847. Investigation of vibro-acoustic properties of modern lathe collet chuck

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Abstract. Manufacturing industry has been attempting to attain the required cutting performance in order to achieve high precision, fast productivity and lower maintenance costs. Vibrations generated during machining can be a serious problem degrading component quality, precision, tool service life, lathe performance and cutting rates. This paper is concerned with analysis of cutting process by using modal testing. Static and dynamic deformations of lathe collet chuck have a significant impact on cutting process stability, which affects workpiece quality and production output. Modal analysis was applied to develop a mathematical model of chucks dynamics, which consist of a number of mode shapes each with natural frequency and modal damping. Modal analysis and experimental measurements were performed on a collet chuck of CNC lathe installed in metal working company UAB "Stevila".

Keywords: vibrations, modal analysis, natural frequencies.

Introduction

Machining operations in turning and milling are used in industrial manufacturing processes to obtain specific characteristics of workpiece such as part geometry, surface roughness, etc. The processes are based on removal of small amounts of metal from the workpiece by using a cutting tool. The cutting tool contacts the workpiece and the uncut chip over a very small area of several square millimeters. Temperature and pressure within the contact zone are relatively high (temperature is about 1200 ^{o}C and pressure is about 3000 N/mm^2), which makes tool wear inevitable [1]. The parts are usually manufactured in 3-axis lathes that have high cutting speeds and tool cooling. A variation of indicated parameters caused by vibrations during machining operations of the lathe can be observed. These vibrations could lead to reduced productivity, since reduced cutting speeds have a negative effect on the workpiece surface by leaving vibration marks (waves) on the surface.

Cutting forces create movements between the cutting tool and the workpiece, which can affect the cutting forces between the tool and the workpiece. Vibration marks left on the surface can affect the cutting forces in the following tool pass. This leads to the systems cutting force growth if the process is not naturally stable against the vibrations due to a large width cut and large cutting coefficients or flexible structure. Cutting forces also depend on tool geometry and material, workpiece material, feed-rate and cutting speed. If the cutting process is unstable, the amplitude of vibrations can start increasing exponentially until a value similar to chip thickness is reached. Tool vibration against the workpiece is called chatter, which can cause growth of cutting forces and lead to machine, cutting tool or workpiece damage [2]. The chatter system dynamics are modeled by delayed differential equations with constant or time varying periodic coefficients, which depend on the type of machining operation [2, 3].

It is well known that vibrations in cutting have a significant impact on machined surface roughness, manufactured part geometry, cutting tool and machines durability. High frequency noise emitted during machining can also cause environmental pollution and reduced productivity. Thus, the machine chatter has been a major issue when investigating cutting processes. However, this issue is not fully understood. It is difficult to construct an accurate mathematical dynamic model for analyzing vibrations in the cutting process.

Vibrations are the main reason of machine chatter. This leads to destructive oscillating cutting forces, which generate vibration marks on the machined surface. Uneven cutting forces can reach values several times higher than those achieved by normal cutting process. This drastically shortens cutting tool and machines durability, may cause cutting tool failure and early lathe spindle bearing wear [4].

