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An Investigation of Cutting Tool Chatter Vibration in Machine Tools

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Abstract

The purpose of this study was to assemble and condense the research and background literature available on cutting tool chatter vibration. Another requirement was to translate the highly technical language of the researcher into a form readily understandable to shop floor personnel.

Support staff called upon to assist in the elimination of chatter problems have not been given the informational resources necessary to effectively deal with the phenomenon. This information should be gathered from university libraries and cutting tool experts and combined into one basic reference work.

If collecting the references were all that was required they could simply be photocopied, transcribed, and tied in one neat bundle. However an additional problem was posed by the technical depth of the typical journal article. When examining any particular aspect of the chatter process in detail this is necessary and might be required to bring about a solution to an individual case of chatter. What is missing is an overview or roadmap to help the novice focus in on the area of the subject needing the exhaustive analysis.

The last step in this process was to verify the accuracy and effectiveness of the guide produced.

An Investigation of Cutting Tool Chatter Vibration in Machine Tools

A Research Paper for Presentation
to the Graduate Faculty
of the
Department of Industrial Technology
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In Partial Fulfillment of the Requirements for
the Non-Thesis Masters of Arts Degree

by
Arneil Olson
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Problem Statement

While much experimental work has been done on cutting tool chatter vibration, many people working with metal cutting processes in industry remain ignorant of its true causes and cures. Wasteful expenditures of time and resources are made in attempts to eliminate the chatter which chronically plagues some types of machining operations.

The body of literature available on cutting tool vibration chatter is highly specialized and technical. This resource is not readily available or intelligible to technicians and engineers called upon to solve chatter problems in industry. As a consequence these people are forced to rely on their intuitive understanding of machining processes to develop solutions, in short they make guesses.

As if making guesses isn't enough impediment to efficient problem solving, the horizons of these members of a manufacturing organization are inevitably limited by their function. For example, a machine repairman given the assignment to rid a process of chatter is somewhat constrained to a range of actions and resources available to this job title. In other words even if their guesses were right they wouldn't be able to try the solution.

The problem of this study was to investigate the literature and expert knowledge available on cutting tool vibration chatter. The first subproblem was to create a guide to the causes and cures of chatter. This guide is to be basic enough to be used at all levels of the organization yet all inclusive as to range of possible solution strategies. The second subproblem was to attempt to verify the accuracy and usefulness of the guide.

Statement of Purpose

The purpose of this study was to assemble and condense the research and background literature available on cutting tool chatter vibration. Another requirement was to translate the highly technical language of the researcher into a form readily understandable to shop floor personnel.

Support staff called upon to assist in the elimination of chatter problems have not been given the informational resources necessary to effectively deal with the phenomenon. This information should be gathered from university libraries and cutting tool experts and combined into one basic reference work.

If collecting the references were all that was required they could simply be photocopied, transcribed, and tied in one neat bundle. However an additional problem was posed by the technical depth of the typical journal article. When examining any particular aspect of the chatter process in detail this is necessary and might be required to bring about a solution to an individual case of chatter. What is missing is an overview or roadmap to help the novice focus in on the area of the subject needing the exhaustive analysis.

The last step in this process was to verify the accuracy and effectiveness of the guide produced.

Statement of Need

"It is well known that chatter vibration is one of the main causes for the decrease in machining accuracy, efficiency, and machine tool life" (Ha & Kim, 1987, p. 58). Liu (1985b) stated that "Machine tool dynamics against chatter vibration is a challenging subject of metal-cutting research ... because of its role as the limiting factor in machining productivity" (p. 107).

In some processes cutting tool chatter vibration can reduce the output to a trickle or shut it off completely. The cost associated with this restricted production can be tremendous and still further magnified if it occurs in a tightly scheduled flexible manufacturing system (Liu, 1985a). This is because it becomes the controlling factor in a series of operations which are dependent upon the one experiencing the chatter.

Inability to quickly diagnose and remedy these situations leads to days worth of unnecessary repairs and no permanent cure. The system used to troubleshoot chatter problems is likely to be one of buck passing. The process engineer doesn't know how to get rid of it, so he says it must be something wrong with the machine. The machine repairman hasn't a clue either so the tool investigator is requested. The cycle goes on with much unnecessary repair and replacement of components. Often some process variable changes enough to cause the chatter to cease for awhile. Then everyone involved breathes a sigh of relief and attempts to disassociate themselves with the process before the problem reappears.

There was a strong need for an instrument that will provide an authoritative reference identifying the true sources of cutting tool chatter vibration. Once the cause is known then the various specialities involved will be able to work together to eliminate it, each contributing what they can to solve the problem. This instrument should also be updated periodically to reflect the most recent discoveries in the field. Fishwick and Tobias (1958) stated: "It is the opinion of the authors that theoretical chatter research is likely to find a practical application only when the stability conditions are discussed in a way which is at once simple to understand and easy to survey" (p. 1079). Tobias (1965) restated the problem this way "the practical man often has to find a quick solution to a given problem and has no time to make a laborious study of the subject. In this situation he needs a reference book which summarizes the results obtained by research and which gives him a pointer to the solution of his problem" (p. v).

Identification and control of the causes of chatter will become more important in the future. Spindle speeds and metal removal rates have been comparatively low till now. The trend to high speed, high power machining will place processes more often in the unstable areas leading to chatter. "In trying to increase metal removal rates it is mostly the requirement of avoiding chatter vibrations which imposes the limit which is then related to the dynamic stiffness between tool and workpiece" (Tlusty, 1988, p. 4-3). Fabricated steel weldments are used in the construction of most machine tools today. They do not dampen vibration as well as the traditional cast iron castings. This will also contribute to higher incidence rates of chatter.

Statement of Hypotheses

It was hypothesized that sufficient research has been done on this subject to allow some insights into the causes of chatter. It was also hypothesized that two machine tool faults often blamed for chatter would not be a contributing factor. These conditions are mechanical looseness and faulty spindle bearings.

Assumptions

The following assumptions were made in pursuit of this study:

1. It was assumed that the processes under consideration by the researchers were similar enough to those commonly used in industry to allow generalizations to be made.

2. It was assumed that identifying and curing chatter will be possible with the resources available to the support personnel of a well equipped production facility.

3.It was assumed that recent increased availability of powerful personal computers and application software make it more likely that analytical tools formerly available only to specialized laboratories will be at the disposal of engineers in the field.

Limitations

This study was conducted in view of the following limitations:

1. It appears that the subject of cutting tool chatter vibration has received a great deal of attention in the countries of Japan and Germany. Several of the references identified in the literature were in the native language of these countries. The researcher was not conversant in these languages nor was it likely that a technically qualified translator would be easily located.

2. While cases of chatter occur periodically in the researchers experience the interval between occurrences is erratic. Validation of this guide by test cases will be an ongoing process. For the present, additional emphasis was to be placed on testing the proposed reference through review by contributing experts.

3. "the basic problem of establishing a universal force relationship with respect to the dynamic variables in metalcutting has apparently not been solved" (Liu, 1985b, p. 107). Obviously all the answers are not known and the proposed guide cannot be a definitive reference work.

Definition of Terms

The following terms are defined to clarify their use in the context of the study (Schneider, 1989):

Build-up; The welding of chips to the cutting tool. It is the major cause of surface roughness.

Cutting tool chatter vibration; Vibration between the tool work sufficient to cause an irregularity in the tool marks on the finished surface.

Chip; A fragment of the work material which has been separated in the machining operation. The ideal steel chip is shaped like a figure 6 or a figure 9.

Clearance; The angle below or behind the cutting edge which allows the cutting edge to be forced into the work. Without clearance, the tool will not cut. It is also the term used for secondary relief in some cases.

Cutting Edge; That part of the face edge along which the chip is separated from the work. The cutting edge consists of the side cutting edge, the nose, and the end cutting edge.

Edge preparation; A conditioning of the cutting edge, such as honing or chamfering.

End Cutting Edge Angle; The angle between the cutting edge on the end of the tool and a line perpendicular to the side edge of the straight portion of the tool shank.

Entrance Angle; The angle which the side-cutting edge of a tool makes with the machined surface of the work, measured on the cutting edge side of the tool point.

