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Finite element analysis for dynamic behavior of a machine tool structure fed in open loop control

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개루프제어로 이송되는 공작기계 구조물의 동적 거동을 위한 유한 요소 해석

최진우+, 이태홍*

Abstract

In this study, a finite element model was developed for analysis of feeding a structure in open loop control. The finite element analysis (FEA) can simulate dynamic behavior of the structure of a machine tool rapidly traveling with a screw feeding driving system. The feeding mechanism was implemented with screw element of the FEA tool used in this study. The procedure was developed for the dynamic transient FEA. First, motion parameters such as jerk and velocity were introduced for the structure to be fed in open loop control. When its traveling distance was determined, set-points for the distance were generated based on the motion parameters. The set-points were applied to the FE model constructed for the traveling structure. The FEA was executed and evaluated. In this study, the FEA procedure was applied to the column of a machine tool and the dynamic behavior of the column was evaluated. The FEA helps in evaluation of the motion characteristics of a structure. The convergence time of the structure vibration posterior to feeding termination can be estimated and the stiffness of the flexible structure is also evaluated against jerk, and acceleration. It provides the feeding force which is helpful in selection of the feeding motor.

Key Words : Finite Element Analysis(유한요소해석), Dynamic behavior (동적거동), Open loop control(개루프제어), Feeding mechanism(이송 메커니즘), Machine tool structure(공작기계 구조물)

1. Introduction

Machine tools have been developed to produce mechanical parts with a variety of machining and forming operations[1]. They include lathes, milling machines, and press machines. They should have a great accuracy to manufacture the mechanical parts in a specified tolerance. A machining center with computer numerical control

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(CNC) cuts a workpiece into a shape with many processes such as face cutting, end milling and drilling. Different tools are used for these processes and therefore, they are exchanged for each process. It is necessary to reduce the time consumed for the tool exchange in order to increase manufacturing efficiency. If the time reduced for tool exchange can be used for a manufacturing process such as drilling, it, therefore, leads to an increase in production rate.

A machine tool system is mainly composed of three groups of parts, which are structure group, drive group, and control group[3]. The structure group includes stationary parts such as beds, columns, and gear boxes and moving parts such as tables, slides, saddles, and carriages. The moving parts are carried on the stationary parts. The stationary ones have rails (guides) and the moving ones have shoes traveling on the rails. The drive group is composed of spindle and feed drives. The spindle drive produces the angular speed and torque required for cutting and the feed drive produces also the speed and torque required to carry a moving structure. The control group has motors, amplifiers, computers, and others. It may include control logics or algorithms. The torque of a servo-motor and its servo-control logic[4] in the CNC have a great influence on the feed velocity and positioning accuracy of a moving structure.

Stiffness of a structure puts a limitation on its rapid travel. High machining productivity requires rapid traveling of structures of a machine tool in order to decrease non-cutting time including movement time from one position to another. The rapid traveling is related to jerk, acceleration (deceleration), velocity and distance. Jerk is the derivative of acceleration with respect to time. Rapid traveling leads to deformation of a structure and that of other structures as well. A large deformation may break the shoes or the rails or lead to collision between the moving part and a stationary such as the automatic tool changer (ATC). Accordingly, it is necessary to make a quantitative evaluation for the deformation of a rapidly traveling structure.

In this study, a finite element (FE) model was developed for identification of the deformation of a flexible structure rapidly traveling in open loop control. Some research was carried out on feeding system[5-7] or deformation of rigid structures of a machine tool[8,9]. Use of rigid bodies may not be able to yield flexible deformation of a structure in analysis. In open loop control[10], motion parameters including jerk and acceleration are first determined and then, lead to generation of set-points for positioning a structure. The motor feeds the structure according to the set points. The FE model yields transient analysis to envisage the dynamic characteristics of the flexible structure in open loop control. The finite element analysis (FEA) enables the motion parameters, especially, jerk and acceleration, to be evaluated in suitability to the rapidly traveling structure.

