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# Prediction of vibration frequencies in milling using modified Nyquist method

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ABSTRACT

Study of the vibration frequencies at different cutting conditions is an alternative to the use of impact hammer test for identification of natural frequencies of the machining structure and calculation of stability lobe diagrams. Vibration frequencies not only depend on the natural frequencies of the structure, but also they are dependent on the spindle speed, damping ratio of the structure and the depth of cut. Ignoring these additional parameters would lead to errors in identification of the natural frequencies of the system and considerable deviation of the calculated stability lobe diagrams from actual cutting tests. In this study modified Nyquist method is used to investigate the effects of spindle speed, depth of cut and damping ratio of the structure on vibration frequencies. The quality of frequency prediction is compared to linear and nonlinear time domain simulations and machining experiments.
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## Introduction

In a metal cutting operation, a closed loop is formed between the machining process and the dynamic vibrations of the structure that positions the tool against the workpiece. This closed loop might have unstable characteristics and self-exited vibrations might grow depending on the dynamic compliance of the structure and the sensitivity of the cutting forces to the vibrations. The time delay between consecutive machining passes, which depends on spindle speed, controls the phase difference between the vibration waves on the inside and outside of machined chips and plays a significant role in the instability dynamics. On the other hand, the depth of cut controls the sensitivity of the cutting forces to the vibrations; therefore, the depth of cut at threshold of stability changes as a function of spindle speed, in a diagram known as the stability lobe diagram. The past research has established the methods for calculation of the stability lobe diagrams and the vibration frequencies at the threshold of stability. After identification of regeneration of cutting force due to the phase difference between the vibration waves inside and outside of the chips by Doi and Kato [1], width or depth of cut at the threshold of stability were calculated [2,3], and the saw-tooth plot for chatter frequencies has been presented using tools such as Nyquist stability criterion [4].

Chatter predictions and construction of stability lobe diagrams are used for selection of optimal cutting conditions (i.e. optimal spindle speed and depth of cut); however, impact tests are often needed for identification of structural parameters such as modal stiffness, natural frequency and damping ratio of the modes that may contribute to chatter. These parameters are then used in a machining dynamics model to calculate the stability lobes and to select optimal cutting parameters as depicted in Fig. 1(a). An alternative algorithm is to record or monitor acoustic waves, displacement, force or acceleration during the cutting tests, extract the vibration frequencies, and use an inverse machining dynamics model to extract the dynamic parameters of the structure. These parameters could be used in a machining dynamics model to find optimal cutting parameters [5–7], as depicted in Fig. 1(b). While this approach needs more calculations, it has the advantage of eliminating the need for impact test equipment in one hand, and extraction of the dynamic parameters of the structure during cutting, thus avoiding the changes in the dynamic parameters that may arise due to the spindle's rotation or changes in preloads and stiffness nonlinearities. Some of such changes are discussed in Refs. [8–10].

In order to extract the structural parameters from the vibration signals, the relationships between the cutting conditions, structural parameters and vibration frequencies should be embedded in

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**Nomenclature**

| | |
|---|---|
| $\omega_n$ | natural frequency of the structure |
| $\omega_t$ | tooth passing frequency |
| $s$ | dominant pole |
| $\omega_d$ | vibration frequency of the dominant pole |
| $\omega_{cr}$ | vibration frequency at the threshold of stability, changes as a function of spindle speed |
| $\zeta$ | damping ratio of the dominant pole |
| $\zeta_{xx}$ | damping ratio of the structure |
| $\alpha$ | depth of cut |
| $a_{\min}$ | smallest depth of cut at the threshold of stability |
| $a_{cr}$ | depth of cut at threshold of stability, which changes as a function of spindle speed |
| $N_z$ | number of flutes on a milling tool |
| $x$ | vibration in the feed direction of milling |
| $c$ | feed per tooth per revolution (maximum uncut chip thickness in slot milling) |

the inverse machining dynamics model. Consequently, having a clear picture about the vibration frequencies above and under stability lobes is necessary for the extraction of the dynamic parameters of the structure in these algorithms.

An example of the effects of errors in estimation of the natural frequency of the machining system on the stability lobe diagram is shown in Fig. 2. With a correct natural frequency, it would be possible to select the spindle speed of 2284 rev/min and have a stable milling at a depth of cut of 4.3 mm. With 1% error in the natural frequency, the selected spindle speed of 2307 rev/min will cause chatter at depth of cuts above 1.0 mm. With a larger error of 5%, the best suggested spindle speed will be 2399 rev/min and the system will chatter at depth of cuts above 0.26 mm; which is a 95% reduction compared to the original 4.3 mm.

