Modelling of chatter vibration in thin-wall turning and its effect on surface roughness of job

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ME F313 - Production Techniques II

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1. Introduction

High speed machining processes involve dynamic conditions. Machining can be adversely affected due to unwanted vibrations which may cause damage to the tool, a poor surface finish and a lot of noise, all of which need to be avoided. All of these are extremely undesirable in any machining process, along with a bad machined part, there is higher consumption of energy and a really low efficiency.

Chatter is the relative movement between the cutting tool and the workpiece in the form of vibrations. These resultant vibrations cause waves on the machined surface. These waves are undulated after 1 tool pass and hence affect the machining in the next tool pass. These undulations cause a change in chip thickness which in turn results in a varied cutting force and a deviation from the required machining process. It is a characteristic of chatter to leave marks in the machined surface. **The main cause of chatter is the lack of rigidity of a multi-component machine-tool**. Most machine tools involve high dynamic movements which is why it is difficult to avoid chatter altogether. Chatter can be non-linear in high speed machining if sudden geometry change is encountered by the cutting tool.

Chatter can be classified into 2 types:

i) **Forced Vibrations**: When the tool encounters interruption in the cutting, tool runout or external vibrations from outside.

ii) **Self-Generated Vibrations**: Since the chip thickness depends on the relative position between tool and workpiece during the previous tool passage, vibrations are generated due to these undulations.

Most chatter vibrations can be estimated by **Delayed Differential equations**. In this project we will try to solve the equations for these vibrations and the associated forces via **MATLAB**.

Regenerative chatter is harmful to any process, because it creates excessive vibration between the tool and the workpiece, resulting in a poor surface finish, high-pitch noise and accelerated tool wear. This in turn **reduces machine tool life, reliability and safety** of the operation. It is therefore very essential to predict and detect chatter where the objective is to avoid chatter occurrence in the cutting process in order to obtain better surface finish of the product, higher productivity and tool life.

Chatter can be **recognized by the noise** associated with these vibrations, by the **chatter marks** on the cut surface, and by the **appearance of the chips produced** in turning. Machining with chatter is not desired because of the chatter marks on the surface and because the large and fluctuating peak values of the variable cutting forces, which might cause breakage of the tool or of some other part of the machine. Chatter is often a factor limiting metal removal rate below the machine’s capacity and hence reduces the productivity of the machine.

Thin Walled Parts and difficulties associated with machining these parts:

Thin walled components are basically components with a wall thickness much smaller compared to the rest of the dimensions of the workpiece, like a thin walled pipe or pressure vessels.

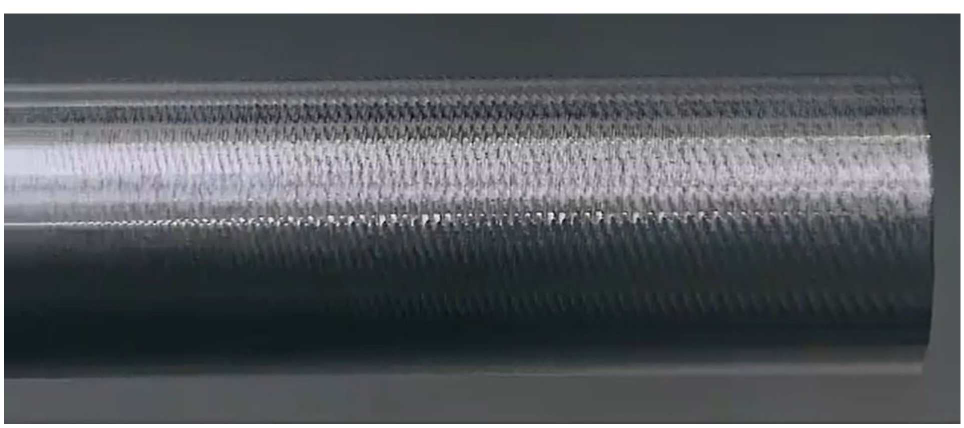
During the CNC turning process, the main challenge for machining thin wall parts is the **deformation**, which may be **caused by the cutting force, which leads to the shape becoming elliptical or small in the middle and big at both ends**. In addition, due to the casing of thin wall workpiece, **poor heat dissipation** further resulting in thermal deformation.

1. The thin walled parts can not bear large radial force, so it is difficult to install with general clamps.
2. Improper clamping, improper clamping force, and poor rigidity of thin wall parts lead to large deformations.
3. The elastic recovery of the workpiece under normal conditions will affect the dimensional accuracy and shape accuracy.
4. Unreasonable fixture design causes positioning error.
5. The cutting heat will also affect the control of parts dimension accuracy.
6. Due to the cutting forces, the workpiece is prone to vibration or deformation, and results in low surface quality and inaccurate size of parts.
7. If the cutting amount is a lot, the production efficiency will be impacted.

Due to the **further lack of rigidity caused due to clamping constraints** in thin-walled turning it becomes even more important to analyse the self generated chatter vibrations as the incremental nature of these vibrations can completely damage the job and destroy the profile initially required by the user. An example of chatter is given in the illustration below.