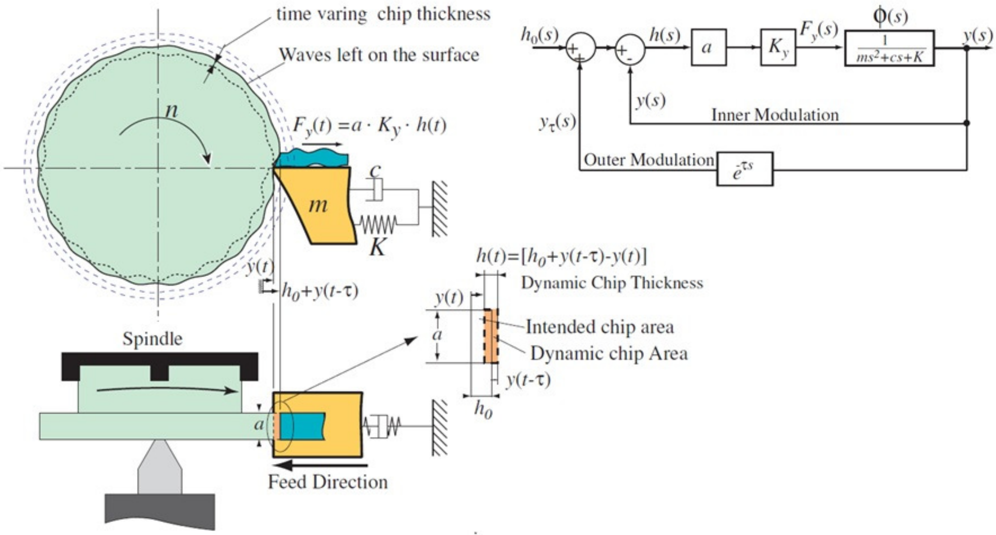


Fig. 1. Chatter in orthogonal cutting with block diagram [5]

A simple cutting tool with one degree of freedom and a block diagram suggested by Eynian is shown in Fig. 1. It describes systems dynamics where τ is spindle lathe period and h_0 is the intended chip thickness. The vibrations in cutting tool feed force direction $y(t)$, called the inner modulation, decrease dynamic chip thickness $h(t)$, where high vibration marks left from last pass $y(t-\tau)$, called outer modulation, increase dynamic chip thickness. Then [5]:

$$h(t) = h_0 + y(t-\tau) - y(t) \tag{1}$$

When $y(t)$ and $y(t-\tau)$ have a phase shift, the dynamic chip thickness will vary at vibration frequency and will induce a vibrating cutting force $F_y(t)$, which could increase vibrations of the cutting tool. This phenomenon occurs only when the cutting depth, a, and cutting coefficient in cutting tool feed direction K_y are sufficiently large in comparison to tool supporting structure stiffness coefficient K and structural damping coefficient $\xi = c/2\sqrt{mK}$. The fluctuating energy of the structure is dissipated by damping [5].

R. N. Arnold suggested that a decrease in cutting force due to cutting speed increase could lead to negative damping effect and can cause cutting process instability [6]. Later R. S. Hahn showed that this effect is not strong enough to act as the main reason for instabilities [7]. The regeneration of undulation was first discovered by Doi and Kato, where they have demonstrated that chip thickness regeneration causes uneven cutting forces [8].

Tlusty et al. [9] and Tobias et al. [10] suggested relationships for calculating stability limits while considering chip regeneration. Merrit showed the same model in a closed loop system [11].

Modal analysis can be utilized for solving vibrations problems of machining operations. Here the mechanical system can be modeled as a set of vibration modes. Applying this analysis, vibrations during the cutting process can be investigated. Experimental modal analysis has rapidly developed in the last decades. A finite element model (FEM) is also commonly applied to investigate the instability of machining process [4, 12, 13].

The aim of the present investigation is to estimate the effect of the CNC lathe collet chuck on vibration amplitude and frequency characteristics.

Methodology and research results

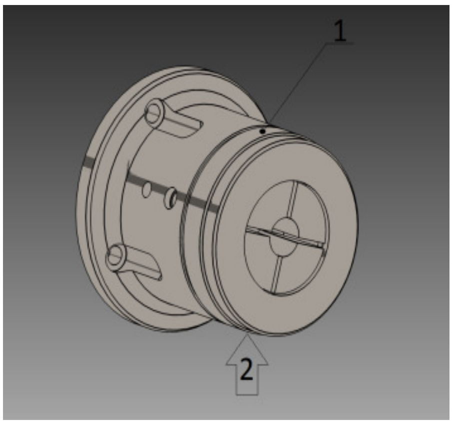
Analytical modal analysis is based on defining the modal parameters from FEM. Experimental modal analysis was performed to determine selected modal parameters of components or the entire structure.

In performing analytical modal analysis, a 3-D geometric model of lathe collet chuck was developed using AUTODESK Inventor software. This model provides a procedure in extracting the natural frequency response values. Observation of vibration modes of collet chuck in space provides a better capability to analyze the vibration model. The elements used in the FEM model meshing are quadratic tetrahedral elements. The boundary conditions of the supports to the base connection of the component and of all the other connecting surfaces are implemented in the final modal analysis and the natural frequencies of the structure are obtained. The calculated natural frequencies by the modal analysis of FEM are presented in Table 1.

