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Identification of stability lobes in high-speed machining of thin ribs

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Abstract - *High speed machining of low rigidity structures is a widely used process in the Aeronautical industry. Along the machining of this type of structures, the so-called monolithic components, large quantities of material are removed using high removal rate conditions, with the risk of the instability of the process. Very thin walls will also be milled, with the possibility of lateral vibration of them in some cutting conditions and at some stages of machining. Chatter is an undesirable phenomenon in all machining processes, causing a reduction in productivity, low quality of the finished work pieces, and a reduction of the machine-spindle's working life. In this study, a method for obtaining the instability or stability lobes, considering dynamic behaviors of machine structure is presented. Thus a stability lobe diagram (SLD) has been developed analytically for machining of thin ribs. The frequency response function (FRF) of the milling process has been predicted along with real and imaginary parts. The mathematical tool MathCAD 8 Professional is used to simulate the FRF and stability lobes. The experiment setup is proposed to find the impulse response of the machine structure at tool tip. Finally the stable and unstable region for high speed machining process has been predicted analytically.*

Keywords – *Chatter, High speed machining, Machining vibrations, Stability lobe diagrams, Thin ribs*

I. INTRODUCTION

The manufacturing process of monolithic components is widely used in the aeronautical sector for the manufacturing of airframe components. The great number of these work pieces is manufactured by high speed milling, where problems can arise related to the breakage of the tools, instability in the process and dimensional errors in the work pieces. The instability of the process is a vibration phenomenon known as chatter, which causes the abovementioned effects. Chatter phenomena appear in the high removal rate roughing, as well as in the finishing of low rigidity airframe components.The stability of machine tool is dependent on the dynamic behavior of machine tool structure, which is often expressed in terms of the frequency response function (FRF) of the system at the tool point[1].Tang et al [2] describes the development of this new method which allows considering the effects of multi-mode dynamics of system, higher excited frequency (i.e. tooth passing frequency) and wider spindle speed range on stability limits in high-speed milling, and these to help in selection of milling parameters for a maximum material removal rates (MRR) in real operations without chatter. Lopez et al [3] describes a technique to vary spindle speed in order to obtain a stable cut. Use of this technique requires a diagnosis and detection of the emergence of chatter vibrations.

Heisel and Feinauer [4] considered the dynamic influence of work piece quality in high speed milling. They also considered the tool, tool holder and spindle dynamics to predict the effect of vibration on surface quality. Zhongqun and Qiang [5] presents a predictive time-domain chatter model for the simulation and analysis of the dynamic milling process and makes synthetic use of several chatter stability criteria to overcome the limitation imposed by the single chatter stability criterion. In order to take into account the dynamic regenerative effects, the instantaneous undeformed chip thickness is modeled to include the dynamic modulations caused by the tool vibrations.Stepan et al [6] introduced two analytical methods for stability prediction of general milling operations. The finite element analysis in time (FEAT) method and the semi-discretization (SD) method. Both methods form a finite dimensional transition matrix as an approximation of the infinite dimensional monodromy operator.Altintas et al [7] presented frequency and discrete time domain chatter stability laws for milling operations in a unified manner. The time periodic dynamics of the milling process are modeled. By averaging time varying directional factors at cutter pitch intervals, the stability lobes are solved directly and analytically. When the process is highly intermittent, which occurs at high speeds and low radial depth of cuts, the stability lobes are more accurately solved either by taking higher harmonics of directional factors in frequency domain, or by using semi-discretization method. He compared the stability solutions against the numerical solutions and experiments, and provides comprehensive mathematical details of both fundamental stability solutions.

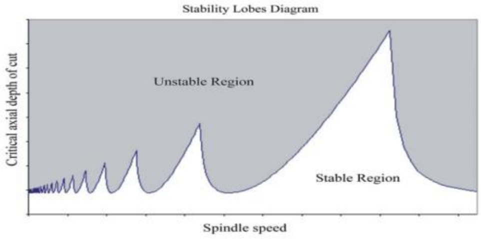


Fig. 1. Example of a stability diagram.