The **steps to improve** the machinability of these parts include:

1. Ensuring uniform clamping of the workpiece
2. Analyzing chatter vibrations and making suitable adjustments to the machining process.
3. It is always suitable to first machine the inner surface of the thin wall and then the outer wall since the inner-wall is more susceptible to deformation.
4. It is always suggested that the machining process be completed in 1 setup. Since every setup comes with it's own calibration and possible errors associated with it. Thus, especially for critical thin walled components the clamping should be designed such to not have multiple setups.



2. Chatter Model

Introduction:

Turning operation is a machining process used to produce a variety of products by cutting metals. Machining of metals is usually followed by a relative motion between workpiece and tool, which is known as the *Chatter vibration.* Chatter vibration is one of the most studied topics this century and it is still a major obstacle in getting automation for the machining processes including milling, drilling, and turning. It creates various problems like poor surface finish, machine tool breakage, more noise, reduced productivity, and tool life.

Chatter and turning Process:

For a turning process, three types of mechanical vibrations exist due to a lack of dynamic stiffness/rigidity of the tool machine system comprising tool holder, tool, work-piece, and the machine tool. These are **forced free and self-excited vibrations**. Forced vibrations emerge due to unbalanced effects in machine tool assemblies like bearings, gears, and spindles. On the other hand, free vibrations are induced by shock. Both of them can be easily identified and eliminated. But self-excited chatter is complex to understand and hence is most harmful.

History and origination of chatter model:

Research on Chatter done before 1990 aimed at cutting process parameters like feed, speed, and depth of cut. These research models were unable to represent the actual machine–tool dynamics and as a result, the prediction accuracy was low. With the introduction of new parameters like tool wear, process damping, tool geometry, stiffness of machine components, etc over the last 2 decades, the relationship between tool and workpiece has been incorporated successfully. Some of these new dynamic models include the Chatter model using SLD, Analysis using Neural networks, Nyquist, Finite-element method, etc. However, **Meritt's Chatter model is the most widely used**. These new dynamic models represent the real dynamic nature of the machine–tool system and proved to be more accurate in predicting the stability/instability of the turning process.

Parameters required for the chatter model:

- The tool parameters **m, k, and c are the mass, stiffness, and damping coefficient**, respectively. The cutting velocity is neglected for this model.

· x(t) is the wave generated during the current revolution or time, and x(t-T) is the wave generated during the previous time delay or revolution of the workpiece.

· **The phase delay (y)** between the waves in the previous time delay x(t-T) and the current time delay x(t) is **the main factor** governing the occurrence of chatter in the turning process. The undulations on the workpiece will not grow if the two waves are in phase, and the process will remain stable because the chip thickness variation is negligible, hence resulting in a constant force on the tool.

Meritt's Model of Chatter Analysis:

Idea: "*The cutting force variations are determined by considering the total force at any point during the cyclic motion of the tool and corresponding to the instantaneous values of the cutting parameters and tool geometry*".

Considering a 1 Degree of Freedom (SDoF) orthogonal turning process, with a flexible tool and rigid workpiece, the model incorporates various forces acting on the physical system like the damping force, inertia force, cutting force, and the spring force. A **sharp tool is considered with only the cutting force in feed direction** acting in the system. The equation of motion can be **modeled in the radial (feed) direction** as:

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=F_f(t)$$

where,

$$F_f(t)=\text{cutting force in feed } (x) \text{ direction}=K_f * b * [x(t-T)-x(t)]$$

· Kf is the cutting coefficient in the feed direction

· b is the width of the chip (width of cut),

· T is the time delay between the current time and previous time,

· [x(t-T)- x(t)] is the dynamic chip thickness due to tool vibration.

Substituting the second equation into the first, and dividing by m gives:

$$\ddot{x}+\frac{c}{m}\dot{x}+\frac{k}{m}x=\frac{K_f b}{k}\frac{k}{m}[x(t-T)-x(t)]$$

Applying Laplace transform and using relations,

$$\omega_n^2=\frac{k}{m},\quad \frac{c}{m}=2\zeta\omega_n \quad \text{and} \quad \text{assuming} \quad \varphi=\frac{K_f b}{k}$$

$$s^2+2\zeta\omega_n s+\omega_n^2=\varphi\omega_n^2(e^{-sT}-1)$$

From the last equation, the transfer function of the system with a sharp tool can be obtained by direct derivation from the differential equation:

$$\Gamma(s)=\frac{1}{s^2+2\zeta\omega_n s+\omega_n^2}$$

The Real and Imaginary part of the transfer function are found to be:

$$G(\omega)=\frac{\omega_n^2-\omega^2}{R(\omega)} \quad \text{(Real part)}$$

$$H(\omega)=\frac{-(2\zeta\omega_n)\omega}{R(\omega)} \quad \text{(Imaginary part)}$$

where,

$$R(\omega)=(\omega_n^2-\omega^2)^2+(2\zeta\omega_n)^2\omega^2 \quad \text{(Denominator)}$$

ω_n is the natural frequency of the system, ω is the frequency chatter vibration.

The **limiting width of cut (b-lim)**, at which the orthogonal **turning process switches from stable to unstable** (chatter free to chatter present) can be found by the relation:

$$b_{lim} = -\frac{1}{2K_f G(\omega)}$$

The stability equation leads to a **positive real depth of cut only when the real part of the transfer function between the tool and workpiece is negative**. So, this equation gives only an absolute depth of cut when the minimum (most negative) value of G is considered.