2. Machine tool structures in open loop control

Fig. 1 shows feeding mechanism of open loop control for a machine tool. The column connected with the linear motion (LM) shoes is moved on the bed with the LM rails. The ball screw is connected with the bed and its nut is with the column. Its rotation leads to a linear movement of the nut and then, the LM shoes of the column are moved on the LM rails of the bed. The position and the velocity of the column is dependant on the position and the velocity controls. Open loop control

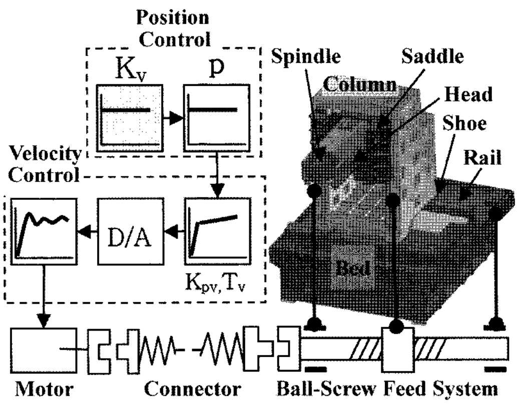
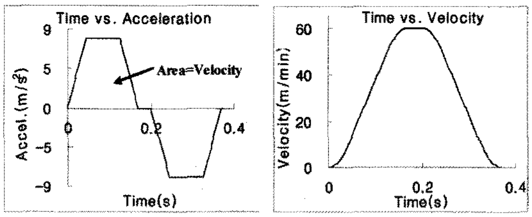
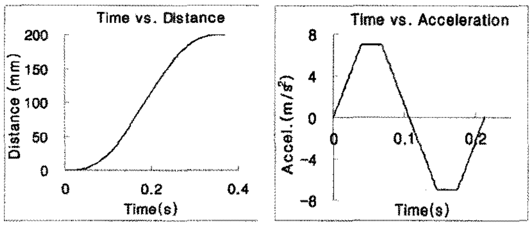


Fig. 1 Feeding system in control[11]



(a) Acceleration profile for a long distance **(b) Velocity profile for a long distance**



(c) Distance profile for a long distance **(d) Acceleration profile for a medium distance**

Fig. 2 Motion profiles for a long distance (200mm) and medium one (50mm)

uses set-points for column position and orders the motor to rotate the ball-screw in order to locate the column on the set-points.

Fig. 2 introduces jerk, acceleration, velocity, and distance(2). They are used to define set-points for feeding a structure in a given distance. A user defines jerk, maximum acceleration and maximum velocity in CNC for rapid feeding. When a feeding distance is defined, set-points are automatically calculated. For example, if jerk, maximum acceleration, and maximum velocity are $180m/s^3$, $8m/s^2$, and 1m/s (=60m/min), respectively, the distance of 200mm leads to 0.3694 sec. of the total traveling time and in addition, it can be seen from Fig. 2 (b) that the feeding of the structure is composed of ascending velocity from zero to 0.1694 sec., constant one to 0.20 sec., and descending one to the end of the traveling time. Again, the ascending velocity is composed of ascending, constant, and descending accelerations. As velocity is integration of the acceleration with respect to time, the maximum ascending velocity is the area of the trapezoid of the acceleration profile in Fig. 2 (a).

However, if a traveling distance is short, for example, 50mm, a constant velocity may not exist, as shown in Fig. 2 (d) because ascending velocity takes half of the total feeding distance during 0.2123 sec. and descending velocities take also the same quantity of the total distance. Accordingly, it can be seen from Fig. 2 that the set-points or the profile for a traveling distance is automatically determined with the magnitude of the jerk, the acceleration, and the velocity defined in CNC.

Jerk and acceleration are limited by the stiffness (or rigidity) of structures of a machine tool even if it is equipped with high-torque motors for feeding the structures. Although high jerk and high acceleration are good for rapid feeding (especially, velocity), they have a great influence on a traveling structure and its connected ones as well. As jerk is the slope of the acceleration profile in Fig. 2 (a), it indicates the degree of impact on the moving structure. High jerk leads to high degree of impact and then possibly breakage or large deformation in mechanical parts. Accordingly, jerk and acceleration need to be properly evaluated for structural deformation and also vibration to identify convertgence time for machining processes.

Appropriate servo-motors for feeding can be also determined with the jerk and the acceleration as their torque is highly related to them. The motor torque is converted by the ball screw into the linear force to move the traveling structure according to its specified velocity. The reaction force corresponding to the linear force is generated in the same magnitude but in the opposite direction. If the reaction force is obtained, the motor torque can be determined. Therefore, it is helpful to obtain the reaction force in selection of a motor.