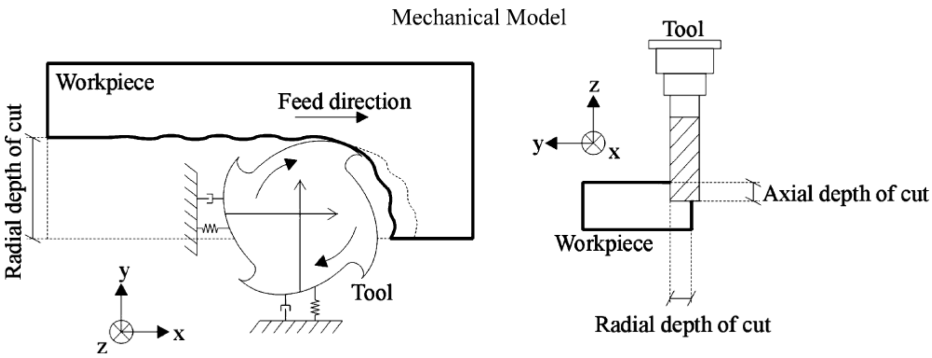
Peres et al [8] described the development of new method which obtains the stability information for some vibration modes that can be used to graph the stability lobes for high-speed milling, and these to help in the selection of parameters for chatter free operations.Tobias [9] assumed that the direction of the cutting force as well as the projected vibrations along the chip thickness are constant, which is true for single point cutting operations like turning, boring and broaching. He also included the influence of the phase between the inner and outer waves left on the chip surface, and invented stability lobes. Fig.1 shows the sample unstable and stable regions of stability is given with the stability lines.

In paper presents an analytical method to predict the stability lobes for high speed machining process. The real and imaginary parts of frequency response function are simulated using MathCAD software. The experimental setup is proposed in order to measure the impulse response of the machine structure at the tool tip.

II. A METHOD TO IDENTIFY THE STABILITY LOBES

2.1 THE CHATTER Problem

In the milling process, material is removed from a workpiece by a rotating cutting tool. While the tool rotates, it translates in the feed direction at a certain speed. A schematic representation of the milling process is shown in Fig. 2.



One of the most common problems in machining is dynamic deformations, which are structural vibrations between the cutting tool and the workpiece. The most common vibrations are the self-excited vibrations of chatter, which grow until the tool leaves its cutting zone due to the exponential increase of the dynamic displacements between the tool and the workpiece (regenerative chatter).Chatter occurs in machining operations due to the interaction between the tool-workpiece structure and the force process. Regenerative chatter is so named because of the closed-loop nature of this interaction (Fig. 3). Each tooth pass leaves a modulated surface on the workpiece due to the vibrations of the tool and workpiece structures, causing a variation in the expected chip thickness.Under certain cutting conditions (i.e. feed of rate, depth of cut, and spindle speed), large chip thickness variations and hence force and displacement variations occur and chatter is present. The results of chatter include a poor surface finish due to the chatter marks, excessive tool wear, reduce dimensional accuracy, and tool damage. Machine-tool operators often select conservative cutting conditions to avoid chatter, thus, decreasing productivity.

2.2 Governing Equations Of Machine Chattering

The method to generate the stability lobes for a certain vibration mode identifies the transfer function of the system with the experimental analysis. The natural frequency (ω), damping factor (ζ) and stiffness of the mechanical system (k) are determined analytically. Once these values are found, the real (AR) and the imaginary (AI) components of the transfer function for a certain chatter frequency can be calculated using:

$$A_R = \frac{1-r^2}{k[(1-r^2)^2 + (2\zeta.r)^2]} \qquad [1]$$

$$A_I = \frac{-2\zeta.r}{k[(1-r^2)^2 + (2\zeta.r)^2]} \qquad [2]$$

where $r = \frac{\omega_C}{\omega}$ and ω_C is a chatter frequency.

It is necessary also to consider the average number of teeth during the cut (m):

$$m = \frac{N}{2}\frac{P_R}{\phi_H} \qquad [3]$$

where ϕ_H is the tool diameter, N the number of teeth of the tool and P_R the radial depth of cut.

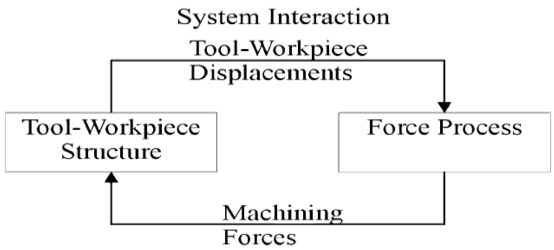


Fig. 3. Closed-loop representation of machining.