In classical modal analysis, the frequencies or impulse response functions are evaluated by measuring input forces and output responses of the structure. Commonly, this analysis is performed in frequency domain using a spectrum analyzer. The analyzer converts the analogue time domain signal into digital frequency domain from which the required parameters are computed digitally.

In order to measure vibrations of the lathe components, PULSE software developed by Brüel&Kjær was used together with PULSE data acquisition module 3580, impact hammer 8206 for creating known or controlled excitation and type 4370 piezoelectric charge accelerometers. Experimental modal analysis was performed in metal working company UAB “Stevila”. The collet chuck of CNC turning lathe CT 200 was used in this investigation (Fig. 2a).

a)

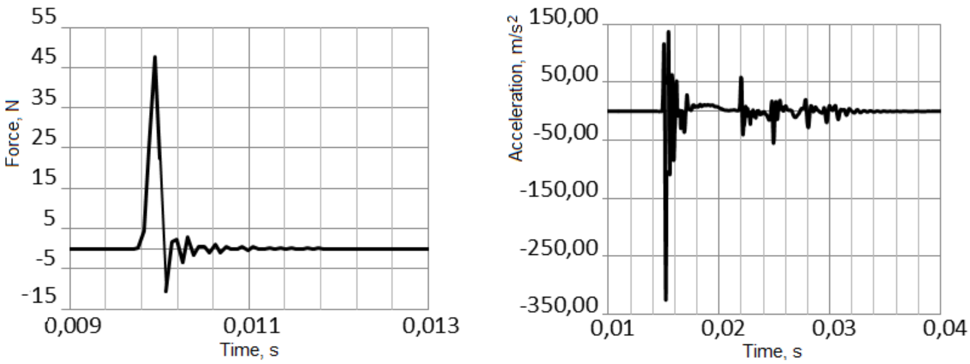


b)

Fig. 2. a) CNC turning lathe CT 200 with measuring equipment: 1 – data acquisition module B&K Type 3580; 2 – CNC turning lathe CT 200; 3 – PC with B&K PULSE software; 4 – collet chuck; 5 – accelerometer; b) 1 – location of accelerometer; 2 – direction of impact

Natural frequencies and mode shapes were measured for static conditions using accelerometers and an impact hammer. The excited frequencies were recorded for static condition with no load. During the machining process, it is not easy to measure vibration response and it is even more difficult to measure the dynamic cutting force. The force measurement was obtained by using the impulse response generated by the impact hammer and the impact force measured by the sensor located at the hammer tip. The accelerometer and impact force locations are shown in Fig. 2b.

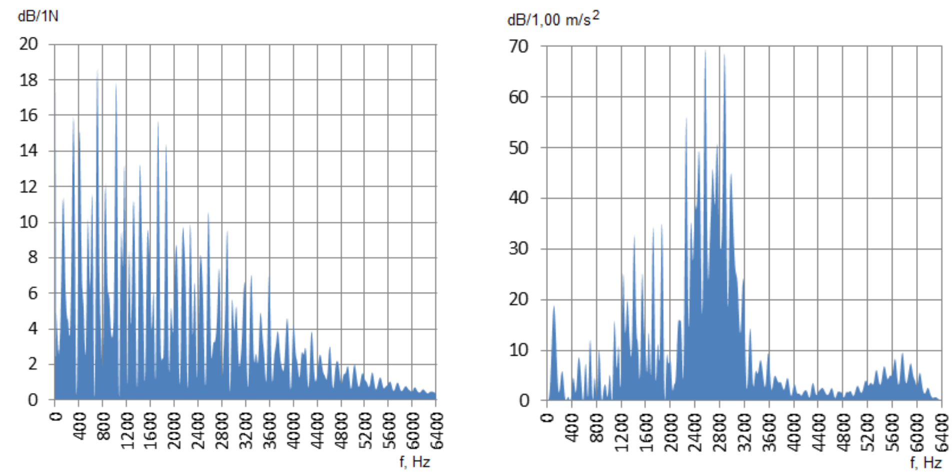
Time history of impulse force is illustrated in Fig. 3a. The acceleration time response of the lathe collet chuck to impact force input is given in Fig. 3b. It can be observed from Fig. 3b that the maximum value of acceleration is 324.84 m/s^2.



