DEVELOPMENT OF MATHEMATICAL MODELS AND ONLINE CHATTER CONTROL SYSTEM IN TURNING AISI 304 STAINLESS STEEL

BY

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ABSTRACT

Chatter is intensive self-excited vibration of the individual components of a Machine-Tool-Fixture-Work (MTFW) system which reduces tool life, accuracy, surface finish quality and productivity. In turning, it manifests itself as bouncing in and out of the tool shank from the flexible work-piece. However, it is a complex process and so no comprehensive theory has yet been developed. Thus, research into the root cause of chatter, its formation mechanism, mathematical modelling and chatter suppression is very important to industry and academia. The prevalent theories on chatter are controversial; often contradicted by experimental evidences. The Regeneration Theory posits that surface waviness left from a previous cut interferes with the next machining pass and leads to chatter. In contrast, the Resonance Theory states that chatter occurs due to resonance when the chip serration frequency coincides with the natural frequencies of the MTFW system. The current research investigated chip serration frequency, cutting force, mode shapes and natural frequencies of the tool shank, and vibration amplitudes during turning of AISI 304 stainless steel under different combinations of primary cutting parameters with the aim to model the responses and gain understanding of chatter. The work material, AISI 304 stainless steel, was turned on an engine lathe using TiN-coated cemented carbide inserts. Small Central Composite Design (CCD) modelling approach in Response Surface Methodology (RSM) was used for designed experiments and resulted in quadratic empirical mathematical models of vibration amplitude and chip serration frequency, and two-factor interaction (2FI) model for cutting force; which were subsequently analysed by ANOVA. It was found that, cutting speed (V_c) and depth of cut (DOC) had quadratic perturbation effect in determining the responses. Next, the postulates of the Resonance Theory of Chatter and energy balance method were used to analytically explain chatter as the consequence of P_{max} (vibration energy) at the resonance of tool shank's mode shapes. It was found that chatter occurred when chip serrations approached even integer multiples of the two dominant resonant frequencies (transverse and torsional) of the tool shank ($f_c = 10f_{n1}$, $20f_{n1}$, $30f_{n1}$ and $f_c = 2f_{n5}$, $4f_{n5}$, $6f_{n5}$) due to mode coupling; resulting in large peak values of cutting force and chatter. The empirical models were numerically and graphically optimised and showed that chatter was more prone to occur for combinations of high cutting speed (near 200 m/min) and large depths of cuts (2 mm or more). Concurrently, an electromagnet-based online chatter control system was developed which was controlled by a closed-loop feedback proportional and integral (PI) controller developed in LabVIEW. This controller detected and minimised chatter amplitude by 46% (on average); treating it as a disturbance in the turning process. The damping was provided by the uniform magnetic field produced by the electromagnet which resisted any movement of the ferromagnetic steel tool shank. This active damper is economical and robust; capable of handling all conditions of cut of the CCD model. Hence, this research developed an in-depth understanding of chatter, modelled it using empirical, statistical and analytical methods which were able to predict stable cutting regions. An economical and effective online chatter control system was successfully developed.

