Finite Element Prediction on the Machining Stability of Boring Machine with Experimental Verification

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Abstract: The occurrence of chatter vibrations in boring operation has a great influence in improving workpiece dimensional accuracy, surface quality and production efficiency. In this paper instability analysis of machining process is presented by dynamic model of boring machine. This model, which consists of the machine tool's structure, is provided by finite element method and ANSYS software. The model is evaluated and corrected with experimental results by modal testing on boring machine in which the natural frequencies and the shape of vibration modes are analyzed. The natural frequencies of this modal testing are extracted through Pulse Labshop and ME'scope modal analysis software. Finally, the stability lobes obtained from this model are plotted and compared with experimental results.

Keywords: Boring Machine Tool, Chatter, Modal Analysis, Stability Lobe

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1 INTRODUCTION

Dynamic forces (that exist in all cutting operations) during machining may cause vibration in the work piece, tool and the machine-tool structure. Vibrations encountered in metal cutting can be categorized into three groups according to Tobias [1]:

1- Free vibrations that might be due to the external or internal shocks etc. In this case, external or internal transient, short time excitations cause the system to vibrate, where an example in the transmitted shocks from other operations is pressing operation.

2- Forced vibrations that are caused by unbalanced spindle or masses on rotary parts etc. These forces usually produce periodic excitations on the system. The sources of these vibrations might be other machines that their vibrations are transmitted through the foundations.

3- Self-excited vibrations that are generated by either metal cutting operation itself or other mechanism in the machine.

Chatter is a self-excited vibration phenomenon and can be generated by different mechanism, where in most machining operations the dominant mechanism is regeneration of chip load [1]. In chatter vibrations, cutting forces grow during the operation [2]. Chatter vibrations may occur in different metal cutting operations, for example milling, turning or boring. Since chatter vibrations cause poor surface finish, large cutting forces and low productivity, it is important to investigate their mechanism [3]. Tobias was one of the pioneers who explained the fundamental theory behind chatter vibrations in an orthogonal cutting operation [1]. Altintas et al., investigated chatter vibration in milling [4]. Altintas et al., presented the frequency domain analysis for chatter stability prediction in plunge milling operations [5]. Atabey et al., investigated mechanism of boring operations [6], [7]. Complex geometry of the chip is modeled analytically for various cutting conditions and tool geometry. The cutting forces are modeled as friction and tangential cutting forces. Lazoglu et al., proposed an analytical model for the force prediction in boring, and using time domain solutions they predicted workpiece topography as well [8]. Altintas et al., investigated the effect of process damping on chatter stability [9]. It is shown that when the tool is worn, the process damping coefficient and the chatter stability limit increase [9]. Eynian, in a comprehensive study, showed how to measure and model process damping mechanism in metal cutting at low cutting speeds [10]. Variable pitch angles can be employed to hinder the regenerative mechanism and consequently increase the process stability [11]. Budak presented an analytical design method to increase the stability for milling cutters with variable pitch angles [11], [12].

In this paper the stability lobe of boring process for determining the stability and instability zone in boring operation is investigated. For this purpose, a three dimensional model of the boring machine tool is developed in CATIA environment and imported to ANSYS software for the FEM modal analysis. This is primarily used for estimation of the natural frequencies and mode shapes of the structure and also used as an initial estimation for utilizing in the experimental modal test. For evaluation the results obtained from finite element model, experimental modal testing of a boring machine tool has also been performed to obtain the mode shapes and modal frequencies of the boring machine structure. Finally with use of dynamic model of structure and response frequency of modal testing, the stability lobe is plotted through a program in MATLAB software and on-line experimental testing of boring operation verified the validity of the stability lobe.

2 CHATTER IN MACHINING PROCESS

Chatter in machine tools is caused by one of the two mechanisms named mode coupling and regeneration of waving surfaces. The critical cutting width based on regeneration mechanism in machining process is calculated from the following equation [13]:

$$a_{\lim} = \frac{-1}{2k_f G(\omega_c)} \tag{1}$$

Where K_f and $G(\omega_c)$ are shearing strength and the real part of vibration conversion function of the system. The stability equation leads to positive width of cut only when the real part of the transfer function between the tool and workpiece ($G(\omega_c)$), is negative. The stability lobe shows the stability without any vibrations and instability region boards. According to this subject maximum cutting speed and width can be determined, so that the machining process is stable. Even though any structure has an infinite number of modes of vibration, chatter analysis is usually performed only around the first mode of vibration due to its high flexibility. Then, stability lobes from the second or third mode would appear above the corresponding first mode. Therefore, the stability lobe of machining process at frequencies which are close to the major modes of the system can be plotted using the frequency responses of the system.

