ANALYTICAL AND EXPERIMENTAL TECHNIQUES FOR CHATTER PREDICTION, SUPPRESSION AND AVOIDANCE IN TURNING: LITERATURE SURVEY

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Abstract: Chatter is a self-excited vibration that takes place during turning operations. It is either to be avoided or reduced for its negative impact on the machine-tool, the workpiece surface finish, and the cutting tool life. A lot of research has been carried out in this domain to understand this phenomenon, which leads to finding ways to detect, identify, avoid, reduce, and control chatter in turning processes. In this paper, chatter research related to turning processes is reviewed and summarized. The main goal of this review paper is to compare different chatter prediction, suppression, and avoidance techniques to find out the most effective technique, so a scope of a work related to turning processes chatter is defined.

Keywords: Chatter, Vibration, Stability, Turning, Spindle

1. INTRODUCTION

Chatter has four main types, regenerative chatter, mode coupling chatter, frictional chatter and force -thermal chatter. In machining when chatter is present, the surface quality is poor, the tool life is shorter and the productivity decreases [1]. The earliest work related to chatter was performed by Arnold. He investigated experimentally and analytically the behaviour of a cutting tool during the cutting process of a lathe machine and came up with an explanation about the chatter generation mechanisms. It was shown that the chatter is a result of the forces generated during the cutting process, not a result of external periodic forces. In the recent years, various methods were suggested to suppress chatter. Yao proposed a method for chatter identification before it is fully developed based on wavelet and support vector machine. Anderson developed a passive adapter to suppress resonance vibrations of an end mill cutter. Albizuri proposed a method to reduce chatter vibrations using actively controlled piezoelectric actuators. Dohner used the so-called active control approach for mitigating chatter. Chen used active magnetic bearings for the aim of suppression of machining chatter. Wu [2], Otto [3] and Kambiz [4] studied using variable spindle speed machining to suppress chatter. Yang [5] used multiple tuned mass dampers to suppress machine tool chatter. Tobais explained

that a machine-tool system including the cutting tool, the tool holder and the work-piece witnesses free, forced and self-excited vibrations. Free and forced vibrations can be detected and suppressed since they are the results of shocks and unbalances respectively. Due to the complex nature of self-excited vibrations in machining processes and due to their harmful effects, they are in interest of research. Chatter that results from the self-excited vibrations is classified into two main categories, primary and secondary chatter. Primary chatter is less of interest as it is the result of mainly the interaction between the cutting tool and the workpiece. When it comes to the secondary chatter as it is the result of the regeneration of the wavy surface on the just machined workpiece surface, it is in more interest of research and investigation. Moreover, compared to the other types of vibrations, this one is the most harmful one. *Figure 1* illustrates the difference between chatter occurrence and smooth turning. In this paper, some of the analytical and experimental techniques for chatter prediction and avoidance are reviewed specifically for turning processes.
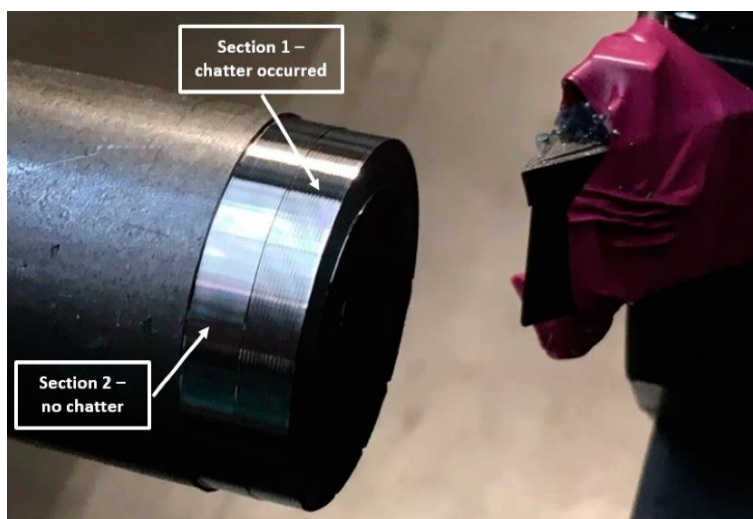