F.P.M.; Feet Per Minute

Face; That surface of the cutting tool on which the chip impinges as it is separated from the work.

Feed; The relative amount of motion of the tool into the work for each revolution , stroke, or unit of time.

Flank; That surface which is adjacent to the cutting edge and below if when the tool is in a horizontal position for turning.

Flank Wear; The wear which occurs along the flank of a tool, below and immediately adjacent to the cutting edge, while cutting. This wear reduces the clearance angle of the tool until failure finally occurs.

<u>Flute</u>; A helical or straight groove cut or formed in the body of a tool to provide cutting lips, to permit removal of chips, and to allow cutting fluid to reach the cutting edge.

<u>Force</u>; Any cause which tends to produce or modify motion. It is usually measured in pounds. Force has three characteristics: Direction, place of application, and magnitude.

<u>Honing</u>; The process of blunting and strengthening of the cutting edge by means of abrasives. This may be done by hand or by machine.

<u>Indexable Insert</u>; A carbide cutting tool which has several cutting edges and is used in milling cutters and single point tooling. An indexable insert is designed so that all cutting edges may be used to the limit of wear before the tool is discarded or reground.

<u>Milling</u>; A method of machining metal which involves multiple cutting edges rotating around an axis with the workpiece being moved past this axis.

<u>Negative Rake</u>; An angle of rake which is less keen or more blunt than zero rake.

Neutral Rake; A rake angle of zero degrees. This angle is perpendicular to the surface of the work and neither positive or negative.

Nose Radius; The radius on the tool between the end and side cutting edges.

Positive Rake; An average of rake which is keener or more acute than zero rake.

Pre-Honed; Machine honed to a uniform size by a carbide manufacturer.

R.P.M.; Revolutions per minute.

Radial Rake; On a milling cutter the angle between the tooth and a radial line passing through the cutting edge in a plane perpendicular to the cutter axis.

Relief; The clearance angle behind or below the cutting edge which allows the cutting edge to be forced into the work. It is sometimes divided into primary relief (adjacent to the cutting edge) and secondary relief (beyond the primary relief).

S.F.M.; Surface feet per minute.

Shank; The projecting portion of a milling cutter which locates and drives the cutter from the machine spindle or adaptor. Also, the main body of a single point tool or toolholder.

Shear Angle; The angle between the shear plane and the face of the work (in milling), or a tangent to the work at a point on the work surface directly above the chip.

Shear Plane; Metal is separated in the machining operation by a shearing action which takes place in a plane passing through the cutting edge of the tool and the surface of the work directly above the chip. This plane is called the shear plane.

Single Point Tool; A cutting tool having only one cutting edge. A lathe tool.

Velocity; The time-rate of change of distance, expressed as distance divided by time. Such as: feet per second, miles per hour, etc.

Wear Land; A flat land worn on the relieved or backed off portion of the tooth, behind the cutting edge. The width of the wear land affects size and finish and is a good indicator for determining the proper time to change or index the tool.

Work; In machining, generally the piece being machined.

Working Angle; Those angles between tool and work which depend not only on the shape of the tool, but also on its position with respect to the work.

Review of Related Literature

The depth of references on the subject of cutting tool chatter vibration range widely. A brief mention may be found in books and articles on related areas such as materials and guides to obtaining better surface finishes in machining. At the other extreme were books devoted completely to machine tool vibration behavior of which chatter was a central concern. In between were the numerous journal articles in which some particular area of chatter behavior was examined in detail. Much of the experimental work was reported in the latter while the former tends to present the theoretical background, basic physics, and mathematics.

Miniaturization of electronic components and advances in computing power have outdated some of the early work in this field as in many others. However because the basic phenomenon has not changed some of the pioneering works remain just as valid today as when they were written.

One type of chatter, velocity dependent, was sometimes referred to as Arnold type chatter. Named after Professor R. N. Arnold who first described it in his report, The Mechanism of Tool Vibration in the Cutting of Steel published in December 1946. Among

Professor Arnold's other fundamental investigations were the distinction between self-induced and forced vibration and the observation that the amplitude of vibration appears to be independent of the depth of cut.

One of the books most often found in reference lists is Machine-Tool Vibration by Professor S. A. Tobias. This is an authorized translation of Schwingungen an Werkzeugmaschinen first published in 1961 in German by Carl Hanser Verlay, Munich. There appears to be a substantial body of work on this subject written in German. This book was of particular value because it gives a glimpse through the language barrier at works which were otherwise unaccessable.

The book was in two parts, the first part being concerned with applying principles of vibration theory to machine tools. The second part has separate chapters dealing with chatter in simple machine-tool systems, drilling machines, lathes, grinders, and vertical milling machines.

This book was an excellent reference and would make the results of this research superfluous if it were not for the progress made since its publication in 1965. Other characteristics which make it somewhat unsuitable for a general guide to chatter problems was its length and technical depth. Literacy levels may not be much beyond high school for many skilled tradesman and it would not be realistic to expect them to distill the basic rules they need from this mass of information. Those who need and want the detailed background are encouraged to consult the work in its entirety.

Professor Tobias is also a co-editor of two Proceedings of the International Machine Tool Design and Research Conference from which sources were obtained for this investigation. In addition several journal articles from among Professor Tobias' other published works furthered the present research.

Another author who appears more than once in the reference list was W. A. Knight. His work entitled Some Observations On The Vibratory Metal Cutting Process Employing High Speed Photography was unique in applying this technique of exploration. This study considered two types of regenerative chatter, the cutting of a wave on a initially smooth surface with an oscillating tool, and the removal of a surface wave with a rigid tool. In this study Knight simulated chatter with a electrodymanic vibrator vibrating the toolholder. I believe this raises the question of how nearly this experimental condition recreates true cutting tool chatter vibration conditions.

In Chatter in Turning : Some Effects of Tool Geometry and Cutting Conditions, Knight attempts to predict the limits of stability theoretically. He then compares the theoretical limits with those obtained experimentally. The influence of Tobias was felt here also as Knight credits his encouragement and advice in the completion of this work.In spite of mediocre results Knight foreshadows later attempts to develop active systems for the control of machine tool chatter.

Klein and Nachtigal propose A Theoretical Basis for the Active Control of a Boring Bar Operation. This system used an analog controller and electro-hydraulic position servo to actuate the tip of a boring bar. Only one reference was found which had made use of the promise of micro-computers in the control of chatter. Forecasting Control of Machining Chatter by K. F. Eman and S. M. Wu overcame the obstacle of changing dynamics of the controlled process with a controller employing a general purpose micro-computer.

The control system used in Automated Chatter Suppression by Tool Geometry Control was not specified.

However one of the co-authors C. R. Liu collaborated with D. W. Wu on another article in the same issue of Journal of Engineering for Industry. In this work the authors must have had micro-computers in mind when they developed An Analytical Model of Cutting Dynamics. The mathematical model they propose attempts to explain all three basic mechanics associated with chatter vibration, velocity dependent, regenerative, and mode coupling. The resulting formula would mandate the use of a micro-computer to solve for successive iterations in the very brief time available between the appearance of conditions conducive to chatter and the onset of the full-blown phenomenon.

Dr. J. Tlusty is another active researcher in the field of cutting tool vibration chatter. In his discussion of the subject entitled Spindles for High Speed, High Power Milling, he advances the remarkable suggestion that the forced chatter from tooth impacts can dynamically dampen occurrences of self-induced chatter. Work was being done on a system which will monitor force or vibration and control speed to the most stable one.

Several other authors who evidence their involvement with this problem by publishing more than an isolated piece or two are, E. Marui, S. Kato, C. Andrew, and F. Ismail.

Methodology

This investigation began with a search of the computerized database, Applied Science and Technology Index (October 1983-present). This database is produced by the H. W. Wilson Company and is trademarked the WilsonDisc.

An initial search using the subject, machine tool chatter yielded no results. Related topics cutting tools, machinery vibration, and metal cutting mathematical models produced a list of eight potentially useful journal articles. Examining the reference lists of these articles expanded the field of references considerably. Also, multiple references to the same authors began to identify seminal works in the field.