3 MODELING PROCEDURES

In order to make a finite element model, a three dimensional model of the machine's structure with

ANSYS software has been considered. The model is applied on boring machine type WEYRAUCH (Fig. 1). After measuring and taking photos from various parts of the structure, its three dimensional model with CATIA software is executed. The model is imported into ANSYS and the necessary input data as material properties like modulus of elasticity, Poison ratio and density is applied. Then, elements of the model are made under solid 186 elements where this model has 107097 elements and 166888 nodes. Relevant boundary conditions are applied on the earth connection of machine tool. The discretized model in the ANSYS is shown in Fig. 2. Finally, modal analysis is performed to obtain natural frequencies of the structure.

Fig. 1 Boring machine tool

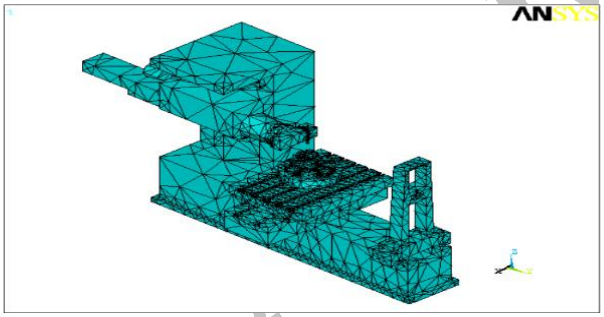


Fig 2 Discretized model of the boring machine

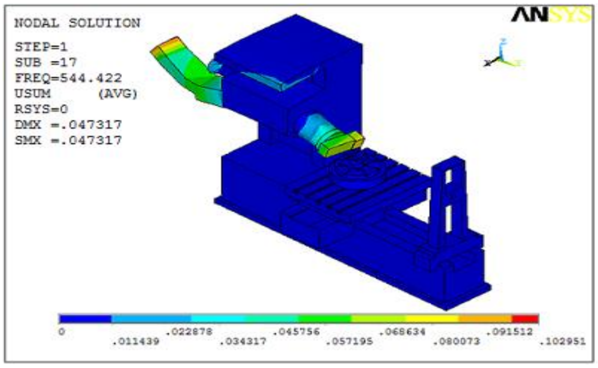


Fig. 3 Extracted mode shape vibration of frequency in 544.422Hz via ANSYS

4 MODAL ANALYSIS

Modal analysis has been done on finite element model to determine the natural frequency of the machine tool structure elements. The modal analyzed natural frequencies of this model via ANSYS software by block lanczos method are shown in Table 1. As an example, Fig. 3 shows the extracted mode shape vibration of frequency in 544.422Hz via ANSYS software.

Table 1 Correspondence frequencies of FEM and modal testing and their errors

Frequency of FEM [Hz]	Frequency of modal testing [Hz]	Error [%]
73.87	78	1.5
101.35	99	2.3
161.44	164	1.6
204.58	216	5.6
294.82	293	0.6
420.7	415	1.3
441.73	446	0.9
487.68	482	1.2
525.83	528	0.4
544.42	548	0.7
703.44	699	0.6
758.25	761	0.4
811.21	808	0.4
836.69	828	1.1
895.33	901	0.6
936.63	929	0.8
949.74	955	0.6
982.62	990	0.8

5 EXPERIMENTAL MODAL TESTING

The stages of the analysis of the dynamic behavior of the structure using the modal tests consist of: Applying the exciting force through an exciter or an impact by hammer to the structure, measuring the forces and acceleration of the system using the related sensors to obtain the frequency response functions (FRF's) and the modal parameters. In order to obtain natural frequencies and mode shapes, boring machine, a piezoelectric accelerometer (type 4507, B&K Inc.) and a hammer (type 8202, B&K Inc.) are used. The signal of the accelerometer and hammer force were collected and analyzed by the pulse system (type 3560, B&K Inc.).