لاصة البحث

الذبذبة هي عبارة عن اهتزاز ذاتي مكثف للمكونات الفردية لنظام (MTFW). و تقوم هذه الذبذبة بالتقليل من عمر الأداة و دقتها و جودة السطح النهائية و انتاجيتها. اثناء الدوران تظهر الذبذبة كارتداد داخل و خارج ذراع الأداة من مرونة قطعة العمل. و مع ذلك فهي تعتبر عملية معقدة و بالتالي لم يتم تطوير أي نظرية شاملة. إن البحث في الأسباب الجذرية للذبذبة و آلية تشكيلها و تصميمها الرياضي و إيقاف هذه الذبذبة لهو أمر مهم جدا للصناعة و للوسط الأكاديمي. النظريات السائدة في الذبذبة مثيرة للجدل و غالبا ما تتناقض مع الأدلة التجريبية. تفترض نظرية التجديد أن التباين السطحي المتبقي من قطع سابق يتداخل مع القطع التالي مما يؤدي إلى الذبذبة. في المقابل تنص نظرية الرنين على أن الذبذبة تحدث بسبب الرنين عندما يتزامن تردد القصاصة مع الترددات الطبيعية لنظام (MTFW). قام الطالب من خلال هذه الدراسة بالتحقيق عن تردد رقاقة الرنين , و قوة القطع , و اشكال الوضع , و الترددات الطبيعية من ذراع الأداة , و سعة الاهتزاز أثناء تحويل AISI 304 (الفولاذ المقاوم للصدأ) تحت مجاميع مختلفة من عوامل القطع الأولية لهدف خلق نموذج للاستجابات لغرض فهم عملية الذبذبة. تم تشغيل مادة AISI 304 (الفولاذ المقاوم للصدأ) على مخرطة محرك باستخدام رؤوس قطع مغلفة ب cemented TiN من الكربيد. وقد تم استخدام منهج التصميم المركب المركزي (CCD) في منهجية الاستجابة السطحية (RSM) للتجارب المصممة , و أسفرت عن نماذج حسابية تجريبية تربيعية لسعة الاهتزاز و تردد رقاقة الرنين , و نموذجين للتفاعل (2FI) لقوة القطع التي تم تحليلها لاحقا باستخدام ANOVA. وجد بأن سرعة القطع (V_c) و عمق القطع (DOC) له تأثير اضطراب تربيعي في تحديد الاستجابات. بعد ذلك تم استخدام فرضيات نظرية الرنين من الذبذبة و طريقة توازن الطاقة لتفسير الذبذبة كنتيجة ل P_{max} (طاقة الاهتزاز) عند رنين اشكال الوضع لذراع الأداة. و قد وجد أيضا أن الذبذبة تحدث نتيجة اقتراب رقاقات القطع من مضاعفات عدد صحيح من ترددات الرنين (المستعرضة و الالتوائية) لذراع الاداة (= fc $10f_{n1}, 20f_{n1}, 30f_{n1}$ and $f_c = 2f_{n5}, 4f_{n5}, 6f_{n5}$) بسبب اقتران الوضع مما أدى إلى قيم ذروة كبيرة من قوة القطع و الذبذبة. كانت النماذج التجريبية محسنة من الناحية العددية والرسومات البيانية , وأظهرت أن الذبذبة كانت أكثر عرضة لمجاميع قطع عالية السرعة (قرب 200 م / دقيقة) و قطع عميقة (2 مليمتر أو أكثر). و في الوقت نفسه تم تطوير نظام للتحكم في الذبذبة و يتم التحكم فيه عن طريق جهاز تحكم (PI) المطور في LabVIEW. قام هذا الجهاز باكتشاف وخفض نسبة سعة الذبذبة الى 46 % (في المتوسط) و تم التعامل معها على انها اضطراب في عملية الدوران. و قد تم تزويد اداة لتخميد الذبذبة عن طريق الحقل المغناطيسي الموحد الناتج عن المغناطيس الكهربائي و الذي يقوم بمقاومة اي حركة من الأداة الحديدية المغناطيسية. اداة التخميد هذة تتسمبالاقتصادية و القوة , و هو قادر على التعامل مع جميع حالات القطع لنموذج ال CCD. فمن خلال هذا البحث حصلنا على فهم موسع للذبذبة باستخدام أساليب تجريبية و إحصائية و تحليلية , و قمنا بالتنبؤ بالمناطق المستقرة للقطع , و أخيرا تمكنا من تطوير نظام تحكم جاهز بالذبذبة.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2FI	Two-factor interaction
3D	Three dimensional
V_c	Cutting speed
f	Feed rate
DOC	Depth of cut
ANOVA	Analysis of variance
DOE	Design of experiment
CCD	Central composite design
RSM	Response surface methodology
CNC	Computer numerical control
DAQ	Data acquisition
DF	Degree of freedom
F_c	Cutting force
f_c	Chip serration frequency
f_n	Natural frequency
FEA	Finite element analysis
FFT	Fast Fourier transforms
Hz	Hertz
mm	millimetre
N	Newton
SEM	Scanning electron microscope
SS	Sum of squares
MRR	Material removal rate

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

A major activity in most manufacturing processes is the removal of materials using tools to produce parts having required shape, dimensions and accuracy. Such subtractive manufacturing or removal processes are termed as machining and are essentially ‘chip or swarf removing’ processes. These processes represent the largest class of manufacturing activities in the industry. As, metals and their alloys represent the most common materials which are machined, the term ‘metal cutting’ is often used instead of machining (Trent & Wright, 2000).

Turning is the most common and basic machining process which has remained virtually unchanged since early 18^{th} century (Trent & Wright, 2000). It is usually accomplished using machine tools known as lathes. Like most machining operations, turning is often plagued by chatter which accelerates tool wear, increases surface roughness, and reduces process predictability and productivity. Therefore, chatter is of serious concern in both research and industry.

Machine tool chatter is a type of intense self-excited vibration between the individual parts of a Machine-Tool-Fixture-Work (MTFW) system. The prevalent practice in chatter avoidance has been to reduce the cutting speed, which unfortunately lowers material removal rate and productivity.

Although, chatter has been extensively investigated since its first identification by Taylor (1907) over a 100 years ago, and several hypotheses and theories have been developed, the root cause of chatter and its mechanism of formation still remain controversial (Amin, 1982). This is because the phenomenon of chatter is very complex and there are many sources of vibration in the MTFW system (Amin & Patwari, 2011).

Most research works have focused on the basic theories and mechanics of mechanical vibration or the role of structural dynamics of the machine tool to understand chatter (Amin & Patwari, 2011). Yet others have viewed chatter from an analytical approach to the mechanics of machining and assessing machinability (Oxley & Young, 1989). However, on most occasions, chatter has remained elusive, inexplicable and unpredictable (Tarng, Young & Lee, 1994).