Over thirty requests for photocopies of journal articles not collected in the University of Northern Iowa library were completed. These requests are typically filled by other university libraries and a very good response was received. All but two of the photocopy requests were complied with, usually by schools with engineering programs like Iowa State University.

Two other items were obtained through the interlibrary loan process. One is a masters thesis by V. R. Vadari done at the University of Waterloo, Ontario, Canada. The other is Machine-Tool Vibration by S. A. Tobias. As previously mentioned in the review of literature section this book is cited in several of the reference lists and appeared to be one of the most influential works in the field. In all copies of more than fifty reference works were obtained.

The process of locating expert sources in the areas of machine tool and cutting tool design began in the author's own shop. A sales representative for Ingersoll Cutting Tools Rockford, Illinois, Mr.Bob Schobert graciously offered to arrange interviews with Mr. Dean Edwards, manager materials technology and Mr. Issac Hogg, manager engineering services, special machines group. These interviews took place in the shops and offices of Ingersoll Cutting Tools and the Ingersoll Milling Machine Company on Monday November 25, 1991. Each interview lasted approximately two hours and interspaced between them was a tour of the facility for producing cutting tool bodies and finishing cutting tool inserts.

Another expert was identified by the authors supervisor Mr. Jim Burkhardt. Mr. Burkhardt recounted that Mr. Ben Colson, formerly an John Deere Waterloo Engine Works employee, had gone on to hold positions in cutting tool design with Ingersoll Cutting Tools and presently with Hertel Cutting Technologies. A telephone interview with Mr. Colson, now Operations Director Hertel Tool Cutting Technologies Special Tooling, was conducted on Monday November 18, 1991.

One result of these interviews was the discovery of further references on the subject of cutting tool chatter vibration. These included additional journal articles, a status report done on machine tool capability by the United States Air Force, and technical and research reports produced by corporate authors. The persons interviewed also identified works that had been of particular value to them, helping to focus on definitive sources. Another result of these interviews was to correct any imbalance or unintentional bias in the body of material obtained in the literature review.

All the experts interviewed were most generous with their time and knowledge. Without exception they also agreed to proofread the result of this investigation, A Guide to the Causes and Cures of Cutting Tool Chatter Vibration. This was one of the two major methods for determining the validity of the guide. The other was utilizing the document to assist in solving chatter problems encountered in the course of the author's duties as a machine repairman. Letters of appreciation were sent to all persons interviewed, a sample of which may be found in appendix B. Other proofreaders were chosen from among the group of potential users. This was done to test the clarity, organization, and usefulness of the guide.

Producing a guide to the fundamental origins and remedies for cutting tool chatter vibration began with identifying the major triggering processes. Then tests for the specific cause were included. Finally corrective measures were spelled out.

Report of Findings

A detailed examination of the findings is reported in the guide to the causes and cures of cutting tool chatter vibration included as appendix A, only the highlights will be presented here.

This area of research might be termed mature in the sense that experimentation has been ongoing since the thirties, much of the basic physics are agreed upon and the experimental designs standardized. However this field is still far from mined out. Tobias (1965) pointed out "The physical causes underlying the mechanism are still not fully understood ..."(p. 143).

Types of Chatter

Researchers are not consistent in establishing categories of chatter. Some identify two types, forced and self-induced, while others ignore the former and further sub-divide the latter into velocity dependent, regenerative, and mode coupling. Still others describe a variation of forced chatter as free chatter. As forced chatter is not chatter at all by my definition I would like to eliminate it from consideration altogether. However because the goal of this study is a guide to the causes and cures of cutting tool chatter vibration, processes that may be mis-diagnosed as chatter will be covered here.

A description of forced chatter may reveal the reason for my reticence in including it in the category of chatter. Forced chatter is that which results from gear and bearing defects, impacts of multiple cutting edges, and vibration transmitted through the foundation from other machines. It is a pattern imprinted on the workpiece from these sources and not self-induced by the cutting process like true chatter. Forced chatter is always present in milling and comparatively easy to diagnose.

D. W. Wu and C. R. Liu (1985b) described the three types of self-induced chatter. The first of these is velocity dependent or Arnold type. This type is based on the negative slope of the cutting force variation with respect to the cutting speed. "The difference in average magnitudes of the cutting forces generated during the upward and downward strokes of tool motion causes net energy to be fed into the system, and results in dynamical instability"(p.107).

Regenerative chatter is the variation in uncut chip thickness caused by the overlap of waves in the tool motion and the work surface during successive cuts. Something such as a hard grain disturbs the cutting process which throws the system into vibration. This vibration decays but leaves a washboard like surface which is magnified by the next passage of the tool until the variation covers the whole work surface. At this point the system is continuously being excited at a resonant frequency.

The last type of self-induces chatter is mode coupling. This occurs when two natural modes of the vibratory system are closely matched. When the cutting force acting in one direction causes a tool motion in another direction mechanical resonance has been created and mode coupling is the cause.

Damping

Damping is one of the two principle elements of the chatter equation, the other being stiffness. Damping can be either passive or dynamic. For example, the automotive shock absorber, which is really a damper, is of the passive type. It changes one form of energy, mechanical vibration, into another type of energy, heat. The active type is the process of adding energy to a machine tool component such that it tends to continue the vibration or dampens it. If it is in phase and frequency with the vibration occurring at the resonant frequency it is termed negative damping, if it is out of phase or of a different frequency it is called positive damping.

The cast iron which was used extensively in machine tool building until about fifteen years ago has inherently more stiffness than the fabricated steel designs of today. Also machine tools manufactured with cast iron often have fewer bolted joints, which are points of reduced stiffness. However good design practices, such as finite element analysis, can result in some very good stiffness values for fabricated steel. If you could design a machine tool to be infinitely stiff you would not need damping at all. As this is not likely to occur in practice damping will remain an important variable in the control of chatter.

Stiffness

Stiffness needs less explanation, it is a measure of the force required to deflect the cutting tool, workpiece interface. Expressed in pounds per inch, it ranges from 250,000 to more than 1.5 million lbs per inch. The higher the value the better, as the value is lowered the likelihood chatter will occur is increased with 250,000 being a bare minimum (I. Hogg, personal communication, November 25,1991). Dividing this by one thousand gives a guideline of 250 lbs per .001". This is a way to quantify the often subjective practice of prying on a machine spindle with lever and observing the results on a sensitive dial indicator. Stiffness also has static and dynamic components. Inertia is the added component resulting in dynamic stiffness.

Diagnosing Chatter

In the field the diagnostic process begins with a visual inspection of the machine-tool, the cutting tool geometry, workpiece support, and chatter marks. If the frequency of the chatter marks on the workpiece coincide with cutting edge impacts, bearing, or gear pass frequencies you have forced chatter. This type of chatter is again not a true chatter by this author's definition and is curable by addressing the forcing component.

Making the diagnostic process somewhat easier is Tobias' (1965) statement that regenerative chatter is the chief physical cause of instability. Mode coupling occurs comparatively rarely and Mr. Hogg stated he had seen only one or two cases in ten years (I. Hogg, personal communication, November 25,1991). While cases of mode coupling between machine components are rare, any case involving the chatter of a symmetrical cutting tool with a length to diameter ratio over 4 to 1 (overhung boring bar, long end mill, etc.) would have to be defined as mode coupling.

As anticipated bearing faults and loose slides were not identified as causes of chatter outside of the forced chatter resulting from severe bearing damage. I make the distinction between slight bearing wear and last stage bearing failure because the former is often blamed for self-induced chatter which it is not. While the results of the latter are not easily overlooked but not often identified as chatter.

Of the fifty resources used in support of this investigation two referred to bearing faults and loose slides as causes for chatter. Both of these were of the forced variety. Mr. Ben Colson (personal communication, November 18,1991) also identified these as causes of chatter, but was not specific on which types of chatter were involved. One corporate author (General Electric, 1980) proposed the idea that "Looseness or lack of stiffness in the machine, tool fixture, and workpiece cannot actually cause chatter, but may be a significant contributing factor to both types of chatter discussed here"(p. 83). They recommended that bearing and slide play be limited to .002" or less. I believe there are arguments that bearing and slide play far from being causes or contributing factors for chatter, can actually be mitigating circumstances. Looseness in a system adds damping. As Tobias (1965) points out in his discussion on chatter in radial drilling machines, "Damping also occurs in the various clamps and locking devices which clamp the saddle to the arm and the arm to the column. As is well known, chatter can often be eliminated by slightly slackening these clamps. The reason is that this brings about an increase in the damping (p. 196)."