(a) (b)

Fig. 3. Time history: (a) - excitation, (b) - response

The auto spectrum of the excitation force is given in Fig. 4a and of the acceleration response in Fig. 4b. Normalizing the acceleration response to the excitation force, the frequency response function shown in Fig. 5 was obtained. Having the frequency response function, the modes, modal frequencies and modal damping of the collet chuck of CNC turning lathe can be obtained.



(a) (b)

Fig. 4. Auto spectrum: (a) – excitation, (b) – response

Table 1 lists natural frequencies obtained from FEM modal analysis and experimental tests. The maximum relative error between the analytical and experimental results is in the range of 0.001-4.981 %. These differences are relatively small and thus the analytical procedure used in this study should be adequate in determining the natural frequencies of the lathe collet chuck.

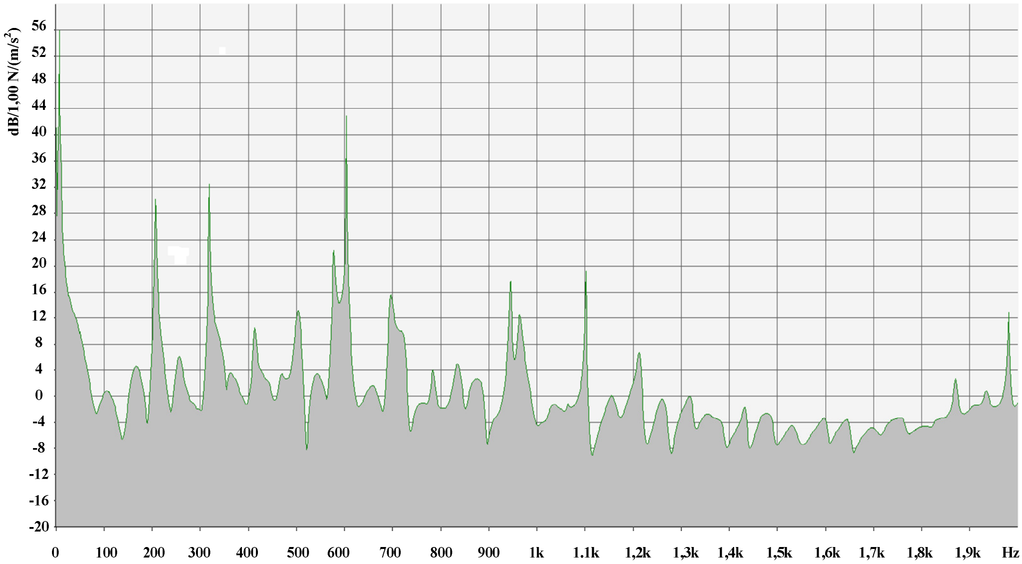


Fig. 5. Frequency response function (FFT)

Table 1. Natural frequencies determined from measurements and simulations

Mode	Experimental, Hz	Analytical, Hz	Difference, %
1	105.0	105.1	0.001
2	166.0	163.0	1.807
3	206.0	214.0	3.883
4	256.3	246.0	4.003
5	318.8	334.7	4.981
6	696.3	704.7	1.208
7	783.8	786.3	0.320
8	833.8	845.6	1.415
9	1101.0	1103.0	0.182
10	1318.0	1327.0	0.683
11	1530.0	1512.0	1.176
12	1980.0	2005.0	1.263
13	2632.0	2653.0	0.030
14	3344.0	3345.0	0.030
15	3660.0	3519.0	3.852

Conclusions

A modal analysis method was adopted in the reported research work in order to analyze the cutting process of the CNC turning lathe CT 200. Modal analysis of lathe collet chuck was performed by means of finite elements method. The calculated natural frequencies could provide useful information in selecting the operating parameter values to avoid chatter in the cutting process that will extend service life of the cutting tools, the lathe and at the same time increase work productivity. The validity of theoretical predictions was conformed by comparisons with the results of experimental studies. The dependence of natural frequencies of mechanical links on geometric parameters and material properties has been demonstrated. The analysis presented can be used to optimize vibro-acoustic characteristics of lathe components with respect to the excitation forces.

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