Figure 1. *Chatter occurrence in turning process* [6]

2. ANALYTICAL CHATTER PREDICTION TECHNIQUES

For the analytical techniques of chatter prediction, A lot of models are available in the literature. The main three ones are the construction of stability lobes diagram (SLD), Nyquist plots and the finite element method. These analytical techniques are reviewed in this paper.

2.1. Stability Lobes Diagram (SLD)

Stability lobe diagrams are essential tools that are used in optimizing some turning processes parameters for maximizing the rate of material removed while keeping stable cutting conditions. In SLD, the stable and unstable areas are distinguished

by the graph itself as illustrated in *Figure 2*. Chatter takes place at high chip widths. The depth of cut (chip width) is the most important factor of cutting in terms of chatter presence. The maximum value of depth of cut without having chatter depends on the workpiece material, cutting speed and feed, and on the geometry of the tool.

Figure 2. Example stability lobe diagram

Analytical models were presented by many researchers based on the number of DoF (degrees of freedom) of the cutting process. Starting with the SDoF (single degree of freedom) models, Hanna and Tobias introduced a model with a time delay-differential equation. The model takes into consideration the cutting force and the structural stiffness. Chatter is predicted in three categories, unconditionally stable, conditionally stable, and unstable which is affected by the width of cut. In the model, even in the stable category there is a presence of unstable periodic motions which is considered a weakness point of the model. Suzuki et al introduced a model defining equivalent transfer function in order to understand the effects of the cutting force ratio and the cross-transfer function on the stability of cutting. An interesting finding is that the critical width of cut in the clockwise and the counter clockwise rotation is different from each other in the experiment. The stability limits were estimated from the vector diagram of the equivalent transfer function. Dombovari et. al [7] analysed large-amplitude motions by introducing a SDoF model that deals with orthogonal cutting. The main equation of the model takes into consideration the non-smoothness when contact between the cutting tool and the workpiece is lost and the regenerative effect of the turning process.

When it comes to the 2DoF models, Chandiramani and Pothala used a 2DoF model of the cutting tool to deal with the dynamics of chatter. The main finding of that model is that increasing the width of cut results in the occurrence of frequent tool-leaving-cut events and the occurrence of increased chatter amplitudes. Suzuki et al introduced a 2DoF model with the same idea of his SDoF which was

mentioned before; it is interesting that both of his models the SDoF one and the 2DoF one gave the same solutions. Chen and Tsao introduced a 2DoF model of a cutting tool with the tailstock supported workpiece and without the tailstock supported workpiece using beam theory. The workpiece is treated as a continuous system and under different spindle speeds, the effect of the critical chip width was studied. The strength of this model is that the ability of predicting the stability and evaluating the influence of the elastic deformation and the workpiece natural frequency on the critical chip width for two different workpiece end conditions.

When it comes to the 3DoF models, tool chatter taking into consideration turning dynamics was studied by Dassanayake by employing a 3DoF model at which the workpiece is modelled as a system of three regions, machined, being machined, and unmachined regions connected by a flexible shaft. It was found that for better results, the workpiece vibration (which is not included in the model) should be considered along with tool vibrations for more accurate results. Eynian and Altintas introduced a 3DoF model of turning by modelling the transfer matrix between the displacements and cutting forces in order to predict the stability regions. Nyquist criterion was used to analytically predict stability regions.

When comparing these analytical models (DoF models), it can be seen that there is no point of going with models that are more than a SDoF unless they result in noticeable higher accuracy. The accuracy of the SDoF models show quite acceptable results in terms of predicting chatter stability for the turning process. However, it would be a good achievement to have a SDoF model with an enhanced accuracy.