<u>Cures for Chatter</u>

The possible cures for chatter are numerous and are covered in detail in the guide. Two of the most recent approaches deserve mention here. Dr. J. Tlusty's suggestion of fighting fire with fire and micro computer based control systems.

Dr. Tlusty concluded (1988) that it is possible to gain a great advantage by adjusting the spindle speed of a milling machine to the "miracle speed" at which tooth frequency equals to the natural frequency of the dominant mode. This "miracle speed" results in the least damage to the tool and the best surface finish. As mentioned previously in the review of literature section a system was being developed which will monitor force or vibration and control the speed to the most stable one.

Other control systems rely on the low speed stability effect (Kegg, 1969) or actively controlling tool geometry (Klein & Nachtigal, 1975) and (C. R. Liu & T. M. Liu, 1985). The low speed stability effect can be described as a strong stabilizing influence which only becomes effective in the lower range of cutting speeds. Control consists of lowering cutting speed in response to increasing vibration parameters. Active control is required so that the cutting speed may remain at economically high levels for the bulk of the machining process and only lowered during episodes of instability.

Tool geometry is another variable which can be altered to control chatter. This is done by changing rake and clearance angles. Moving from positive to negative rake increases cutting force hence the damping force increases. Changing clearance angles varies the geometric interference between the tool and the finished surface of the workpiece also increasing damping force. The same trade off obtains here of course with higher cutting forces comes less material removed per unit of energy. For best economy cutting force should be as low as possible when possible and raised only during conditions of transient instability.

Conclusions

It was hoped that hard and fast answers existed for cutting tool chatter vibration. This proved not to be the case. However the situation is far from bleak and work proceeds apace on new solutions to this problem. The remaining mysteries about chatter will be explained and the diagnostic process improved to the point that specific cause and effect relationships are established.

For the time being there is a wide variety of proven fixes for chatter. In spite of the lack of connections between symptoms and specific cures I am confident that with persistence individual cases of chatter can be eliminated. For the present all the "black art" cannot be excised from the process of curing chatter but its influence is rapidly diminishing.

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A Guide to the Causes and Cures of Cutting Tool Chatter Vibration

The intent of this guide is to provide a general overview of the subject of cutting tool chatter vibration. Specific details for remedying chatter problems from any particular source will not be included. References will be provided in the discussion of individual cases of chatter for persons interested in or requiring the in depth analysis.

While much is known about this subject all the answers have not been discovered. This guide is not the last word and involved professionals should keep watch for the appearance of the results of additional research.

Types of Chatter

Researchers are not consistent in establishing categories of chatter. Some identify two types, forced and self-induced, while others ignore the former and further sub-divide the latter into velocity dependent, regenerative, and mode coupling. Still others describe a variation of forced chatter as free chatter. As forced chatter is not chatter at all by my definition I would like to eliminate it from consideration altogether. However because the goal of this guide is to identify the causes and cures of cutting tool chatter vibration, processes that may be mis-diagnosed as chatter should be dealt with.

A description of forced chatter may reveal the reason for my reticence in including it in the category of chatter. Forced chatter is that which results from gear and bearing defects, impacts of multiple cutting edges, and vibration transmitted through the foundation from other machines. It is a pattern imprinted on the workpiece from these sources and not self-induced by the cutting process like true chatter. Forced chatter is always present in milling and comparatively easy to diagnose.

The first of the three types of self-induced chatter (Liu & Wu, 1985b) is velocity dependent or Arnold type. This type is based on the negative slope of the cutting force variation with respect to the cutting speed.

Regenerative chatter is the variation in uncut chip thickness caused by the overlap of waves in the tool motion and the work surface during successive cuts. Something such as a hard grain or void in a casting disturbs the cutting process which throws the system into vibration. This vibration decays but leaves a washboard like surface which is magnified by the next passage of the tool until the variation covers the whole work surface. At this point the system is continuously being excited at a resonant frequency.

The last type of self-induces chatter is mode coupling. This occurs when two natural modes of the vibratory system are closely matched. When the cutting force acting in one direction causes a tool motion in another direction mechanical resonance has been created and mode coupling is the cause.

Damping

Damping is one of the two principle elements of the chatter equation, the other being stiffness. Damping can be either passive or dynamic. For example, the automotive shock absorber, which is really a damper, is of the passive type. It changes one form of energy, mechanical vibration, into another type of energy, heat. The active type is the process of adding energy to a machine tool component such that it tends to continue the vibration or dampens it. If it excites the machine tool at one of its' resonant frequencies it is termed negative damping. If it is out of phase or of a different frequency it is called positive damping.

The cast iron which was used extensively in machine tool building until about fifteen years ago has inherently more stiffness than the fabricated steel designs of today. Also machine tools manufactured with cast iron often have fewer bolted joints, which are points of reduced stiffness. However good design practices, such as finite element analysis, can result in some very good stiffness values for fabricated steel machine tools. If you could design a machine tool to be infinitely stiff no damping would be required. As this is not likely to occur in practice, damping will remain an important variable in the control of chatter.

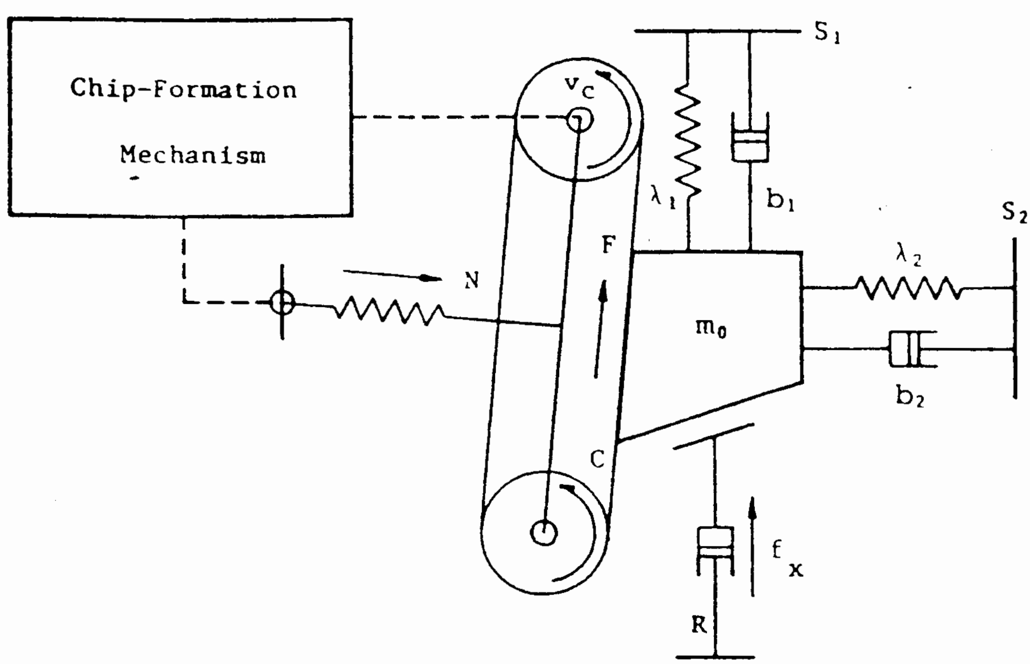
Stiffness

Stiffness needs less explanation, it is a measure of the force required to deflect the cutting tool, workpiece interface. Expressed in pounds per inch, it ranges from 250,000 to more than 1.5 million lbs per inch. The higher the value the better, as the value is lowered the likelihood chatter will occur is increased with 250,000 being a bare minimum. Dividing this by one thousand gives a guideline of 250 lbs per .001". This is a way to quantify the often subjective practice of prying on a machine spindle with lever and observing the results on a sensitive dial indicator. Stiffness also has static and dynamic components.