3. Development of a finite element model

A finite element (FE) model was developed in this research to simulate dynamic behavior of a structure fed in open loop control. This dynamic FE analysis is used to evaluate jerk and acceleration determined for the feeding. The commercial FEA tool, ANSYS R12, is employed for the FEA. Its element of MPC 184 with the

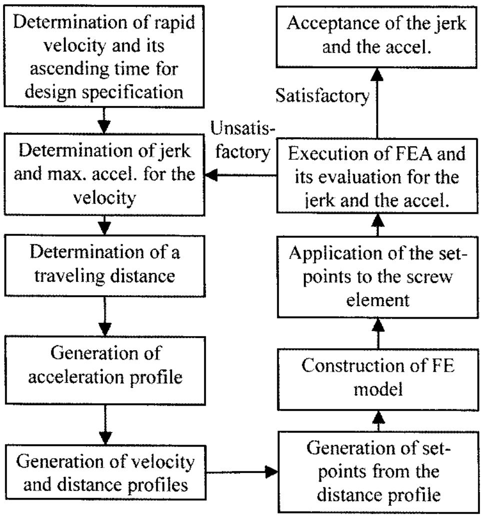


Fig. 3 Flowchart for the procedure of the dynamic FEA for feeding

feature of screw joint[12] is used to implement ball-screw mechanism for feeding.

Fig. 3 shows the procedure of the FEA for feeding a structure in open loop control. First of all, a design engineer determines the rapid traveling velocity and its ascending time for the machine tool under design. Jerk and acceleration are determined to reach the velocity in the given ascending time. When a traveling distance is determined, the profiles of acceleration, velocity, and distance are constructed as shown in Fig. 2. Set-points are generated from the distance profile for feeding. The set-points are applied to the screw element in corresponding rotation considering its pitch after construction of FE model. Posterior to execution of the FEA, deformation and vibration of the structure are evaluated. If they are satisfactory, the jerk and the acceleration are accepted, and otherwise, the FEA process is repeated.

Fig. 4 shows the FE model for the dynamic transient analysis for feeding the column in open loop as shown in Fig. 1. The bed in Fig. 1 was excluded for the FEA in order to reduce much of the solving time. It may have little influence on the analysis because it plays the role to rigidly support the LM rails. The ball screws connecting the column with the saddle and connecting the saddle with

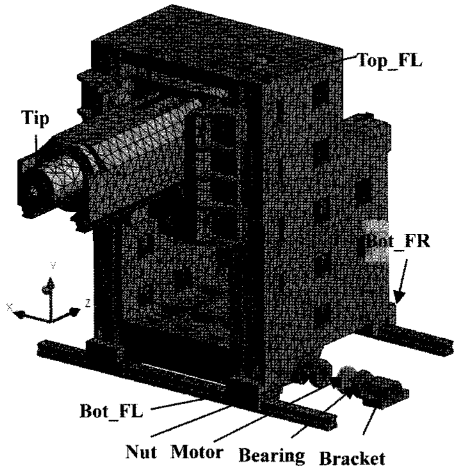


Fig. 4 FE model for screw feeding

Table 1 Input data for the FEA

Type	Item	Property	Value
Material	Casting Iron	Young Modulus	125GPa
		Poisson's ratio	0.28
		Damping	0.0015
Analysis	FE model	Number of nodes	182,122
		Number of elements	96,047
	Feeding	Jerk	180 m/s^3
		Distance	1mm
		Time	0.0562 sec.
		Ball screw size (Y, Z)	40mm, 36mm
	Extra mass	Motor (Y, Z)	100Kg

the head were implemented with beam elements. The boundary constraint had the LM rails and the bracket fixed.

Some parts were made to implement the ball screw feeding system in X direction. They were the nut, the motor, and the bearing in Fig. 4. The screw joint element of MPC 184 connected the motor and the nut but is not shown graphically in Fig. 4. The bearing was also connected with the motor and the bracket together in order to perform its function of rotation. The set-points for the feeding distance were applied to the motor in rotation.

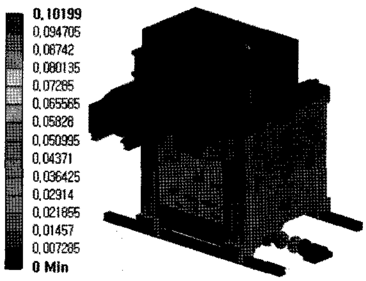
Table 1 presents the input data for the FEA for feeding the column in open loop control. The material used for the structures including the column in Fig. 1 is the casting iron in Table 1. Properties for the LM rails and the shoes were required for the FEA and then extracted from Ref. 13. The feeding distance was 1mm with jerk of 180m/s3. It leads to 0.0562 sec for the feeding time. The set-points were generated with these values. The motor mass was applied to its joining location.