2.2. Nyquist Plots

A complex vibration frequency response function can be visualized using Nyquist chart. The dynamic behaviour close to resonances is shown by charting the real and imaginary parts of the response as illustrated in *Figure 3*. This offers a way to distinguish the modes and provides insight into how they are coupled. Hardware used for frequency analysis frequently incorporates mathematical models like the Nyquist analysis.
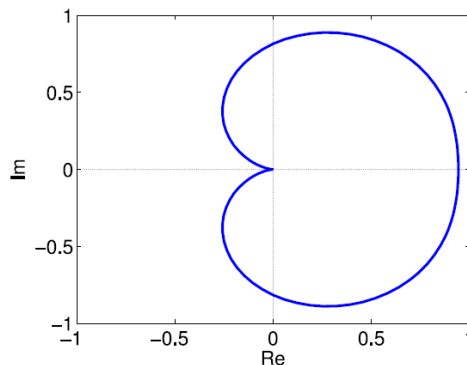

Figure 3. *Nyquist plot example*

Many researchers used control theory to predict chatter vibrations and they implemented Nyquist plots. By modelling the process using an oriented transfer function using τ decomposition forms, Turkes et al. [8] was able to predict chatter vibrations in orthogonal cutting with a SDoF turning system. The stability of the system was investigated using Nyquist criterion in conjunction with an oriented transfer function and a τ decomposition form. Finally, Nyquist technique which is an analytical technique was compared with the time domain simulation technique.

Eynian and Altintas – as mentioned earlier – used Nyquist criterion to analytically predict stability regions. Based on the feedback control theory, Merritt proposed a method that uses Nyquist criterion to predict the stability. Using the same concept and based on the feedback control theory as in Merritt, Nigm introduced another method that has the benefit of taking the dynamics of the cutting process into consideration. The analysis approach could account for the whole spectrum of regeneration and was robust enough to be implemented either analytically or graphically. Nigm used Nyquist criterion to predict the stability. Instead of plotting the open-loop frequency response locus as required by the Nyquist criterion, the method only requires plotting the operative receptance. Even faster than plotting the open-loop frequency response locus is plotting the operative receptance. The critical stability parameter was found by Minis et al. It was derived by using the Nyquist criterion, the criterion was used as an alternative approach by finding the left-most intersection of the Nyquist plot with the negative real axis. Only two-dimensional orthogonal machining could be used with this approach. Also, stability analysis using the Nyquist criterion was performed by Wang and Cleghorn and Altintas et al.

2.3. The Finite Element Method

The literature presents a variety of additional methodologies for the improvement of analytical stability analysis. FEM/FEA is one of them. Urbikain et al. created a FE model for the workpiece in ANSYS using 3D 10-node tetrahedral solid elements type SOLID92. A final workpiece with 35,516 elements was produced after several geometries were designed and analysed. The model parameters were then periodically adjusted to include workpiece evolution during machining into account inside the stability algorithm, which was followed by a FE analysis to create a workpiece. Brecher et al. proposed a 3-dimensional turning model based on FEA. This 3D-FEA model has the capability of predicting the cutting forces that will be generated even for complex-shaped tool geometries. Focusing on the thrust and feed forces, a method was employed to shorten the calculation time by employing characteristic diagrams for the computed process forces in the FEA-model. In any production environment, the FEM/FEA approach is very helpful for predicting stability at the design stage of any process, saving time and money. Mahdavine- jad used finite element analysis and ANSYS software to predict the stability of a turning operation. This FEA model takes into account the flexibility of the machine's structure, workpiece, and tool. Baker and Rouch used ANSYS software to build a structural model of the machine tool system and used the FEM

approach to investigate the instability of a machining process. However, the validity of the results is not supported by experimental data. Without considering the dynamics of the cutting process models, the impact of structural parameters on machine instability was examined. However, the approach described allows the analysis to take into account the flexibility of both the cutting tool and the workpiece. Airao and Chandrakant used the FEA to analyse a turning process and to understand the effect of temperature, vibration amplitude, frequency and cutting speed on the machining responses.