Diagnosing Chatter

Figure 1 may help in visualizing the cutting process. It is a schematic diagram of machining dynamics including the: M_o; tool block, C; chip material, R; work material around the tool nose region, S_1 and S_2; rigid supports on machine basis. It is a spring mass system with two degrees of freedom and damping represented by dashpots b_1 and b_2. In reality a system will contain an infinite number of degrees of freedom.

Figure 1. Schematic diagram of machining dynamics. From "An Analytical Model of Cutting Dynamics. Part 1: Model Building" by C. R. Liu and D. W. Wu, 1985, *Journal of Engineering for Industry*, 107, p. 107.



In the field the diagnostic process begins with a visual inspection of the machine-tool, the cutting tool geometry, workpiece support, and chatter marks. The fixture supporting the workpiece should be checked for wear and sufficient rigidity.

If the frequency of the chatter marks on the workpiece coincide with cutting edge impacts, bearing, or gear pass frequencies you have forced chatter. This type of chatter is again not a true chatter by this author's definition and is curable by addressing the forcing component.

Making the diagnostic process easier is Tobias' (1965) statement that regenerative chatter is the chief physical cause of instability . Mode coupling occurs comparatively rarely and Mr. Issac Hogg, Manager Engineering Services, Special Machines Group, Ingersoll Milling Machine Company, Rockford, Illinois, stated he had seen only one or two cases in ten years (I. Hogg, personal communication, November 25,1991). However any case involving the chatter of a symmetrical cutting tool (overhung boring bar, long end mill, etc.) would have to be defined as mode coupling. Any boring bar or tool adapter with a length to diameter ratio greater than four to one is instantly suspect and could profit from increased rigidity. Making such components from tungsten carbide is an expensive but effective means of attaining the required rigidity.

Bearing faults and loose slides are not identified as causes of chatter outside of the forced chatter resulting from severe bearing damage. I make the distinction between slight bearing wear and last stage bearing failure because the former is often blamed for self-induced chatter which it is not. While the results of the latter are not easily overlooked but not often identified as a type of chatter.

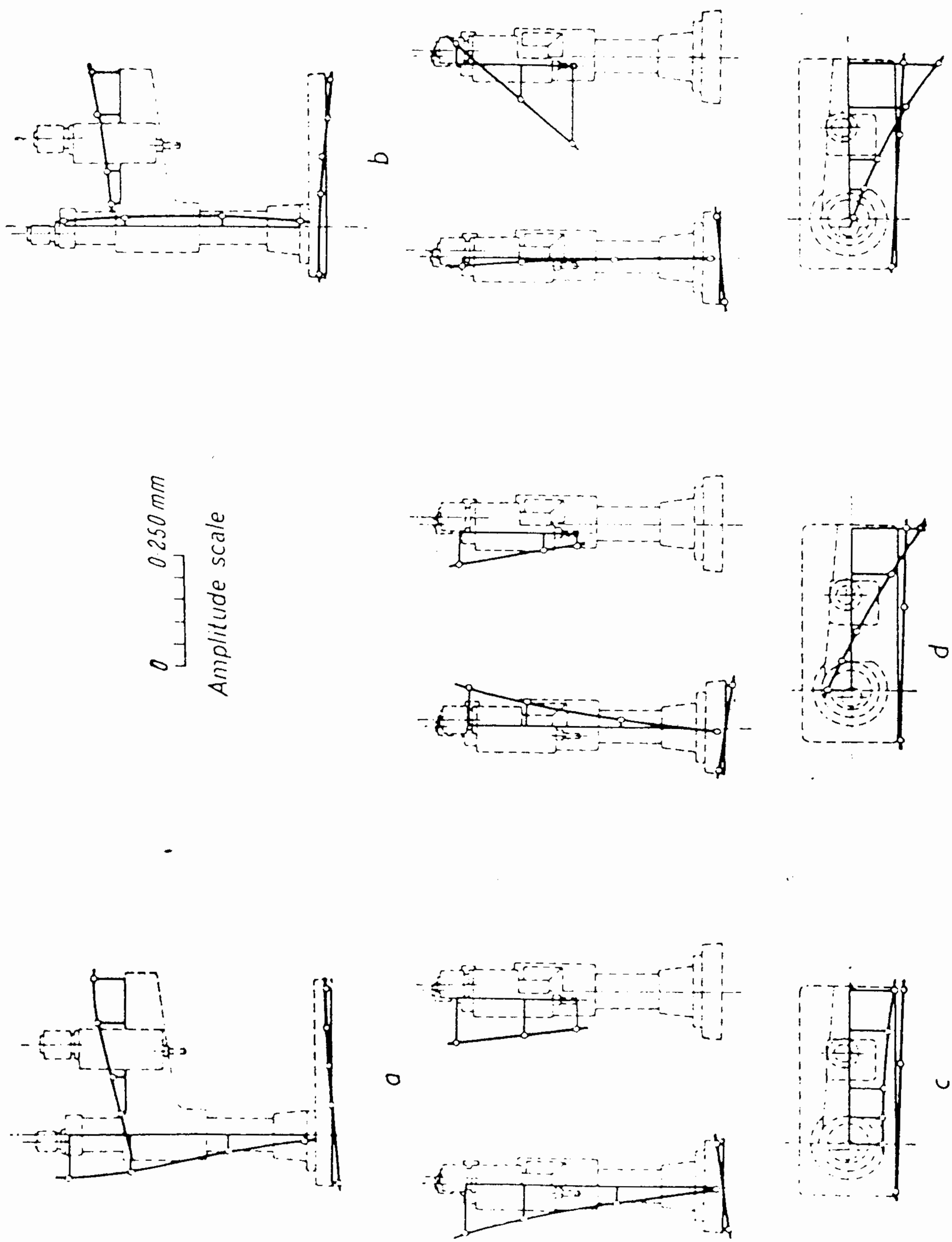
Of the fifty resources used in support of this investigation two referred to bearing faults and loose slides as causes for chatter. Both of these were of the forced variety. Mr. Ben Colson, Operations Director, Special Tooling, Hertel Tool Cutting Technologies, Plymouth, Michigan (personal communication, November 18,1991) also identified these as causes of chatter, but was not specific on which types of chatter were involved. One corporate author (General Electric, 1980) proposed the idea that "Looseness or lack of stiffness in the machine, tool fixture, and workpiece cannot actually cause chatter, but may be a significant contributing factor to both types of chatter discussed here"(p. 83). They recommended that bearing and slide play be limited to .002" or less. I believe there are arguments that bearing and slide play far from being causes or contributing factors for chatter, can actually be mitigating circumstances. Looseness in a system adds damping. As Tobias (1965) points out in his discussion of chatter in radial drilling machines, "Damping also occurs in the various clamps and locking devices which clamp the saddle to the arm and the arm to the column. As is well known, chatter can often be eliminated by slightly slackening these clamps. The reason is that this brings about an increase in the damping (p. 196)."

If a visual inspection of the machine tool and process yields no obvious problem areas with which to begin, modal analysis can avoid the expensive task of modifying and strengthening members without knowledge as to which elements are dynamically weak (Barwick & Lemon, 1967). The complexity and technical requirements of modal analysis have confined it to the facilities of the machine tool builder in the past. Today advances in micro-computers have allowed application of this technology by end users of machine tools. As previously stated mode coupling is not a common cause of chatter but if you suspect it, modal analysis will identify the elements which are linked by their mutual natural frequencies. DLI Engineering Corporation of Bainbridge, Wa. offers a software program for modal analysis by the maintenance professional. A vibration analyzer capable of measuring vibration amplitude and phase is also required. Figure 2, shows the bending modes for a radial drill at different frequencies. Other types of machine tools exhibit similar bending modes at points in their construction. For instance a boring mill will likely have some bending motion at the base of its' column. The fixture must also be surveyed for motion relative to the cutting tool.

The modal analysis is performed by exciting the machine tool structure with a electrohydraulic or electromechanical exciter usually mounted at the cutting tool, workpiece interface. A range of frequencies is used to force the structure while vibration transducers measure the displacement and phase of the resulting motion of the various elements. This result is compared with the frequencies observed during the chattering process to determine which component is dynamically weak and needs corrective measures.

