view of the bed. Type 2 and type 3 were taken for front and top views of the column. By the combination of those patterns, the internal holes are also designed with a rectangular shape.

The design result can be exported to the analysis model file through the model interface function. By reading the file with ANSYS, without any additional modelling or parameter setting, structural analysis can be carried out as shown in Figure 45.14. A designer learns that the maximum displacement of the design column is 103 (μm), and changes the configuration or geometry of the rib if reinforcement is required. Therefore, even a designer not familiar with structural analysis can evaluate the stability of his design quickly and conveniently, and reflect the evaluation of the design.

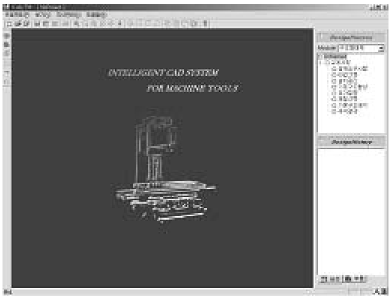


Figure 45.9 Main window of the system

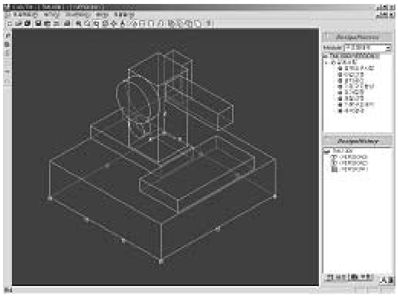


Figure 45.10 Design of configuration

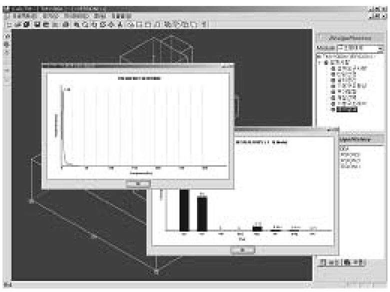


Figure 45.11 Results of modal analysis

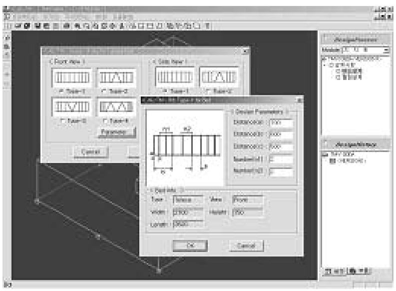


Figure 45.12 Process of rib design

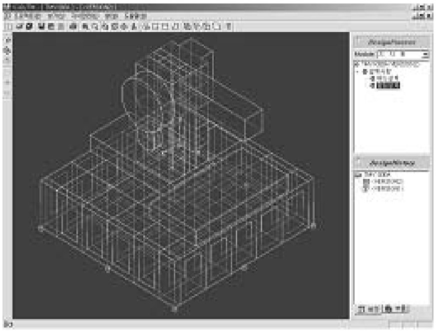


Figure 45.13 Structural element design

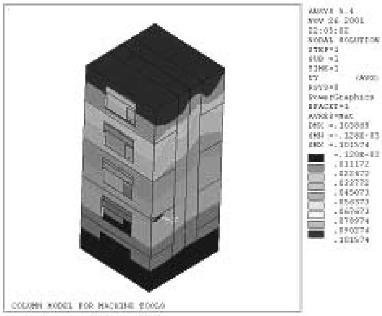


Figure 45.14 Result of FEA of column

45.6 Conclusion

An integrated design system enabling efficient design and swift evaluation of machine tools structures has been developed. The system has been implemented by integrating configuration design and analysis, and structural element design and analysis. During the process of design and analysis, human dependency could be minimized by establishing a knowledge base and decision making algorithm for design, analysis, and preparation for analysis. The implemented system was proven efficient and convenient while the system was used by design engineers developing a new model of tapping machine.

45.7 References

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