4. Results from the dynamic transient FEA

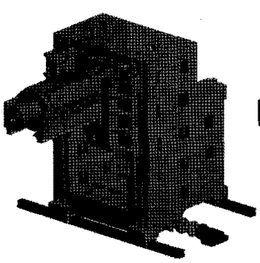
Fig. 5 presents deformation of the column at the different times, 0.010, 0.012, and 0.015 sec. As the motor is rotated, the column is moved following the nut. As the column is flexible, its bottom follows the nut fully but its top cannot. The degree to which its top can follow the nut depends on its dynamic stiffness. Also other structures such as the saddle affect the degree of its obedience. The location of the saddle, for example, at the top side or at the bottom side, may result in a different obedience.

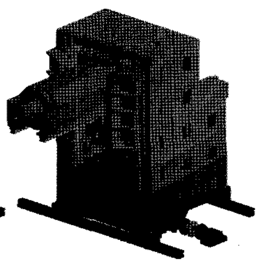
The chart in Fig. 6 plots the displacement of the vertices in Fig. 4. The letters, 'X' and 'Y' in Fig. 4 represent X and Y directions, respectively. Thus, 'Bot_FL_X' is the displacement of the vertex, 'Bot_FL' in X direction. It also can be seen that the bottom of the column well obeys the set points whereas its top diverts from the set point by 0.0347mm at 0.05 sec. After the traveling time of 0.0562 sec. ends, its top still vibrates. The tip of the spindle diverts more than the top of the column due to the torsion of the head by the moment of inertia. The spindle tip also vibrates in both X and Y directions. Its convergence time is importantly evaluated in order to avoid collision with other objects such as the ATC (automatic tool changer) and the workpiece.

The difference between the displacements of 'Bot_FL' and of 'Bot_FR' in X direction is shown in Fig. 7 (a) and the reaction force of the bracket is shown in Fig. 7 (b). The displacement difference indicates yawing of the column where 'Bot_FL' precedes 'Bot_FR' or recedes iteratively in X direction. The yawing motion, the rigid rotation of the column, occurs due to absence of the center of gravity of the column on the feeding element.



(a) At 0.010 sec





(b) At 0.012 sec. (c) At 0.015sec

Fig. 5 Deformation of the column at different times

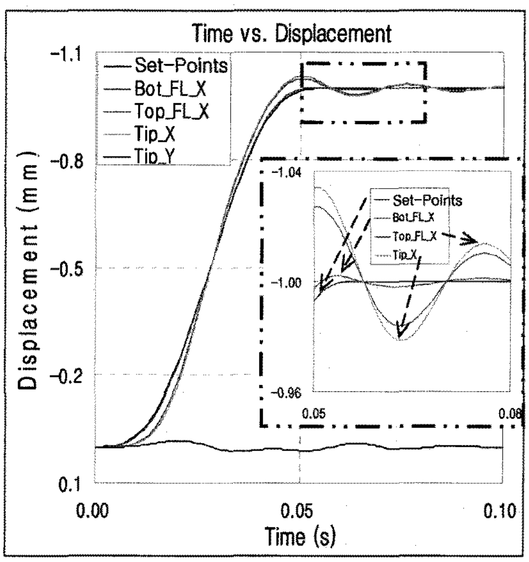
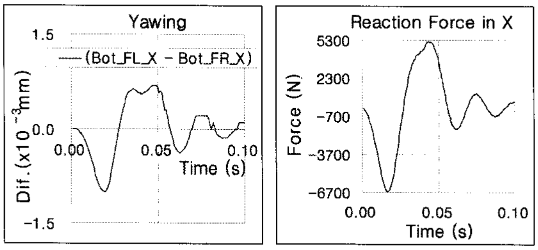


Fig. 6 Displacement of each vertex of the column



(a) Yawing **(b) Reaction force**

Fig. 7 Yawing of the column and reaction force

Rolling of the column also can be seen if the displacements of 'Bot_FL' and 'Bot_FR' are investigated in Y direction. Pitching would be seen in the same way.