<u>Figure 2</u>. Modal Analysis of a Radial Drill.

From <u>Machine Tool Vibration</u> by S. A. Tobias, 1965, New York: Wiley.

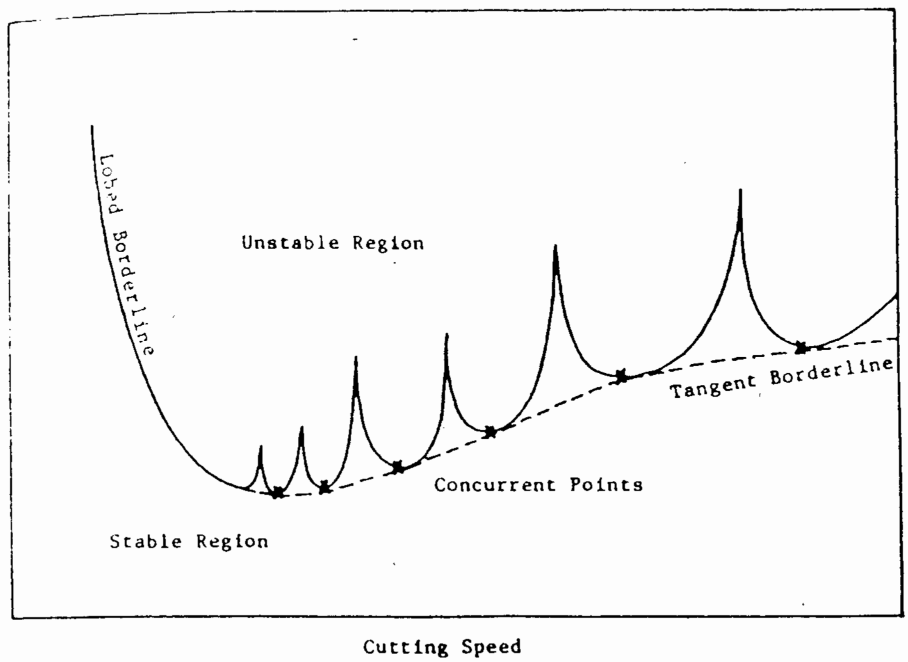


Cures for Chatter

The possible cures for chatter are numerous and I will arrange them by the type of machining operation involved beginning with cures with universal applicability

One common cure for chatter mentioned in several studies is the low speed stability effect (Kegg, 1969, Kegg & Sisson, 1969). The low speed stability effect can be described as a very strong stabilizing influence which only becomes effective in the lower range of cutting speeds. This involves slowing the cutting speed while keeping the feed constant. The result is higher cutting force which in turn loads the machine tool components heavier. Higher positive damping results which resists the onset of chatter. Slowing down the cutting speed will provide relief in most situations. However, in some cases, because of the sawtooth shape of the cutting stability boundary upping speeds and feeds may also cure the problem and keep metal removal rates economically high (Tobias, 1965). Figure 3 shows a typical borderline. The sawtooth shape results from the different frequencies at which various bending modes occur, see figure 2. This strategy runs counter to most peoples tendency to "take their foot off the gas" when chatter sets in.

Figure 3. Lobed Borderline Between Stable and Unstable Cutting Regions. From "An Analytical Model of Cutting Dynamics. Part 2: Verification." by C. R. Liu and D. W. Wu, 1985, *Journal of Engineering for Industry*, 107, p. 112.



Tool geometry is another area which is involved in every type of metal cutting. Honing the cutting edge of a new tool is an old machinist trick for eliminating chatter. The TIN coated carbide indexable inserts available today have the edge preparation (.001"-.002" radius) built in because of the requirements of the coating process. Mr. Dean Edwards, Manager Materials Technology, Igersoll Cutting Tool Company, pointed out that inserts for cylinder boring typically have more radius (.005"-.007") on their cutting edges to help control chatter.

Mr. Edwards also stated that moving towards more negative rake tool geometry loads the machine more uniformly. This is in contrast to C. R. Liu and T. M. Liu (1985) who experimentally found that lowering the clearance angle and altering the rake angle to a more positive value resulted in a more stable cutting process. The lesson to be learned here is that varying rake and clearance angles can have a dramatic effect on chatter and is worth exploring. See Chatter in Turning : Some Effects of Tool Geometry and Cutting Conditions, by W. A. Knight (1972) for additional discussion. Mr. Edwards also described the process of spin grinding the inserts of a multiple cutting edge boring head. This would have the effect of reducing the clearance angle and simultaneously creating a piloting feature.

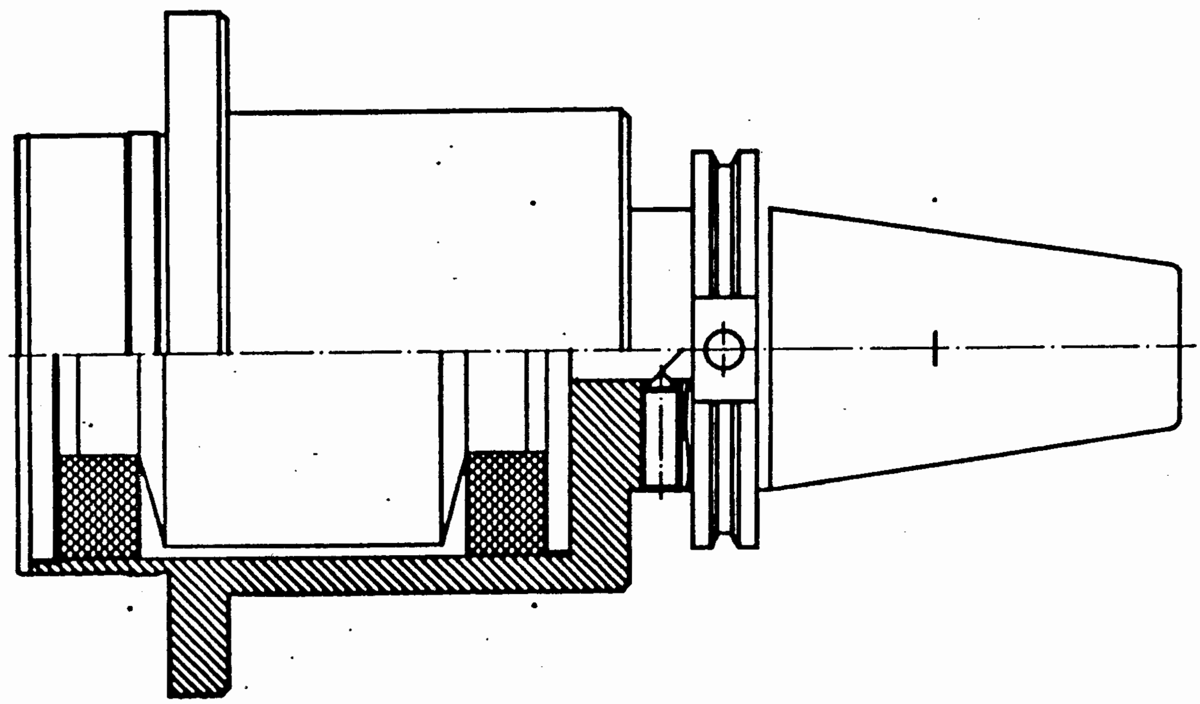
Any process employing a cutter with multiple cutting edges can profit from uneven interval spacing of the cutting edges. While cutting tools which have such unequal spacing built in will become more readily available a quick fix may be possible by simply leaving one or more inserts out of a cutter body that features multiple pockets. Mr. Colson is encouraging his designers to incorporate unequal interval spacing more frequently in their designs.

Breaking up a long depth of cut using stepped inserts or slotted ones is a example of ways to change cutter geometry to overcome chatter.

Dr. J. Tlusty (1988) suggests that where possible redesigning the machine tool spindle to use straight or tapered roller bearings in place of angular contact spherical ball bearings results in superior stiffness values. This is radical surgery and is not always possible especially on high speed spindles, but should be kept in mind as a alternative when it is feasible.