Defining the phase angle:

$$\psi = \tan^{-1}\frac{H(j\omega)}{G(j\omega)}$$

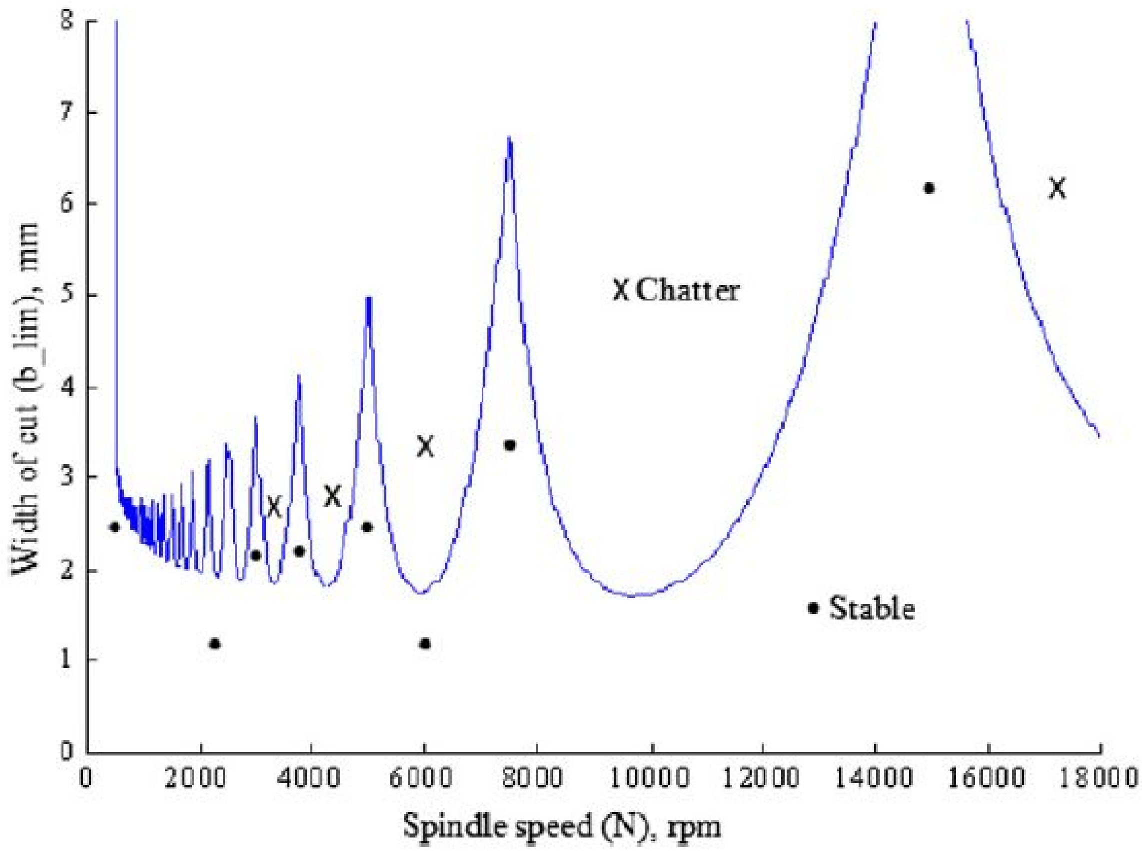
and with some mathematical manipulation, the spindle period(T) and phase shift(theta) can be obtained as:

$$T = \frac{1}{\omega}\left[2n\pi + \theta\right], \quad \theta = 3\pi + 2\psi$$

The spindle speed can be obtained by:

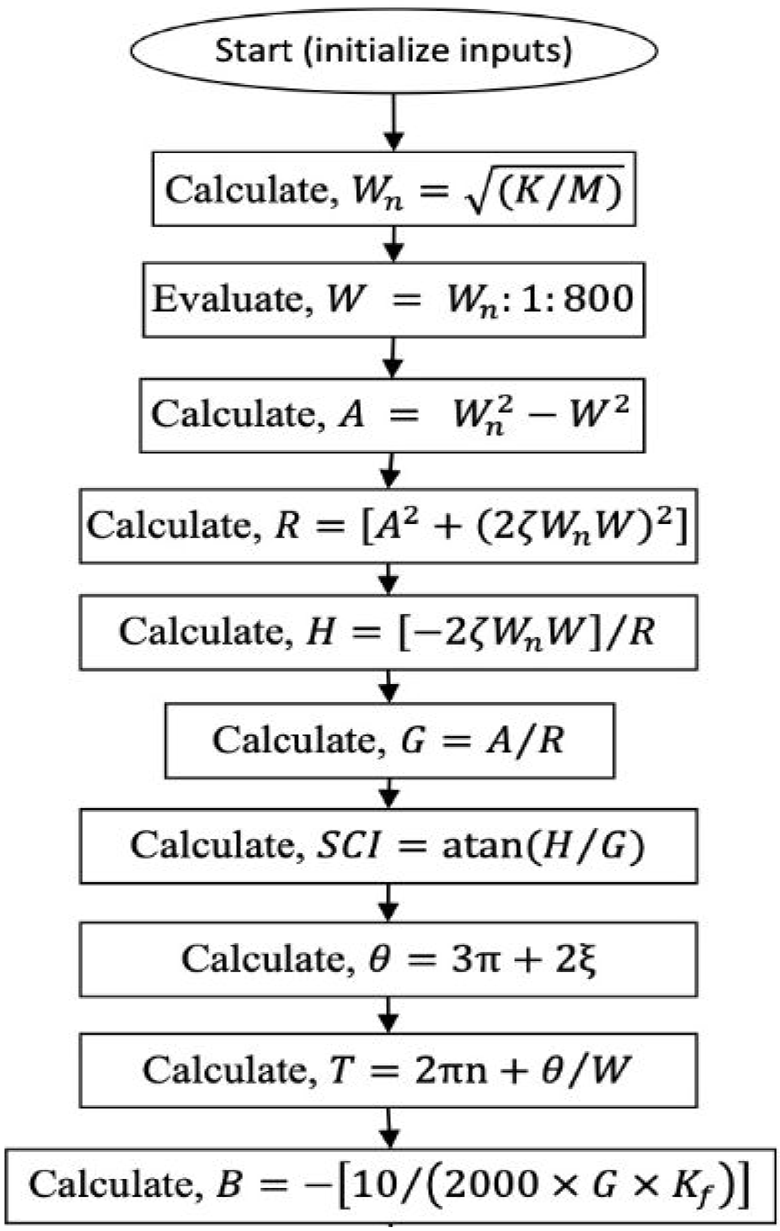
$$N = 60/T$$

These equations can be used to produce the so-called stability lobes diagram (SLD) showing the relationship between the limiting width of cut(b-lim) and spindle speed(N) for the turning operation as shown:



How Stability Lobes Diagram could reduce/avoid the Chatter and Vibrations:

The **most significant cutting parameter**, which decides the generation of chatter in a turning process, is the **depth of cut (chip width) b**. When the chip width is smaller, the cutting process is more stable. By increasing chip width, chatter starts to occur at a certain chip-width b-lim (limiting depth of cut) and **becomes more energetic for all values of b>b-lim**. The value of blim depends on the dynamic characteristics of the structure, on the workpiece material, cutting speed and feed, and on the geometry of the tool. On the SLD, the limiting depth of cut blim is plotted against spindle speed (N). Vibrations between the tool and workpiece appear on the plot as different lobes and any depth of cut and spindle speed combination which falls below these lobes results in a **stable operation, also known as "chatter free",** and above these lobes in an **unstable (chatter present) operation**. By using SLDs, thus it becomes relatively easy to select ideal spindle speed and depth of cut combinations for maximizing MRR in a turning process. This flowchart explains the process more clearly:

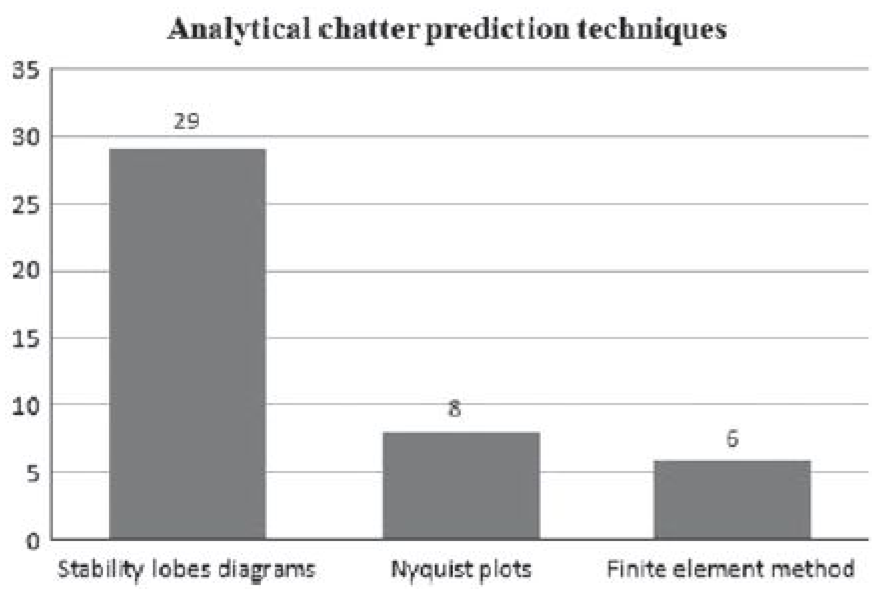

Start (initialize inputs)
Calculate, $W_n = \sqrt{(K/M)}$
Evaluate, $W = W_n : 1 : 800$
Calculate, $A = W_n^2 - W^2$
Calculate, $R = [A^2 + (2\zeta W_n W)^2]$
Calculate, $H = [-2\zeta W_n W]/R$
Calculate, $G = A/R$
Calculate, $SCI = \text{atan}(H/G)$
Calculate, $\theta = 3\pi + 2\xi$
Calculate, $T = 2\pi n + \theta/W$
Calculate, $B = -[10/(2000 \times G \times K_f)]$

