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Development of a Tool for Automation of Analysis of a Spindle System of Machine Tools

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공작기계 주축 시스템의 해석 자동화를 위한 툴 개발

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ABSTRACT

In this research, a tool was developed for the rapid performance of three-dimensional finite element analysis (3D FEA) of a machine tool spindle system made of a shaft and bearings. It runs the FEA with data, such as the bearing stiffness and the coordinates of the points, to define the section of the shaft, bearing positions, and cutting point. developed for the spindle system and then implemented with the tool using an object-oriented programing technique that allows the use of the objects of the CAD system used in this research. Graphic user interfaces were designed for a user to interact with the tool. It provides rapid evaluation of the design of a spindle system, and therefore, it would be helpful to identify a near optimal design of a spindle system based on, say, static stiffness with design changes and, consequently, FEA.

Keywords : Finite Element Analysis(유한요소해석), Graphic User Interface(사용자 인터페이스), Optimal Design(최적설계), Spindle System(스핀들시스템), Tool Development(툴개발)

1. Introduction

A shaft, an arrangement of bearings, and a housing are the key components to construct a spindle system and thus highly affect its performance such as cutting accuracy and the removal efficiency. Recently, machine tools have required high speed, high efficiency, and high precision and, therefore, their spindle system has been required to be designed for a high technical performance including dynamic stiffness and precision for cutting[1,2]. Dynamic stiffness is highly determined with mass and static stiffness. Thus, the key components need to be designed to have low mass and high static stiffness.

The performance of a spindle system such as stiffness or thermal characteristics[3-5] is evaluated using finite element analysis (FEA). The spindle system including its shaft and bearings is fully designed into three-dimensional (3D) configuration in a computer-aided design (CAD) system and, therefore, can be evaluated based on 3D FEA using solid

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elements for the shaft and spring elements for the bearings.

3D FEA has some advantages against 1D FEA. An advantage is that the 3D model can be used directly to generation of 3D finite solid elements without conversion into 1D beam elements with different cross-sections. If a certain segment of the shaft is variable in cross-section, it is necessary to divide it into smaller elements of 1D beams with different cross-sections for compensation of the cross-section variation.

In this research, an analytical model was developed for 3D FEA of a spindle system composed of a shaft and bearings and was implemented into a tool to automate the FEA. The VBA (Visual Basic for Application)[6] embedded in the CAD system, CATIA[7] provided the environment of object-oriented programming (OOP)[8] and accessibility to many objects of the CAD system regarding geometric modeling, FEA and others. Graphic user interfaces (GUIs) were designed for a user to interact with the tool with ease. It would be helpful for design engineers to identify an optimal design of the spindle system for its shaft and bearings by making design changes and consequently performing FEA. Besides, it is expected to save time and efforts for the evaluation of the spindle system under design.

2. Development of an analytical model

2.1 Configuration of a spindle system

A typical direct-connection spindle system[5], shown in Fig. 1, is normally composed of a shaft, bearings, a housing, and a motor. The shaft is connected directly with the motor with a coupling. Thus, the motor does not make a considerable contribution to static stiffness of the spindle system as it is fixed with the housing whereas the cutting tool heavily contributes to the stiffness due to the bending moment proportional to the distance from the cutting location to the shaft tip.

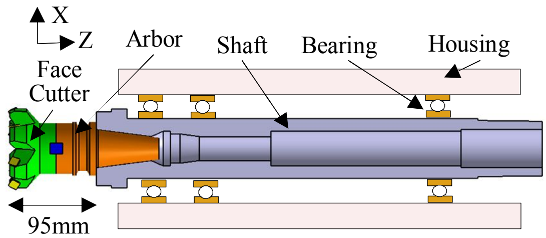


Fig. 1 Configuration of a spindle system

Therefore, the shaft, the bearings, especially, their stiffness and location, and the cutting tool, especially, its location heavily determine the static stiffness of the spindle system.

2.2 Development of a analytical model

As shown in Fig. 2, an analytical model was developed for FEA of the spindle system in Fig. 1. The shaft of the spindle system is meshed into solid elements. The tetrahedral element of 10 nodes is selected and its size is half of the minimum thickness in the section for analysis accuracy.

The bearings are converted into spring elements with bearing stiffness in radial and axial directions. A center point is made to be rigidly connected with its corresponding bearing seat of the shaft. Despite rigid connection, the bearing seat is deformable to allow the shaft to be bent at the bearing support. A spring element is constructed at the point and then, the boundary constraint is applied to the spring element to be fixed in translation in X, Y, and Z directions, respectively. The shaft is fixed at the end in Z rotation. These boundary constraints prevent the spindle system from the rigid motion in all directions in translation and rotation.