Adding a vibration damper is another possible cure for many different types of chatter. The damper may be attached to some component of the machine tool structure where it is effective or installed in the tool holder or cutter body itself. Figure 4 is a toolholder with a build in damper. This remedy utilizes a mass supported in such a way that it may oscillate at the frequency of the chatter vibration but in opposite phase tending to dynamically dampen the vibration.

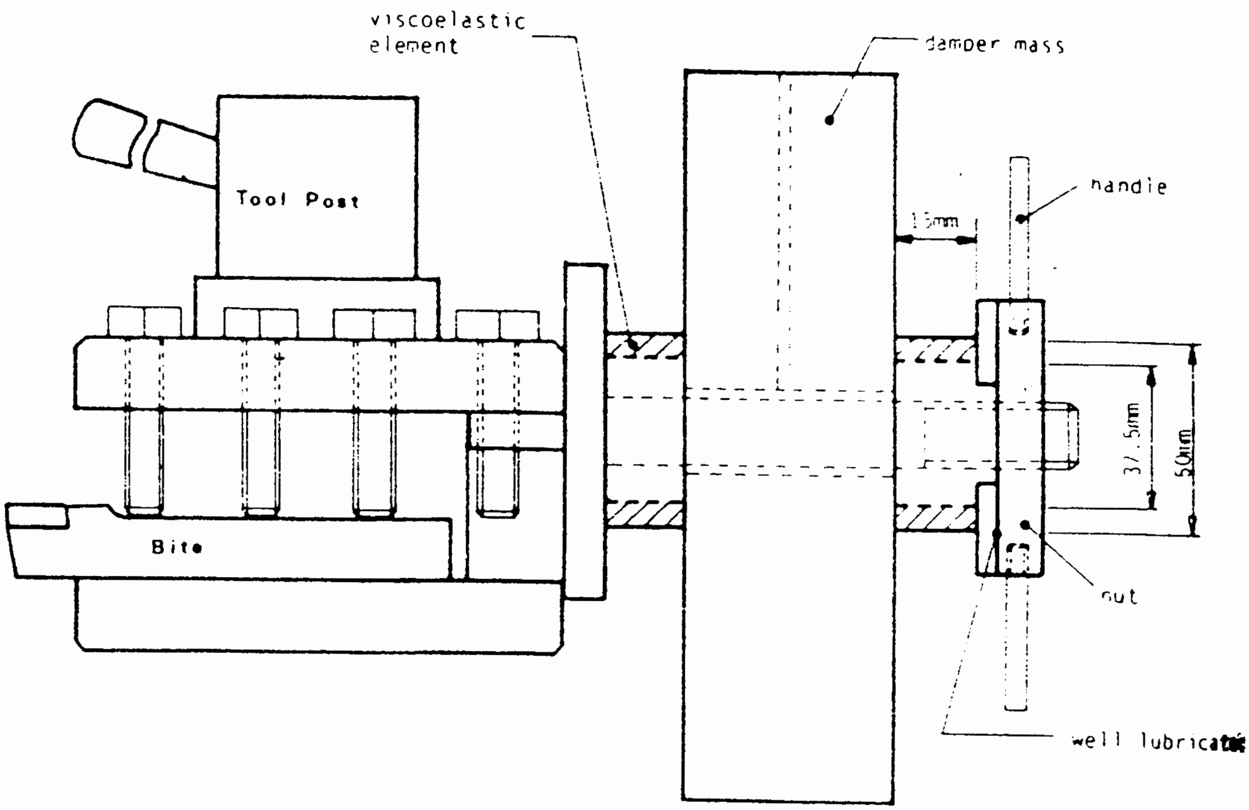
Figure 4. Toolholder with built in damper. From Vibration In Milling Applications by the Sandvik Coromant Company, 1986, Fair Lawn, New Jersey.



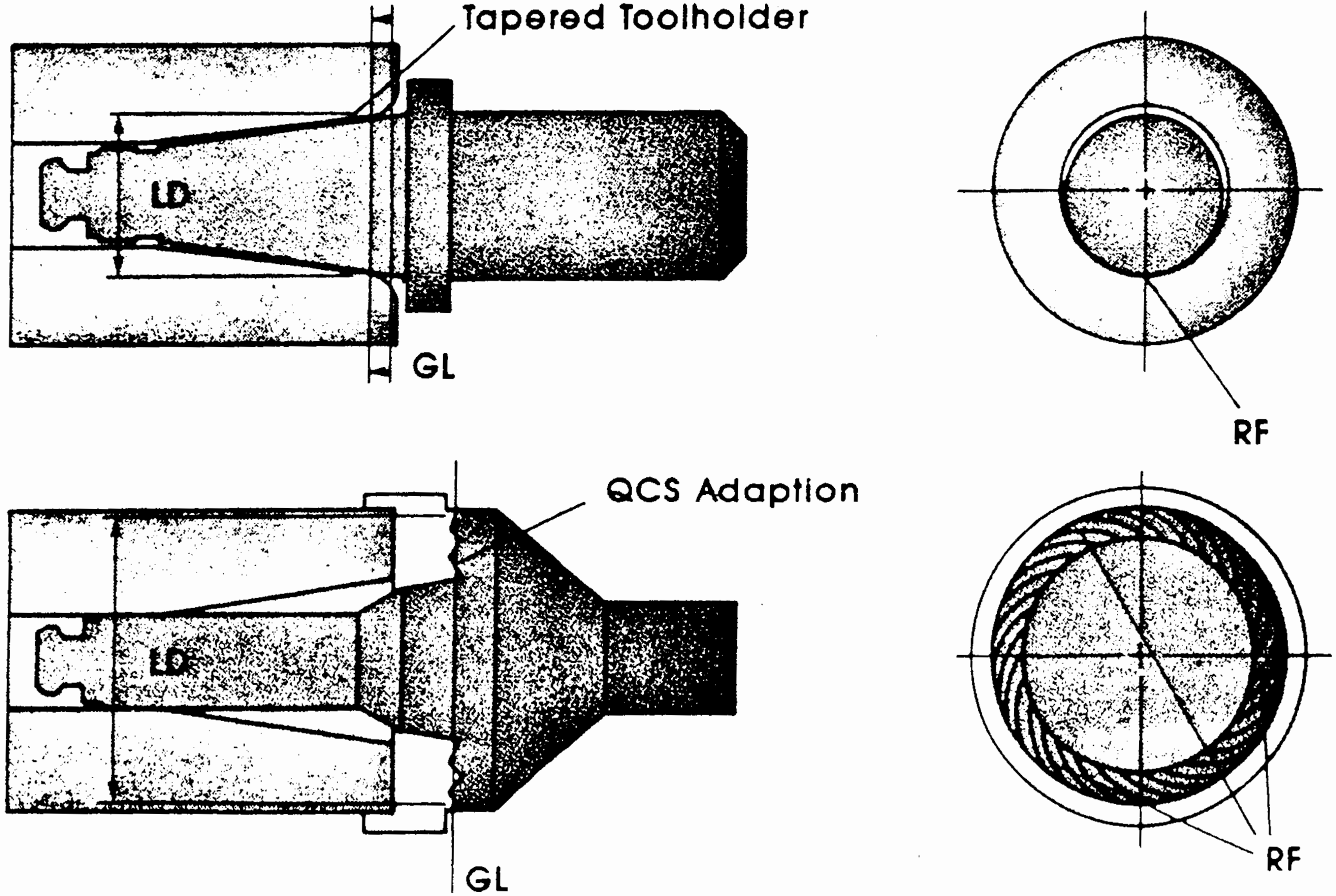
A damper mounted on the machine tool structure is not a very elegant solution and suffers the additional drawback of requiring to be tuned to the frequency of interest which may change during the process. Figure 5 is a dynamic damper mounted on a lathe toolpost. Authors discussing the design of dynamic absorbers for particular situations are D. J. Pilkington & E. R. Austin (1967), G. K. Grover & R. J. Harker (1968), B. J. Stone & C. Andrew (1968), G. L. Nessier, D. L.

Brown, D. C. Stouffer, and K. C. Maddox (1977), K. J. Kim & J. Y. Ha (1987), Sandvik (1986) and M. de Ro (1968). The last researcher utilized a magnetic exciter as a active damper which allowed it to adjust to changing vibration frequencies and led to a much smaller physical size. Smaller size allows flexibility in mounting the damper in locations of maximum effectiveness.