3.   EXPERIMENTAL CHATTER PREDICTION TECHNIQUES

When it comes to chatter prediction experimental techniques, two main methods have received researchers' attention, the first one is the on-line chatter classification, detection, and monitoring and the second one is the traditional experimental techniques for chatter avoidance.

3.1. On-Line Chatter Classification, Detection, and Monitoring

In order to minimize or suppress chatter in real-time applications before it completely develops, it is essential to identify it early on. For this reason, it is crucial that CNC controllers and other external devices provide a time-efficient technique for monitoring vibration or/and process signals. For chatter recognition based on pattern recognition, a variety of methods have been employed, such as support vector machines, sensor-less methods based on power-factor theory indexes, topological data analysis, or the use of regression neural networks when non-linear effects must be addressed.

A method for sensor-less chatter detection was presented by Yamato et al. They achieved this by using two evaluation measures, a mechanical energy factor (MEF) and a mechanical power factor (MPF), both of which are helpful for tracking unstable cutting. The phase difference between the dynamic cutting force and velocity-displacement is shown by these indicators. The authors were able to identify chatter vibration from experimental tests in a precision lathe using only a few calculations. Topological Data Analysis (TDA) and supervised machine learning were integrated by Khasawneh et al. [9] to provide an indicator of chatter's impending presence. In this method, deterministic and stochastic turning models (with different cutting coefficients) work together. Tansel used a neural network technique to study a three-dimensional turning process. In comparison to traditional time series models, their model demonstrated superior nonlinear effect representation. In addition, precision was improved at higher cutting speeds since there is more space between the lobes. Cherukuri et al. evaluated the behaviour of implementing an artificial neural network (ANN) when it comes to modelling stability in turning. The datasets needed to train the ANN were created using the stability boundaries as a starting point. They discovered that over 90% of the time, the ANN was successful in predicting stability. With the aid of an artificial neural network and a mathematical model of responses based on response surface

methodology (RSM), Kumar and Singh analysed the relationship between cutting parameters and chatter degree (ANN). Wavelet Transform was used to eliminate noise from the raw data, and the results demonstrated that ANN was more reliable than RSM. Chatter severity was detected by obtaining a chatter index. Similar methods were employed by Shrivastava et al., who used the wavelet transformation to denoise the raw signal, identify chatter frequency, and calculate chatter index. An operational modal analysis was proposed by Kim and Ahmadi to predict the start of chatter in turning operations. They employed a stability margin of the process, allowing them to predict the start of chatter before the vibrations became intolerable.

In a turning system, the reliability probability of chatter was computed by Liu et al. They compared their results with a Monte Carlo simulation that presented a modified version of conventional stability lobes, using the first order second moment method (FOSM) and fourth moment method. They coded deeper cuts to cross the stability boundary limitations for the experimental validation. Similar to this, Huang et al. used the Laplace transform to calculate the depth of cut to spindle speed ratio utilizing the Monte Carlo method and advanced first order second moment method. Their predictions were verified by real experiments. With adequate precision, Jimenez Cortadi et al. employed the Linear Mixed Model (LMM) for chatter prediction as well as for wear prediction. A neural network analysis for identifying chatter vibration in turning was carried out by Tian. It was proven that this approach was more effective and reliable than the frequency domain approach.

3.2. Experimental Techniques for Chatter Avoidance

When it comes to the experimental techniques for chatter avoidance, it specifically means optimizing the cutting parameters of machining. A time-varying delay can be produced using the spindle speed variation (SSV) approach by distorting chip thickness. As a result, the chatter feedback mechanism is reduced by new, more desirable phase delays between inner and outer chip modulation. There are other approaches to change the head's rotational speed, but the most effective ones introduce a sinusoidal SSV, in which the spindle speed oscillates sinusoidally at a favourable frequency and amplitude.