The axial depth of cut limit of stability is calculated with the following equation:

$$a_{\lim} = -\frac{1}{2K_m\mu.m.A_R} \qquad [4]$$

where μ is directional orientation factor and K_m the cutting stiffness. The spindle speed n is simply calculated by finding the tooth passing period:

$$T = \frac{1}{\omega_C}(\varepsilon + 2k\pi) \rightarrow n = \frac{60}{NT} \qquad [5]$$

where N is the number of the tool teeth. To identify the phase shift (ε) between the inner and outer modulations (present and previous vibrations marks), with the equation:

$$\varepsilon = 2\pi - (2\cot(\frac{A_R}{A_I})) \qquad [6]$$

The new proposed method to identify the stability lobes for high-speed milling using a combination between the analytical prediction of chatter and the experimental modal analysis for multi degree-of freedom systems is:

Step 1: Obtain the characteristics of the tool, material to mechanise and milling process, and obtain the characteristics of the system using the experimental analysis of the system;
Step 2: Calculate the real and imaginary component of the transfer functions (AR, AI), Eq. (1&2);
Step 3: Select a chatter frequency from the transfer function around a dominant mode;
Step 4: Calculate the critical depth of cut from Eq. (4);
Step 5: Calculate the spindle speed from n=60/NT for each stability lobe k = 0, 1, 2, and,
Step 6: Repeat from step 2 by scanning the chatter frequencies.

To obtain the stability lobes of all the vibration modes, it is necessary apply this method to all dominant modes of the structure evident on the transfer functions. It is the superposition of all the stability lobes the one that indicates the stable and unstable zone for milling.

III. PROPOSED EXPERIMENTAL SETUP TO FIND IMPULSE RESPONSE

Transfer functions of existing multi degree-of-freedom systems are identified by a structural dynamic test. An impact hammer instrumented with a piezoelectric transducer and a accelerometer can be used as shown in Fig. 4. With this method, we try to excite a range of frequencies that contain the natural modes of the system. In order to obtain our objective, we need to generate an impulse and this can be given with a short impact. To choose the appropriate hammer and sensor, we have to consider the mass, the stiffness and the material of the structure.

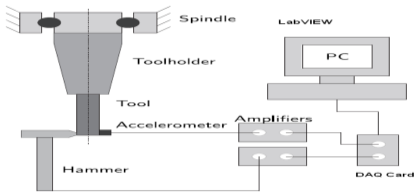


Fig. 4. Schematic representation Impact hammer test

The real and imaginary parts of the FRF can be taken by interfacing with LabVIEW. The FRF from the simulation and experiment can be compared to find the agreement of values.

IV. ANALYTICAL SIMULATION OF FRF USING MATHCAD SOFTWARE

The simulation is carried out by selecting following input parameters., helix angle of the tool 30^0, natural frequency of the system 160 rad/sec, operating speed range 0-40,000 rpm, damping factor 0.02, stiffness of the work piece 100 N/mm, operating stiffness 5.9 x 10^3 N/mm, tool diameter 19mm, no of teeth 2 and radial depth of cut 0.1mm.The simulation of real part of the FRF from Eq. (1) shows the phase shift from positive region to negative region as shown in Fig. 5.

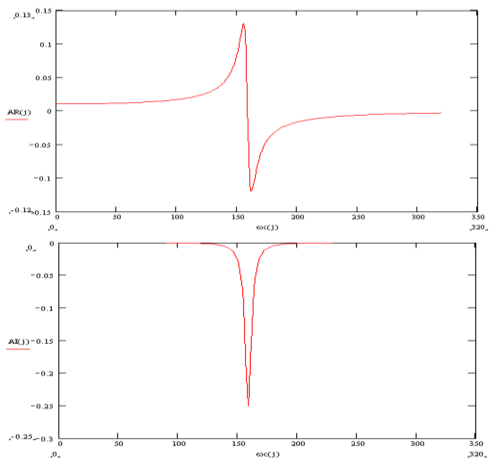


Fig. 6. Simulation of imaginary part of FRF

The simulation of imaginary part of FRF shows that the curve lies only in the negative region. The lobes can be generated by negative region of the real part.