Considering the especial boundary condition of the boring machine with fixed DOFs in earth connection of the structure, the roving accelerometer technique is selected for the modal analysis. In the roving accelerometer technique of present study, the impact forces are applied in a specified point of the structure for obtaining the response of the twenty two separate points of the surface boring machine structure. The responses are obtained by the accelerometer in the X, Y and Z directions for each of fifteen selected points separately; therefore forty-one different responses are obtained for several directions and points. The frequency response functions of the system have been extracted between the mentioned points using Fast Fourier Transform (FFT) algorithm. The results have been analyzed and presented as FRF curves, using Pulse Labshop software, for different points of the boring machine.

6 DATA ANALYSIS OF MODAL TESTING

The natural frequencies of the experimental test are extracted via ME'scope modal analysis software. It worth to note that the measured frequency domain is [0 1000] Hz. Throughout the mentioned domain eighteen natural frequencies have been estimated for the machine tool structure as listed in Table 1. As an example, Fig. 4 shows the extracted mode shape vibration of the frequency in 548Hz via Me'scope.

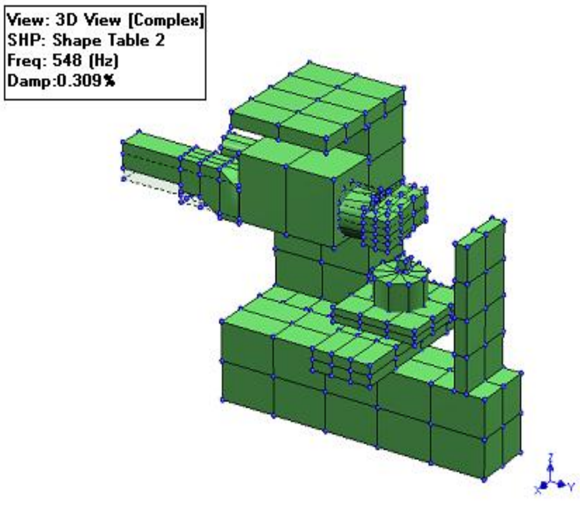


Fig. 4 Extracted mode shape vibration of frequency in 548Hz via Me'scope

7 EVALUATION OF THE FE MODEL PREDICTIONS

The related frequencies of FEM and modal testing and the percentage of their errors are listed in Table 1. While the comparison between the natural frequencies of finite element modeling and the model testing shows the closeness of the results.

8 STABILITY LOBES

High metal removal rate with quality surface finish is undoubtedly the most important issue in machining. While the applicable metal removal rate depends on the dynamics of the machine tool system, an instability threshold exists for a given machining system. Stability lobes describe the relationship among the stability threshold, the maximum allowable cutting depth, the tool dynamics and the rotational speed of the tool/work piece. The stability lobe diagram has been an important tool in the study of chatter in machining systems that can be obtained through frequency response modal testing result. The transmission functions of the system are needed to this purpose. The real part of receptance transmission function diagram of the one point of the tool is shown in Fig. 5. In this diagram the mode with 162Hz has the max pick, so it is used to obtain the stability lobe diagram.