The method is adaptable to various cutting systems and dynamics. However, when the variation is used, certain previously stable regions of the stability lobe diagram may become unstable. The high spindle accelerations and decelerations, as well as the difficulty in adjusting the frequency and amplitude of the variation, are additional disadvantages of this method. SSV was initially presented in scientific literature to enhance milling processes stability. Al-Regib et al. introduced a simple criterion for determining the ideal amplitude ratio was proposed, along with a heuristic criterion to assist in the process' stability. Based on an energy analysis of the process, Zhang et al. suggested a criterion for determining the ideal SSV amplitude. They also suggested a stability increment index (SII) of SSV in relation to constant spindle speed (CSS). The Ideko-IK4 research team produced various works on the SSV technique used in milling and grinding operations. In

some circumstances, such as those involving small workpiece diameters, this approach might be challenging to use. The reference spindle speed, which is limited by the workpiece diameter and work material, is frequently correlated with the SSV amplitude. High spindle speeds are required for smaller workpiece diameters in order to maintain acceptable cutting speeds. Additionally, the variations in spindle speed cause spindle speeds to increase.

A comprehensive formulation for modelling stability in turning and milling operations utilizing SSV for the semi-discretization approach was presented by Insperger et al. in. However, according to some researchers, the SSV approach is more effective in turning than milling since turning naturally involves slower cutting speeds. The tool's stability analysis was created by Wu et al. utilizing a discrete angle approach. The workpiece's angular position is given by C-axis works as the independent variable in this method. Along with using a stability index criterion, they examined the impact of variable speed machining on the stability of noncircular turning. A closed-loop dynamic model of the noncircular turning process was added by Wu and Chen to the earlier work. They found that both constant and variable spindle speeds led to some improvements in the stability of noncircular turning.

As demonstrated by Yilmaz et al., the most unstable eigenmode was strongly dampened and stabilized in turning. An interesting model for the prediction of stability lobes using the SSV approach was proposed by Otto and Radons [3] in turning. They outlined the procedures for putting this technology into practice and noted that, as compared to milling processes, turning processes may achieve greater stable chip widths. Additionally, they suggested advantageous circumstances to regulate the spindle speed's maximum acceleration. The outcomes of the experiments were not included in that research. Adapting the Chebyshev collocation approach and the Homotopy Perturbation Method (HPM) for chatter onset prediction, Urbikain et al. investigated the use of varying turning speeds during the turning of a piece to mitigate this. Speed functions of the sine-wave variety were created and tested for validity using a laser tachometer. Good agreements were reached for chatter types A and B. However, they did not take into account temperature effects on spindle speed in their investigation.

It is well known that the stability boundaries depend on a specific spindle speed and uncut chip load combination; nevertheless, the single time-varying parameters (STVP) approach has demonstrated chatter reduction by, for example, time-varying tool rake angle and time-varying federate. However, the Multiple Time-Varying Parameter (MTVP), which in certain circumstances gave chatter reductions up to 80%, can be used to strengthen the resilience of this method, according to the authors.

4. CONCLUSIONS

The first focus of the literature review was stability prediction using analytical and numerical techniques. As a result, specific sections that highlight the key developments in these techniques (analytical and experimental) are presented.

Numerous scholars attempted to generalize the problem of chatter in turning since it is not a problem with many chatter types and variations. SLDs are the most practical method of chatter vibration process prediction. Even SLDs created using a basic SDoF orthogonal turning model produces results and prediction accuracy that are acceptable. Nyquist Plots is a good method when dealing with chatter, still it is in less interest compared to SLDs. The finite element method gives interesting results, yet with the development of the fields with high capabilities, the results are expected to be enhanced. Experimental techniques are an adequate and practical alternative when analytical modelling becomes very complicated and challenging. Among the mentioned experimental techniques, the SSV is a promising one and still have room for further development.

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