The cutting tool is replaced with a rigid connection with the tip of the shaft in order to accommodate the cutting force of -1,000N for static stiffness. The tool developed in this research automates the process of generation of the analytical model in Fig. 2 including the rigid connection for bearing springs.

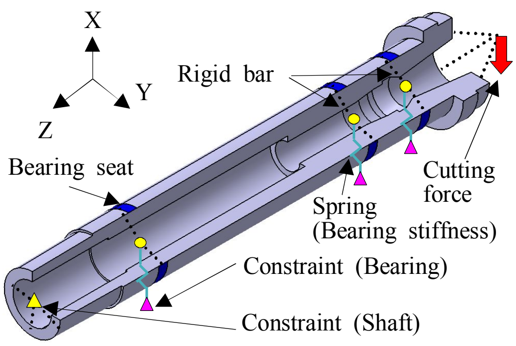


Fig. 2 Analytical model for the spindle system

2.3 Procedure of FEA of the spindle system

Fig. 3 shows the procedure for the FEA of the spindle system composed mainly of a shaft and bearings at a CAD system with FEA environment such as CATIA in this research. Points are generated to define the location of the bearings and the section of the shaft, which revolves into a solid of the shaft. Material is manually applied from CATIA material interface with use of 'drag and drop'.

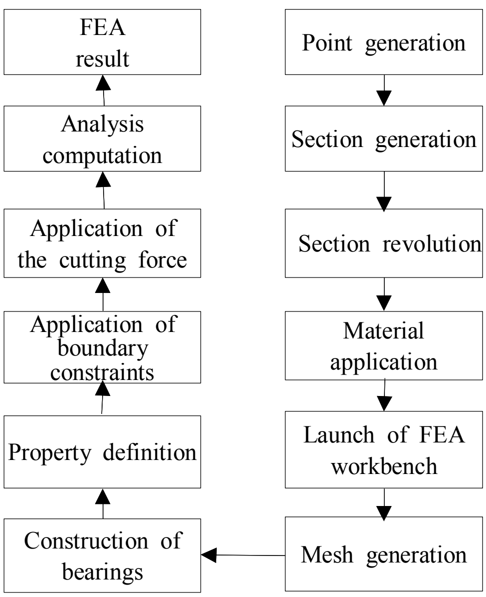


Fig. 3 Procedure of 3D FEA of Spindle system

The FEA workbench is launched and the shaft is meshed into finite solid elements. Spring elements are constructed for the bearings and connected with the bearing seats of the shaft. Property is defined for the solid elements of the shaft, The boundary constraints are applied to the bearing springs and the end of the shaft and the cutting load of -1,000N is applied to the cutting point in X direction. The cutting force is constant because it is a linear analysis to obtain the static stiffness of the spindle system.

All the analytical data applied to the geometric elements such as bearing seats is transferred to their corresponding finite elements and then computation is performed to produce node displacements. The FEA workbench displays the result of FEA such as displacement or stress.

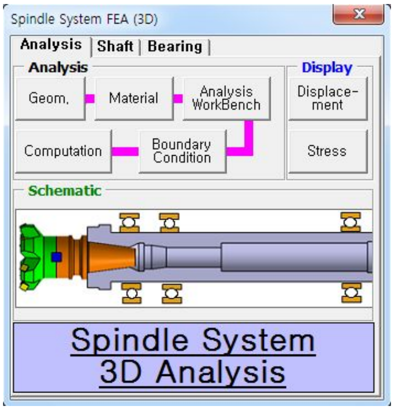
3. Development of an automation tool

The analytical model in Fig. 2 and the FEA procedure in Fig. 3 were implemented into a tool to automate FEA of a spindle system. The tool has some modules to generate a geometric model at the geometry workbench and a FE model at the FEA workbench. It also exchanges data with the external system of data arrangement, EXCEL[9]. The user interfaces developed allow the tool for the data exchange.

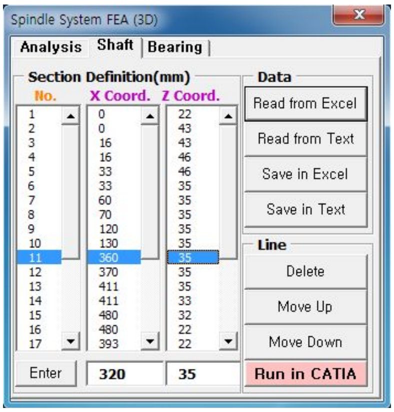
3.1 Development of graphic user interfaces

Graphic user interfaces (GUIs) shown in Fig. 4 were developed for the tool in this research. They allow a user to interact with the tool by placing commands and receiving responses. 'Multi-Page' of VBA was used for the GUIs to be designed to take a small space to accept minimum information for FEA and not to cover the main GUI of the CAD system.