<u>**Why SLD technique is preferred over other techniques like FEM**</u>:

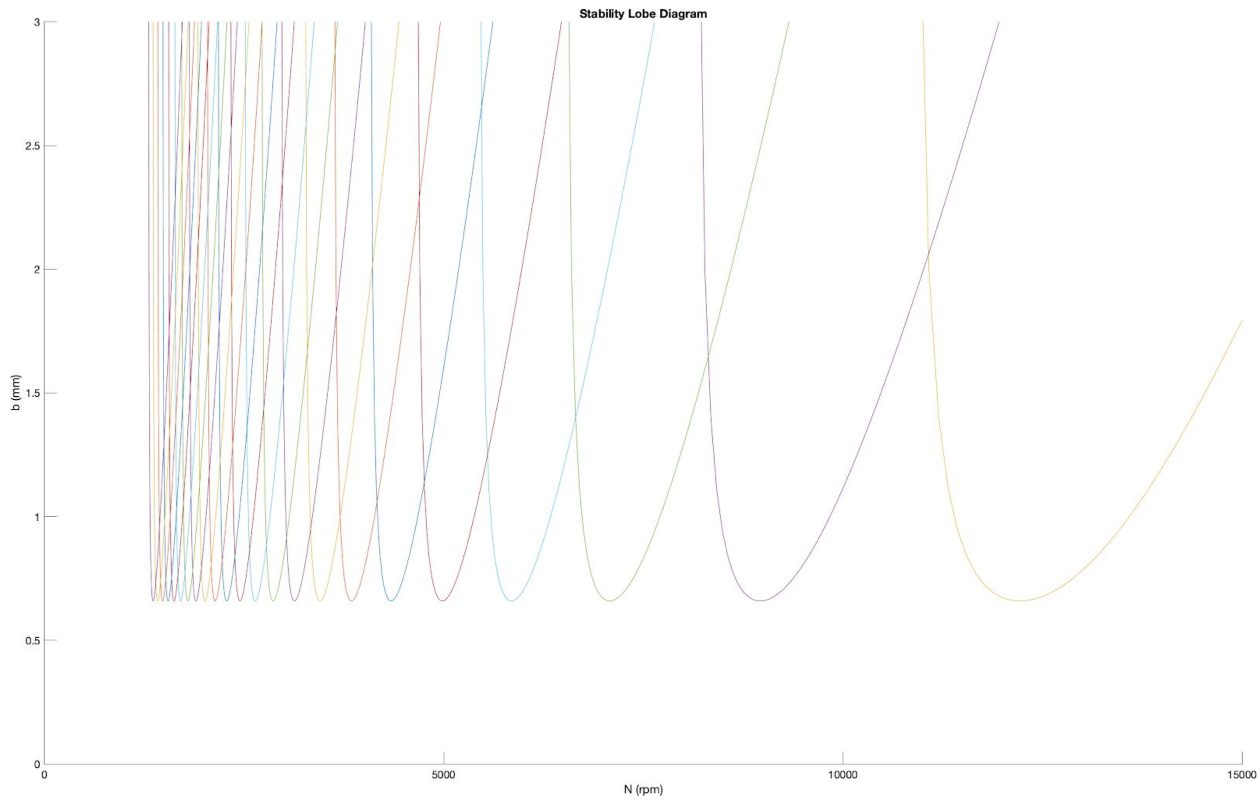
· The construction of stability lobe diagrams is the **most popular technique** because of its **clarity and simplicity** in defining unstable and stable cutting states.

· The stability lobe diagrams can be produced for mathematical models containing **any number of DoF** (degrees of freedom) cutting processes. For higher degrees however, Nyquist criterion of stability is used to give the SLD diagrams.

This figure shows **the number of publications over the years for SLD techniques over other techniques**, and hence we prefer using the SLD technique in this project:

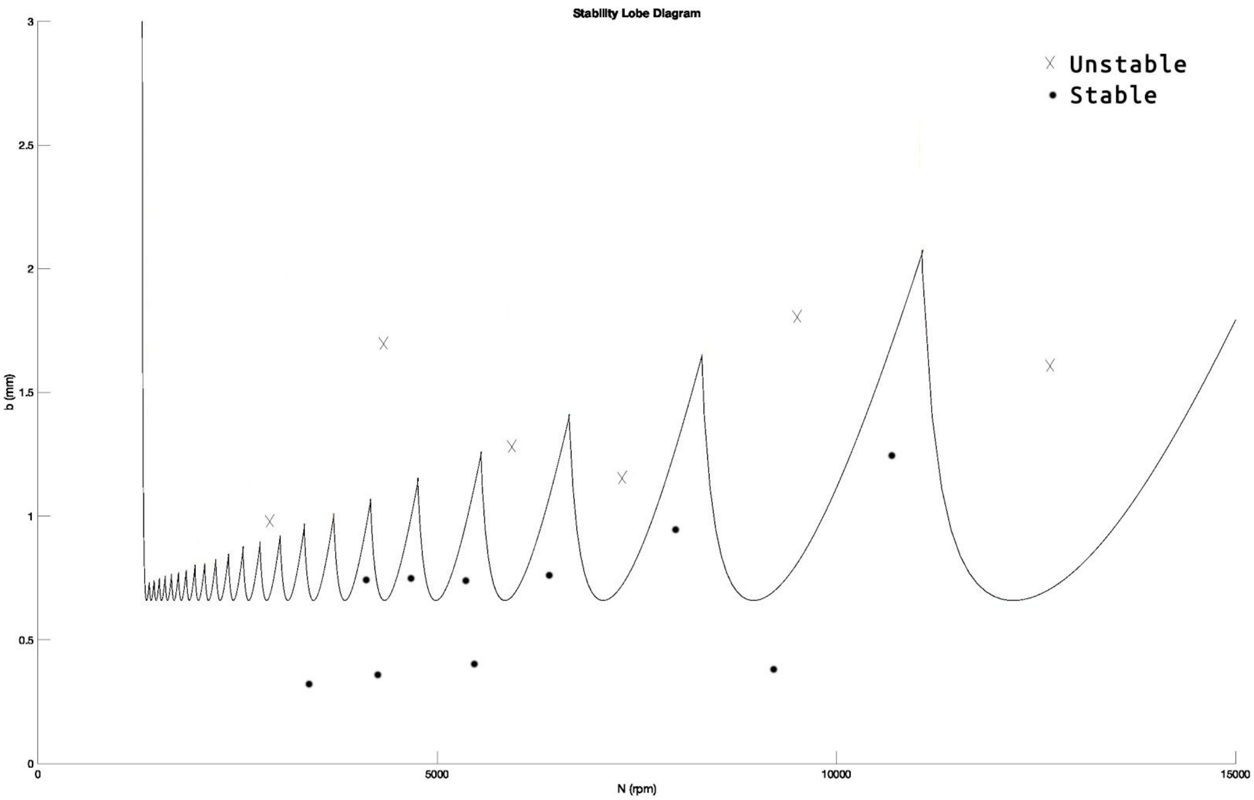


Using the MATLAB code as given in the appendix, the raw graph obtained is given in the figure below. The constants taken are: **m = 0.561; k = 6.48e6; c = 145; Kf = 1384**.



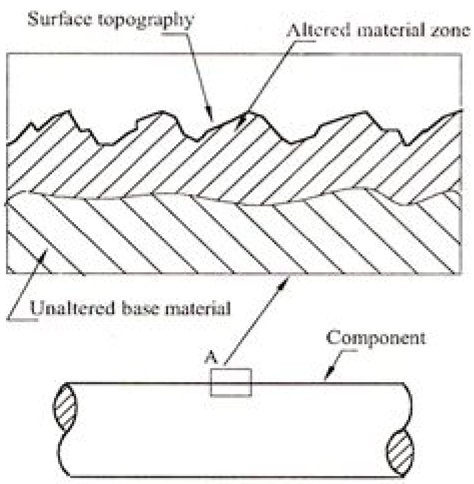
The chart includes lobes for each mode of vibration and provides the limiting depth of cut for each spindle revolution. **Above each lobe, chatter occurs**. We have taken 25 lobes in this graph.

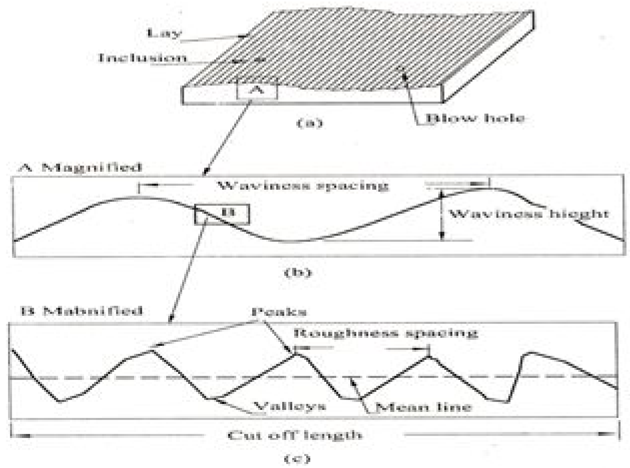
The chart was formatted and cleaned to make it more informative. All intersection plots were removed, and only the limiting values were shown. The formatted chart, given below, also shows the areas of stable and unstable machining.


Stability Lobe Diagram
Unstable
Stable
b (mm)
N (rpm)
0
0.5
1
1.5
2
2.5
3
5000
10000
15000

3. Surface Roughness due to Chatter Vibration

Roughness: Relatively fine-spaced surface irregularities. It is produced by **cutting actions of the tool edge, abrasive grains and feed marks** by the cutting tool.





Some factors which affect surface quality

- Machine tool rigidity and bearing accuracies.
- Finishability of work material.
- Type and condition of cutting tool.
- Applications of cutting fluid.
- Method of chip removal.
- Geometry of cutting tool.
- Cutting variables.

Chatter, which arises due to **tool or workpiece vibrations**, may occur due to non-rigid connections. We have solved the **delay differential equation** given in the first chapter to find radial displacement of the tool with respect to time. Using these radial displacements, the surface topology of the workpiece can be predicted during the chatter process.