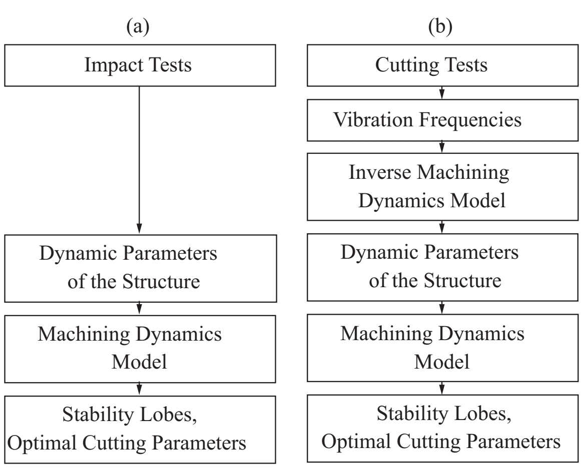


**Fig. 1.** (a) The conventional approach; (b) the inverse approach for construction of stability lobes.

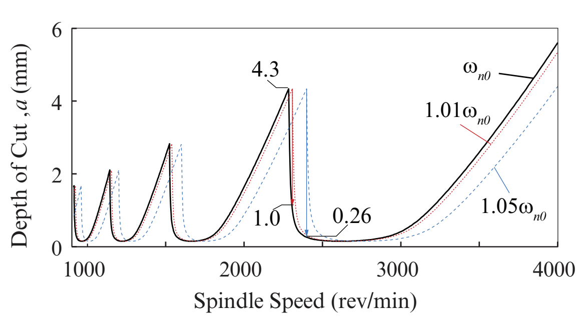


**Fig. 2.** Effect of errors in natural frequency on position of the peaks of the stability chart. See Table 1 for system parameters.

Additionally, a clear understanding of the vibration frequencies above and under the stability lobes would help in distinguishing regenerative chatter from forced vibrations that arise in interrupted machining with flexible structures by answering the following questions:

- What is the frequency of unstable vibrations ($\omega_d$) at a depth of cut ($a$) above threshold depth of cut ($a > a_{cr}$)? Is it equal to instability frequency at the threshold of instability ($\omega_{cr}$)?
- What is the frequency of damped vibration of a stable machining system ($a > a_{cr}$) in response to disturbance forces? Is it equal to the vibration frequency at the threshold ($\omega_{cr}$), or is it equal to the natural frequency of the flexible mode ($\omega_n$)?
- Is there a recognizable change in vibration frequencies in transition from stable to unstable cutting conditions?

While vibration frequency is an important characteristics of a dynamic system, many studies in the field of machining dynamics, using different methods such as time domain simulations [11,12], single frequency and zero order approximation methods [4,13], multi-frequency methods [14,15], and semi-discretization methods [16–18] are focused on the determining the stability condition of the machining process and determining the boundary between the stable and unstable regions. Dombovari et al. have used semi-discretization to predict multiple vibration frequencies at the boundary of stability and have presented the relative strength of these dominant frequencies [18]; however, while a fractal method is used for finding the boundaries of stability, i.e. the system properties were also investigated in points other than the boundary of stability, the vibration frequencies are only calculated and discussed at the boundary of stability.

Nyquist stability criterion is a convenient and powerful tool for deciding the stability of linearized delay differential equations and it has been used in prediction of chatter in 3D turning problems [19] and milling problems [13,20]. In this paper, a modification of the Nyquist stability criterion is used to investigate the vibration condition at cutting conditions away from the boundary of stability.

The remainder of the paper is organized as follows. In the second section, modified Nyquist stability method for calculation of the complex poles is explained. The method is used to study the effects of depth of cut, spindle speed and damping ratio of the structure on vibration frequencies in the third section. In the fourth section the vibration frequencies from the time domain simulation are compared to frequencies calculated analytically, and the effects of nonlinearities are discussed. The fifth section presents the results of an experiment where the changes in vibration frequencies due to the increase of depth of cut at two different spindle speeds are compared to the analytical predictions. The final section presents discussions and conclusions.

## Modified Nyquist contours

A standard Nyquist contour, Fig. 3(a), maps the imaginary axis by the characteristic equation of closed loop machining system to the complex plane and if the mapped contour encircles the center of the complex plane in the clockwise direction, the presence of unstable poles (poles in the right side of the imaginary axis) is indicated. A pole is on the imaginary axis if the mapped contour passes through the center of the complex plane. While the

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