<u>Figure 5</u>. Dynamic Damper Installed on a Lathe Toolpost. From "Suppression of Machine Tool Chatter Using a Viscoelastic Dynamic Damper" by J. Y. Ha & K. J. Kim, 1987, *Journal of Engineering For Industry*, 109, p. 58.



Machine builders in the past sometimes left the core sand in the castings making up the major components of a machine tool to add dampening. Following that lead sand has sometimes been used to fill machine cavities to increase damping, cement has also been used and Mr. Hogg favored talcum powder as being the most effective material and makes the machine smell better.



s a spindle bell-mouths, the age line (GL) moves down the aper to a smaller locating iameter (LD). The QCS adapter nd spindle cap provide a wide, ccurate locating base. '

With a conventional toolholder, the radial force (RF) is applied on a single point between the taper and spindle. The QCS spiral design spreads radial forces evenly over all the gear teeth.

Figure 6. QSC Adapter
From The Cutting Edge, Ingersoll Cutting Tool Company

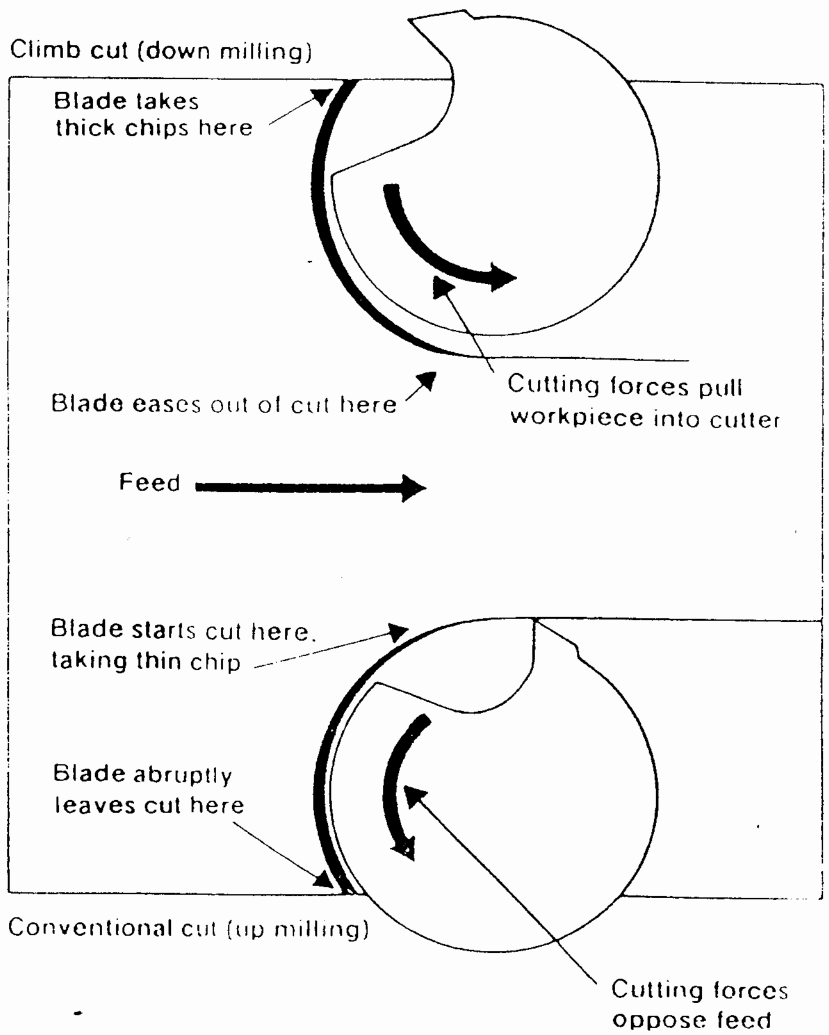
Using a flatback or QSC tool adapter instead of the standard taper designs can increase the stiffness of the tool spindle interface by 25 to 50%. The QSC adapter uses two mirror image spiral gears to provide positive locating of the tool holder and increase stiffness. A QSC adapter is pictured in Figure 6.

Active control of machining parameters relevant to chatter instability is been experimentally verified by K. F. Eman and S. M. Wu in their research paper Forecasting Control of Machining Chatter (1980). This solution strategy could find wide application in metal cutting operations of all types. The trend to spindle and feed drives employing electronically controlled variable speed motors will make this cure must easier to apply.

In milling climb milling should be used when ever the machine design will allow. Climb milling loads the machine components better by forcing the workpiece down on the table instead of attempting to lift it, as conventional milling does. The effect of climb milling vs conventional is illustrated in figure 7.

Figure 7. Conventional VS Climb Milling

From The Cutting Edge, Ingersoll Cutting Tool Company



Another solution involves changing the lead angle on the milling cutter to change the direction in which the major part of the cutting force is applied to the machine, (Sandvik, 1986). The same author pointed out that vibration situations can often be overcome by moving the cutter center line relative to the workpiece center line for the same reason as changing the lead angle. Using a left handed cutter is still another way of redirecting the cutting forces to a more stable direction.

A flywheel mounted as close as possible to the cutter will help control torsional vibration of the arbor in horizontal milling. Additionally it is easy to underestimate the forces when using carbide cutters and the old rule of the bigger the better applies to arbor size.

One innovative technique investigated by Vadari and Ismail (1990) was to grind parallel flats on the shank of end mills to moderate the mode coupling in the cutter itself. The study involved varying the angle between the flats and the cutting edges and resulted in improved stability at any orientation.

In a variation of the solution presented in the previous paragraph Kuchma (1956) examined boring bars of unequal cross section for resistance to vibration. Again the angle between the cutting edge and the flats milled on the boring bar were varied with improvements of an order of magnitude noted.

In drilling it is customary to drill a small pilot hole to reduce the cutting force required to force the chisel edge of the drill through the material. H. Fujii, E. Marui, and S. Ema (1986) studied the role of the chisel edge in whirling vibration and concluded that the chisel edge provided a stabilizing effect against the initiatalization of vibration. Drill point geometry has several characteristics in common with other cutting tools. Where rake and clearance angles are similar the guidelines presented in the section on tool geometry apply. Drills however are unique in possessing a chisel point and where possible advantage should be taken of the stabilizing effect they provide by not drilling a pilot hole.

In reaming through holes where it is possible to clear chips by pushing them ahead of the tool reamers with a reverse helix may be employed. This is another variation of techniques which attempt to more uniformly load the machine spindle. A right hand helix turning in a clockwise rotation has a tendency to screw itself out of the tool holder or alternatively pick the workpiece up. A left hand helix turning the same direction forces the workpiece down on the table.

Finally when spot facing or counter boring some dwell is often programed in at the bottom of the feed. Dwell should be restricted to 1 to 1 1/2 revolutions after reaching full depth, just enough to relieve tool pressure and insure full depth of cut. Longer dwells lead to chip loads which are too small to generate sufficient positive damping.

There are several other suggested solutions, some under development and some purely theoretical. They include dynamic hot machining (Mac Manus, 1968), active control of boring bars (Klein & Nachtigal, 1975), and in milling, setting the frequency of the cutting tooth impacts equal to the frequency of the dominant mode (Tlusty, 1988). The final chapter hasn't been written and those individuals who are charged with addressing chatter vibration problems in the course of their daily duties are also charged with keeping abreast of developments in this challenging and intriguing field.

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November 30, 1991

«Title» «First» «Last»
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Dear «Title» «Last»:

Thank you very much for the gift of your time and knowledge in furthering my research into cutting tool chatter vibration. I'm sure the additional literature and expert resources you identified will also be of great assistance.

This subject is proving to be very challenging and simultaneously a very interesting and rewarding area of research. I hope my paper will be of some use to individuals in industry faced with solving chatter problems, especially those confronting this task for the first time.

I am hoping to do some validation of this document at the John Deere Waterloo Engine Works in the course of my duties there. However your assistance in proofreading the report would be of inestimable value particularly in connection to any remarks or data I may have attributed to you. I hope I may rely on your continued generosity in this regard.

Sincerely yours

Arneil Olson