The graph of y vs t is given in the figure below. The algorithm used in obtaining the graph involves the following steps:

1. Converting the second order delay differential equation to **state-space form**.
2. Modelling the chatter history function, which serves as the boundary conditions - At time t = 0, **tool is just touching the workpiece. y is negligible and y' = 0.**
3. Modelling the dde function, based on the documentation given for ddesd in matlab.
4. Modelling the delay function = **60/N, N = 4000 rpm** taken.
5. Use the following constants: **m = 1.742 [kg], k = 7.92 · 10^6 [N/m], c = 176.8 [N/m/s], Kf = 2585 [N/mm2]**
6. Use the following equation, plug the constants into dde function:

$$\dot{y}_2 = -\frac{c}{m} y_2 - \left(\frac{k}{m} + \frac{K_f b}{m}\right) y_1 + \frac{K_f b}{m} YL(1)$$

7. Use **ddesd**, solve for y, plot the graph.

The **documentation** followed for solving delay differential equations with state dependencies is given as follows:

ddesd

Solve delay differential equations (DDEs) with general delays

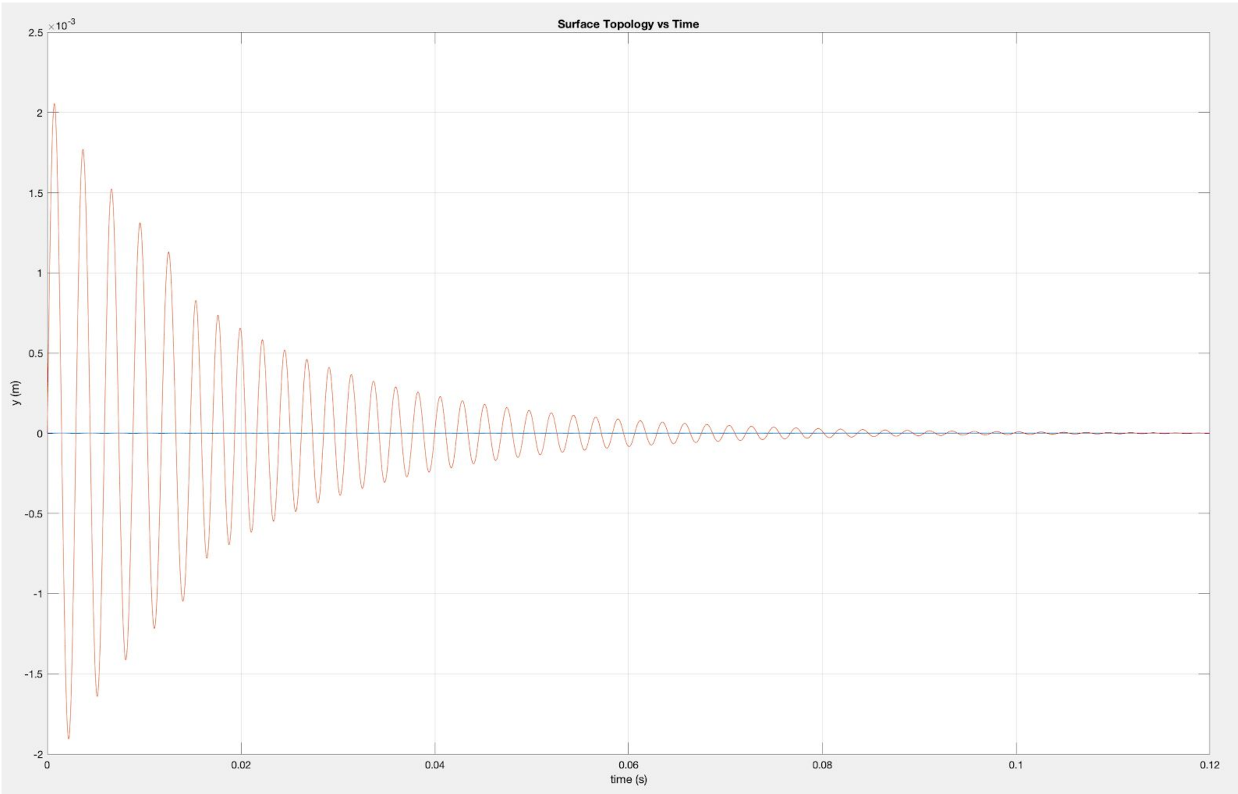
Syntax

```
sol = ddesd(ddefun,delays,history,tspan)
sol = ddesd(ddefun,delays,history,tspan,options)
```