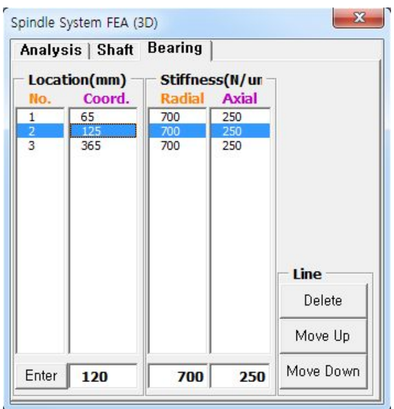
The GUI in Fig. 4 (a) provides some command buttons to perform the FEA process of generation of geometric and analytical models and to display analysis results at the workbenches. A shaft is defined with the section determined with the data input in the GUI in Fig. 4 (b). The GUI in Fig. 3 (c) accepts bearing information including position and stiffness.



(a) GUI for analysis performance



(b) GUI for shaft definition



(c) GUI for bearing definition

Fig. 4 Graphic user interfaces

3.2 Algorithms for the automation tool

Some algorithms were developed to automate of the FEA process of geometric and analytical model generation. Although VBA is embedded in the CAD system, it has a limited access to its objects. The system has scripting function of 'Macro' to record a series of tasks in script and run it for repetition. 'Macro' has a better accessibility to certain objects such as the object, *arrayOfVariantOfShort1* in Table 1 to launch the FEA workbench. VBA cannot use the object but 'Macro' does. Some macros were written to automate the process of the FEA and are externally executed by the tool.

An algorithm was developed to select the face for rigid connections of the bearings and the cutting force, respectively. The FEA workbench prevents the boundary condition from being applied to finite elements or nodes and thus all analytical data shall be defined on geometries such as points and faces. Accordingly, the geometries should be identified automatically.

The algorithm used the rule of geometry generation of the CAD system with geometric naming. It memorizes the point numbers, defined at the GUI in Fig. 4 (b), and uses them to identify the cylindrical face, for example, made with revolution of 'Line 1' made of 'Point 1' and 'Point 2' shown in Table 2 and Fig. 5. It automatically replaces point or line numbers with those corresponding to other faces.

Table 1 CATIA object to provoke the FEA workbench

Dim arrayOfVariantOfShort1(0); *arrayOfVariantOfShort1(0) = 0;* *analysisManager1.ImportDefineFile "Part1.CATPart", "CATAnalysisImport", arrayOfVariantOfShort1;*

Table 2 Face selection based on lines and points

Dim reference1 As Reference; *Set reference1 =* *part1.CreateReferenceFromName("Selection_RSur:(Face:(Brp:(Shaft.1;0:(Brp:(GSMLineCorner.**1**;(Brp:(GSMPoint.**2**);Brp:(GSMPoint.**1**)))));None:();Cf11:());Shaft.1_ResultOUT;Last;Z0;G2703)");*

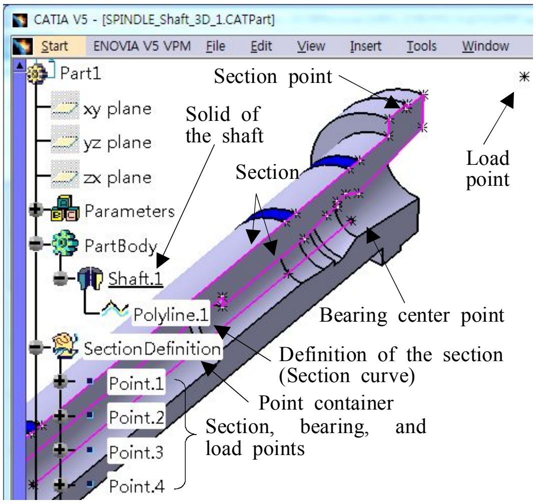


Fig. 5 Geometric elements generated for the spindle

4. Application of the automation tool

The spindle system, shown in Fig. 1, was used to validate the usefulness of the tool developed in this research. It automatically carried out the tasks of geometry generation and FEA making multiple containers to include the FE model of boundary constraints, properties, and others as shown in Fig. 6. The mesh container has ten-node tetrahedral elements of 5 mm in size and spring elements. All the containers are automatically registered in the tree as shown in Fig. 6. In addition, it constructed the rigid connections at the bearings, the cutting load, and the boundary constraint at the shaft end.