Reaction force is the same, in magnitude, with the force to move the column at the specified velocity each time. It has to be similar to the torque of the motor for feeding the column and therefore, is useful for selection of a motor for the column feeding.

5. Conclusion

A finite element model was developed for dynamic transient analysis for feeding in open loop control. Screw element of the commercial FEA tool, ANSYS R12, was employed to implement the ball screw feeding mechanism in the FE model. The joint element played the role of convert rotation into linear translation to feed the structure, column in this study, to the set-points generated with given jerk and distance.

The procedure was established for the FEA to simulate the dynamic behavior of a structure fed in open loop control. First, the motion parameters such as acceleration are determined for the structure and then, a distance is determined for the simulation of the rapid feeding. The set-points are generated to construct the distance profile and applied to the structure through the ball screw. The dynamic behavior of the structure such as vibration is evaluated to satisfy the design criteria of the structure. In this study, the column of a machining center was an example to apply the procedure of FEA to evaluate its structural dynamic behavior including rigid motions such as yawing.

The FEA helps an engineer to envision the dynamic behavior of the structure fed in open loop control and to determine motion parameters including jerk and acceleration. It is also useful for selection of motor torque for the feeding. It presents convergence time for the structure vibration in rapid traveling, rigid motions including yawing, and the reaction force useable to predict the feeding force.

While this study focused on development of a finite element model for dynamic transient analysis, a further work needs to be carried out for extension of this study to different jerks and accelerations. The different jerks as a motion parameter yield various input data, as presented in Table 1, to make comparisons. The comparisons may evaluate the influence of the motion parameters such as the jerks and the accelerations on the stiffness of a structure and then, optimal motion parameters can be selected to have the minimum influence on the dynamic behavior of the structure.

References

(1) Weck, M., 1984, *Handbook of Machine Tools*, Vol. 1, English translation, John Wiley, New York, pp. 1~229.

(2) Joshi, P. J., 2007, *Machine Tools Handbook: Design and Operation*, Tata McGraw-Hill, New Delhi, India, pp. 1~92.

(3) Altintas, Y., 2000, *Manufacturing Automation: metal cutting mechanics, machine tool vibrations, and CNC design*, Cambridge University Press, Cambridge, UK, pp. 65~228.

(4) Kim, M. H. and Jung, J. S., 2006, *Control and Experimental for Industrial Servo System Drives of SPMSM*, BoSungGak, Seoul, pp. 11~230.

(5) Younkin, G. W., 1991, "Modeling Machine Tool Feed Servo Drives Using Simulation Techniques to Predict Performance," *IEEE Transactions on Industry Applications*, Vol. 27, No. 2, pp. 268~274.

(6) Choi, Y. H. and Hong, J. H., 2004, "A Study on the Feed Rate Optimization of a Ball Screw Drive Sys-

tem for Minimum Vibrations," *Proceedings of Autumn Conf. of Korean Society for Noise and Vibration Engineering*, pp. 962~966.
(7) Kim, S. H., Jung, J. H., and Kim, H. J., 2009, "Experiment Based Dynamic Analysis for High Accuracy Control of Feed System," *Journal of the Korean Society of Marine Engineering*, Vol. 33, No. 5, pp. 729~737.
(8) Cho, Y. D., Chung, W. J., Lee, C. M., and Yoon, S. H., 2008, "Study on decreasing displacement of the MC (machining center) moved column with high-speed for optimization of acceleration and DOE (Design Of Experiment)," *Transactions of the Korean Society of Machine Tool Engineers*, Vol. 17, No. 1, pp. 35~42.
(9) Kim, D. M., Kim, D. H., Park, K. K., and Choi, H. C., 2010, "Coupled Flexible Multi-Body Dynamics and Controller Analysis of Machine tool," *Transactions of the Korean Society of Machine Tool Engineers*, Vol. 19, No. 3, pp. 307~312.
(10) Han, S. H., 1997, *Automatic Control System Engineering*, DaesSinGiSul Press Ltd., Seoul, pp. 9~28.
(11) Vesely, J., 2009, "Complex model of machine structure with feed drive," *Int. J of Natural Sciences and Engineering*, Vol. 2, No. 4, pp. 193~199.
(12) ANSYS, 2010, *ANSYS User's Manual Version 12.0*, ANSYS Inc.
(13) NSK, 2010, *NSK Ball-Screws and Linear Guides*, Korean Edition, Korea NSK Ltd.