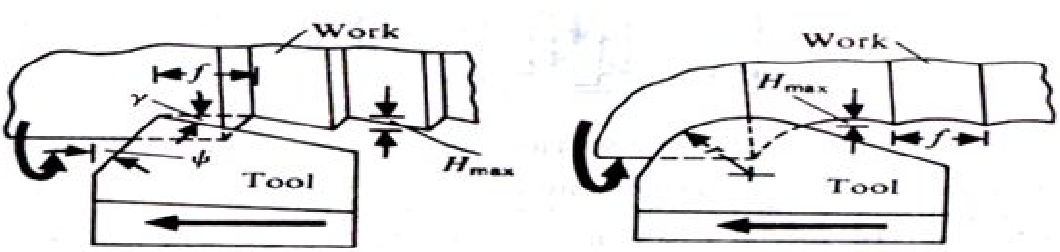
Arguments

`ddefun`	Function handle that evaluates the right side of the differential equations $y'(t) = f(t,y(t),y(d(1),...,y(d(k)))$. The function must have the form `dydt = ddefun(t,y,Z)` where `t` corresponds to the current t, `y` is a column vector that approximates $y(t)$, and `Z(:,j)` approximates $y(d(j))$ for delay $d(j)$ given as component j of `delays(t,y)`. The output is a column vector corresponding to $f(t,y(t),y(d(1),...,y(d(k)))$.
`delays`	Function handle that returns a column vector of delays $d(j)$. The delays can depend on both t and $y(t)$. `ddesd` imposes the requirement that $d(j) \le t$ by using `min`$(d(j),t)$. If all the delay functions have the form $d(j) = t - \tau_j$, you can set the argument `delays` to a constant vector `delays`(j) = τ_j. With delay functions of this form, `ddesd` is used exactly like `dde23`.
`history`	Specify `history` in one of three ways: • A function of t such that `y = history(t)` returns the solution $y(t)$ for $t \le t_0$ as a column vector • A constant column vector, if $y(t)$ is constant • The solution `sol` from a previous integration, if this call continues that integration
`tspan`	Interval of integration from `t0=tspan(1)` to `tf=tspan(end)` with `t0 < tf`.
`options`	Optional integration argument. A structure you create using the `ddeset` function. See `ddeset` for details.

The state dependence here is simple, **y2 is assumed to be y1'**, which makes **y2' = y1"**. Such state dependencies are commonly used in solving DDEs and ODEs using computational methods on MATLAB and Python.



Ideal roughness: **Turning**



(a) Using tool without nose radius

(b) Using tool with nose radius

Generation of ideal roughness in turning.

$$H_{max} = \frac{f}{\tan\psi + \cot\gamma}$$

$$f = Feed\ per\ revolution$$

$\psi = Side\ cutting\ edge\ angle$

$\gamma = End\ cutting\ edge\ angle$

$H_{avg} = H_{max} /4$

Comparing chatter results with theoretical values

H_{max} obtained from solving delay differential equation = 2mm

Therefore $H_{av} = H_{max}/4 = 0.5$mm

$H_{av,theoretical} = f/4(\tan\psi + \cot\Upsilon) = 0.0113/(4*(\tan(15)+\cot(5))) = 0.24$mm

Therefore, it can be seen here that based on the input parameters, ψ = 15 deg, Υ=5 deg, N = 4000 rpm, f = 0.17 mm/rev, the surface roughness in the chattered region was **double** that of the theoretical surface roughness obtained by orthogonal turning without chatter, assuming negligible nose radius.

Appendix

MATLAB Code for obtaining stability characteristics:

```
clear;
clc;

m = 0.561;
k = 6.48e6;
c = 145;
Kf = 1384;

omega_n = sqrt(k/m);
zy = c/(2*m*omega_n);

omega = 500:10:20000;

G = (omega_n^2 - omega.^2) ./ ( (omega_n^2 - omega.^2).^2 + (2*zy*omega_n*omega).^2 ) ;
H = -(2*zy*omega_n*omega) ./ ( (omega_n^2 - omega.^2).^2 + (2*zy*omega_n*omega).^2 ) ;

psy = PhaseAngle(H,G);

j = find(G<0,1);
negOmega = omega(j:end);
negG = G(j:end);
negPsy = psy(j:end);

N = zeros(25,size(negG,2));
A = zeros(25,size(negG,2));

transferFunction = complex(G,H);

hold on;

for i = 0:24                    %25 lobes
    N(i+1,:) = 60*negOmega ./ (2*i*pi + 3*pi + 2*negPsy);
    A(i+1,:) = -1e-3 ./ (Kf*2*negG);
    plot(N(i+1,:),A(i+1,:));
end

title('Stability Lobe Diagram')
xlabel('N (rpm)')
ylabel('b (mm)')
ylim([0 3]);
xlim([0 15000]);

function angle = PhaseAngle(H,G)
```

```
angle = zeros(1,size(G,2));
for i=1:size(G,2)
    if (G(i)>0) && (H(i)<0)
        angle(i) = - atan(abs(H(i)/G(i)));
    elseif (G(i)<0) && (H(i)<0)
        angle(i) = -pi + atan(abs(H(i)/G(i)));
    elseif (G(i)<0) && (H(i)>0)
        angle(i) = -pi - atan(abs(H(i)/G(i)));
    else
        angle(i) = -2*pi + atan(abs(H(i)/G(i)));
    end
end

end
```

MATLAB Code for solving Delay Differential Equation:

```
clc;
clear;
close all;
tf=0.12;
sol = ddesd(@ddefunc,@delays,@yhist,[0 tf]);
t=linspace(0,tf,60000);
y=deval(sol,t);
figure;
subplot(1,1,1);
plot(t,y);
grid on;

function d=delays(~,y)
  d=0.015;
end

function yp = ddefunc(~,y,YL)
yp=[ y(2)
    (2967853*YL(1)-(7514351)*y(1)-101.5*y(2))];
end

function y=yhist(t)
 y=[-1e-6 0];
end
```

Code files available on GitHub at https://github.com/kannykanishk/chatter-turning

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