Fig. 7 shows the displacement of the spindle system composed of the shaft and the bearings after the FEA completion and Table 3 presents reaction forces and static stiffness. As seen in Fig. 7, the maximum displacement occurred at the load point for both of the spindle systems with 2 bearings or 3 bearings since the load was applied at the cutting point connected with the shaft tip. The sum of the reaction forces for each of the spindle systems has the same magnitude with the cutting force applied but the opposite sign.

The static stiffness is nearly the same for both 2-bearing spindle and 3-bearing spindle. This is because of the bearing stiffness of 700N/μm in radial direction[5] or the reaction force at the first bearing or both. The reaction force of the 3-bearing spindle is 22% greater than that of the 2-bearing spindle. The force could be reduced if the second bearing was moved closer to the first bearing and, therefore, could reduce the displacement of the first bearing consequently leading to an increase in the static stiffness.

The number, the location, and even the stiffness of bearings can be determined with more FEAs pursuing high static stiffness of the spindle system. The shaft also can be re-designed in geometry for high stiffness of the spindle system. These design changes should be evaluated in, for example, stiffness or manufacturing in order to identify an optimal design of the spindle system. This tool is helpful to perform rapid evaluation of spindle system designs in technical performance such as static stiffness with FEA. Moreover, it can reduce much of the time and efforts to perform the FEAs by automation.

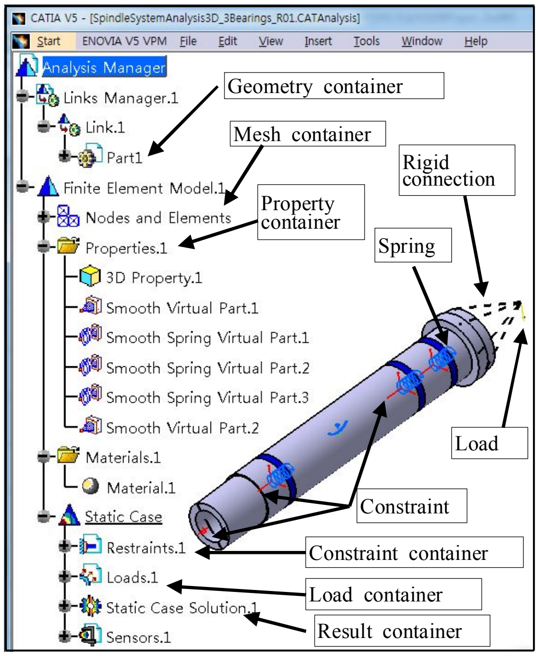
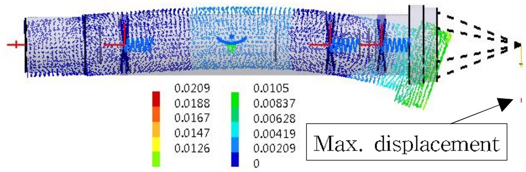
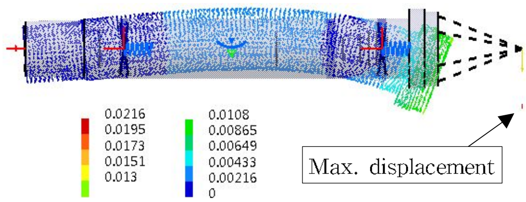


Fig. 6 Analytical model developed at FEA workbench



(a) Spindle of 3 bearings



(b) Spindle of 2 bearings

Fig. 7 Displacement of the spindle system (Unit: mm)

Table 3 Reaction force at the bearing points

No. of bearings	Reaction force (N)			Max. displacement (mm)	Static stiffness ($\times10^3$N/mm)
	B#01	B#02	B#03		
3	1,889	-432	-456	0.0209	48
2	1,543	-	-543	0.0216	46

5. Conclusion

A tool was developed in this research to automate three-dimensional finite element analysis of a machine tool spindle system under design. It was implemented in object-oriented programming technique at the programming environment of a CAD system to make use of its objects. It requires minimum data to be input in order to design a spindle system and to perform its FEA. They are bearing stiffness and the coordinate of the points to define the section of the spindle shaft and bearing locations. The tool would help design engineers to perform the FEAs that are usually performed by analysis engineers.

This tool can be used in search of a near optimal design of a spindle system based on an objective such as static stiffness or mass. The tool performs the design optimization by allowing design changes and FEA of the spindle system to be easily and quickly performed requiring the minimum geometric data and bearing information. Therefore, it can save a large amount of time and efforts for the design changes and the FEA in order to identify an optimal design.

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