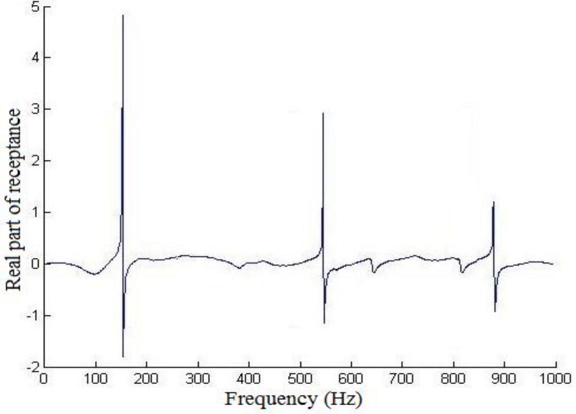


Fig. 5 Real part of receptance function diagram of the structure

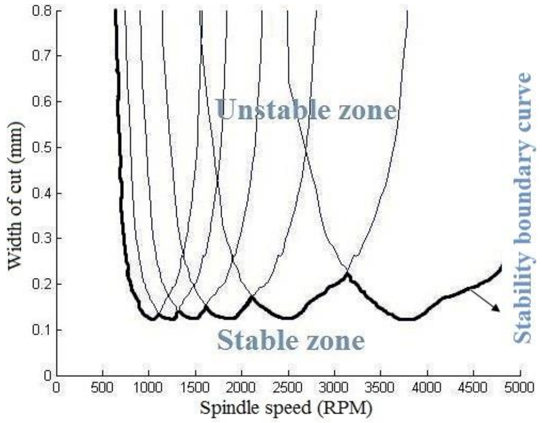
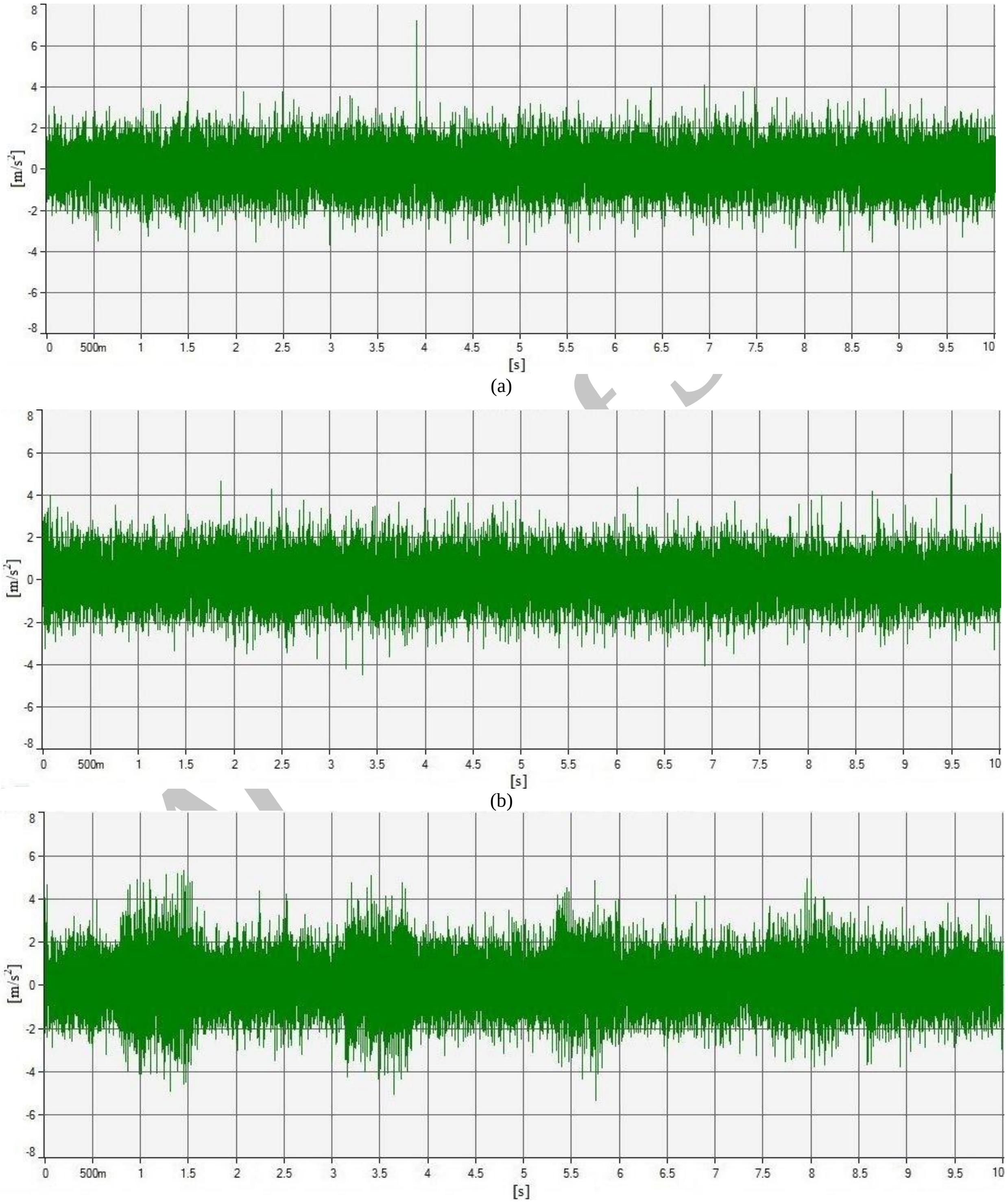