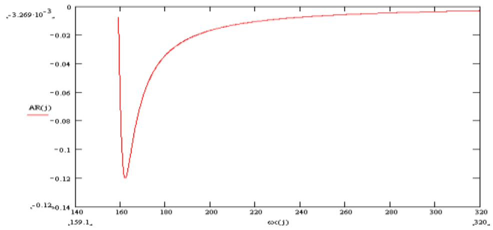


Fig. 7. Minimum of Real part of FRF (f_n=f_c)

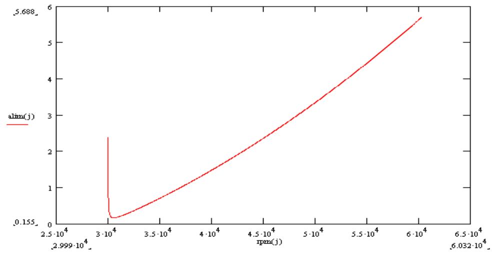


Fig. 8. Prediction of Lobe 0 from the real part of FRF

The lobe 0 can be drawn by inferring the minimum values of real part of FRF as shown in Fig. 7 and substituting in Eq (4 & 5) gives the axial depth of cut limit and speed in rpm as shown in Fig. 8.The successive lobes can be generated by using Eq (5) substituting k=0,1,2….; that resembles the Fig. 9.

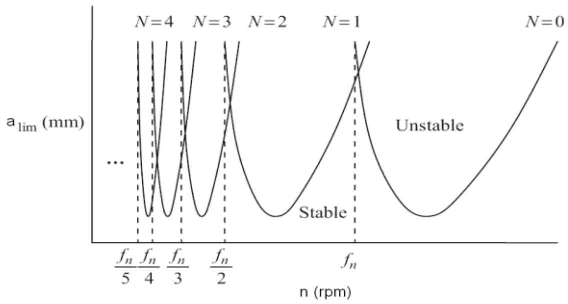


Fig. 9. Depiction of multiple stability lobes

The stability lobes considering the selected input parameters are drawn as Excel chart showing Lobe 0, Lobe 1, Lobe 2 and Lobe 3 as shown in Fig. 10. Since the series of relationship curves in Fig. 10 are shaped like lobes, the graph is usually called a stability lobe diagram. A stability lobe diagram shows the relationship between chip width (or depth of cut) and spindle speed, with the lobe number as a parameter.

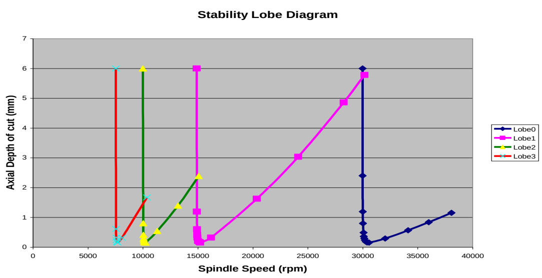


Fig. 10.Analytical Stability lobe diagram

V. PROPERTIES OF THE STABILITY LOBE DIAGRAM

In a stability lobe diagram, a series of scallop-shaped lobes intersect with each other. These lobes form the limits for chattering. Locally, for each lobe, it is stable below the lobe, and unstable above the lobe. Since the lobes intersect, a point located below one lobe could be above the neighboring lobe. This point must be treated as unstable. Therefore, globally, we must consider the relationship between adjacent lobes in determining stability.ALL THE POINTS ABOVE THE CHATTER LINES ARE UNSTABLE, AND BELOW ARE STABLE. AS SPINDLE SPEED INCREASES, THE LOBES BECOME WIDER WITH LARGER INTERVENING SPACES BETWEEN CONSECUTIVE LOBES, AND INTERSECTION POINTS ARE HIGHER. THIS PHENOMENON CREATES A DESIRABLE SITUATION FOR MACHINING AT BOTH HIGHER SPEED AND DEEPER CUT SIMULTANEOUSLY, AS WELL AS AT A WIDER SPEED RANGE.

VI. CONCLUSION

In this paper, a new analytical method to obtain the information related to the stability of a machine-tool-work piece system for a milling process was proposed. The simulation of FRF is based on the equations of single degree of freedom system forced vibration. Considering the flexibility of the work piece will influence more on stability lobes. The real and imaginary parts of FRF have been simulated using MathCAD software. The experimental setup has been proposed for finding the impulse response of the machine structure at tool tip. In future the experimental values will be adopted for predicting the stability lobes.

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