Fig. 6 Stability lobe of boring process

For achieving stability lobe diagram, a computer program which is written in MATLAB software has been applied (Fig. 6). In a stability lobe diagram, a series of scallop-shaped lobes intersect with each other, where these lobes form the limits for chattering. Locally, for each lobe, it is stable below the lobe, and unstable above the lobe. For example, from Fig. 5, it can be seen that, at 1500rpm, cutting depth (a) being 0.1 corresponds to a stable cutting, while increasing cutting depth to 0.2, results in an unstable cutting according to the stability lobe.



(a)

(b)

(c)

Fig. 8 Vibration amplitude of boring machine in different conditions for: a) a = 0.05mm, b) a = 0.1mm and c) a = 0.2mm

9 ON-LINE EXPERIMENTAL TEST

Some experimental vibration tests have been carried out to verify the validity of the obtained critical frequencies and chatter stability diagram. The tests were performed on boring machine type WEYRAUCH. Figs. 7 and 8 show the natural frequencies and vibration amplitude of boring machine in the experimental test, respectively. These diagrams are achieved after obtaining frequency response function from the experimental test, with use of Pulse Labshop software and computer program which is written in MATLAB software. It is evident from Fig. 7 that there are three max picks in 165.7, 546.5 and 891.1Hz that show the critical frequency and have good comparison with result of Fig. 5.

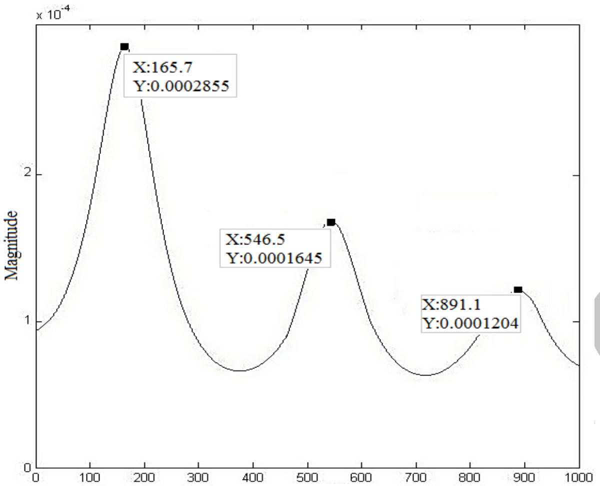


Fig. 7 Natural frequencies obtained from experimental test

Fig. 8 (a, b and c) show the vibration amplitude in the experimental test with variable conditions, where horizontal and vertical axis indicate the machining time and amplitude of vibration, respectively. Fig. 8 shows that in constant spindle speed, with increase in the cutting depth from 0.05 to 0.1mm, there is no variation in the vibration amplitude. However, with increase in the cutting depth to 0.2mm, vibration amplitude in some areas increase too, because according to Fig. 6 at constant spindle speed, the area of cutting depth of 0.05 and 0.1mm, is stable but at cutting depth of 0.2mm is in unstable zone where in this area chatter is occurred. Comparing the experimental results with the analytical results of Fig. 6, a strong correlation between the two is clearly evident.

10 CONCLUSION

In this paper regenerative self-excited vibration in boring machine tool is studied. The stability limit and the increase rate of self-excited vibration caused by the regenerative effect are investigated and the experimental test is done to verify the stability lobe. The real dimensions model of WEYRAUCH boring machine is executed, then the model imported to ANSYS software in order to determine the natural frequency and vibration modes shape. For evaluation of the results obtained from finite element model, the modal analysis testing is carried out on this system. The natural frequencies of this modal testing are extracted via Pulse Labshop and Me'scope modal analysis software. The comparison between natural frequencies of finite element modeling and modal testing shows the closeness of the result. Then with use of response frequency of modal testing, the stability lobe is plotted via a program in MATLAB software. In order to evaluate the stability lobe, experimental testing is done on boring machine, showing that theoretical results have a good agreement with the experimental ones.

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