Among the established theories of chatter, the most widely used one is the Regenerative Chatter theory (Tobias, 1965). The theory posits that vibration marks on the work-piece, left from previous cuts in the form of surface waviness, are responsible for generating chatter in the subsequent cuts (Wiercigroch & Budak, 2001). However, the regenerative theory of chatter fails to explain the incidence of chatter in helical turning of a ground work-piece having no chatter marks from the previous pass (Amin & Patwari, 2011). Therefore, a more generalized and effective theory and model for chatter, especially in metal turning operations, is required.

Amin (1982), and Amin and Patwari (2011) have explained chatter as a resonance phenomenon which arises in the system when the chip serration frequency coincides with the prominent natural frequencies (or higher harmonics) of the MTFW system. They investigated in detail the instability of chip formation in machining and observed the formation of primary and secondary ‘serration or saw teeth’ on the resultant chips. This led to the insight that the root cause of chatter in end milling was a resonance phenomenon (Amin, 1982; Patwari, Amin & Faris, 2010). Building on this conclusion, turning, which is also a basic metal cutting process, is expected to have a similar formative mechanism of chatter. Nevertheless, the elastic system of turning is different from that of a vertical milling machine and the components of the system have different configurations and natural frequencies. For instance, milling is an interrupted cutting process whereas turning is a continuous process. In addition, there is as yet no consensus among the different researchers on the main cause of chatter in turning and how best to model it. Hence, it is essential to study in detail the system dynamics and the cutting parameters related to chip formation instabilities and the interaction of the chip serration frequencies with the system's natural frequencies. This would lead to a correct understanding of the mechanism of chatter in turning, which is the main focus of this research.

Chatter control is another important area in manufacturing industry where its detrimental effects on process economics and its unpredictability have spurred the development of many chatter control methods. However, most, if not all, of these existent chatter control methods are expensive or difficult to implement. Thus, this research also focuses on the development of a simple, yet robust and economical, online chatter control method.

1.2 PROBLEM STATEMENT

Although many research works have been conducted on chatter and its modelling, an extensive literature search seems to indicate the absence of a comprehensive chatter theory for turning with reliable predictions of the onset of chatter under varying conditions of cut. Existing theories and hypotheses are mostly contradictory in nature and sometimes do not agree with experimental observations. The prevalent Regenerative Theory of Chatter by Tobias (1965) fails to explain chatter during helical thread cutting or turning of highly polished metals. Other works are purely experimental in nature, trying to understand the phenomenon of chatter from empirical observations and devising ways to eliminate it (Amin & Patwari, 2011; Amin, 1982). Yet others, for instance Patwari (2010), addressed the phenomenon of chatter for end milling operations only. Thus there are few, if any, contemporary research work effectively explaining and modelling chatter, especially for turning of stainless steel. Therefore, it is of paramount importance to develop an effective model of chatter and to validate it using experimental data for different conditions of cut. The proposed model of chatter in the current research work is intended to be formulated based on chip serration, dynamic characteristics of the MTFW system, cutting force, primary cutting parameters and resultant machining vibrations; all of which have not been taken into consideration, in a comprehensive manner, in previous research works. The intended model will be developed based on an in-depth understanding of chatter formation mechanism derived from experimental observations of the chip serration process during turning of AISI 304 stainless steel and its interaction with system dynamics via mode coupling as the primary player in the generation of chatter.

In addition, a viable and effective chatter control strategy in turning of stainless steel is needed. Most existing chatter damping methods are costly, complicated or difficult to implement. Yet others are based solely on heuristics, such as variations in spindle speed or trial and error methods. Thus, coincident with model development, the current research work intends to develop an online chatter control strategy and test its ability to reduce vibration amplitude during turning of stainless steel at different conditions of cut. The technique proposed for such chatter control is the application of magnetic fields from electromagnet controlled via a closed-loop computerised control system.

1.3 SIGNIFICANCE AND BENEFITS OF THE RESEARCH

The developed mathematical models of chatter and the online damping technique will be very useful for metal cutting industries, especially the automotive and structural member fabrication industries which use steel very widely. The theory will also help researchers gain a clearer understanding of chatter as well as enable them to standardize and optimise chatter free steel turning operations for industrial applications. The model and theory will pave the way for newer avenues of research in this field. Upon completion, the current research will lead to the following specific benefits:

1. Better in-depth and quantitative understanding of the mechanics of chatter formation in turning operations involving AISI 304 stainless steel.
2. Accurate prediction of the incidence of chatter which can be implemented in research work or industrial processes involving turning of stainless steel, a very common and important work material in aerospace, automotive, structural part or component manufacturing and food processing industries.
3. Development of a novel online chatter control system based on electromagnetic damping technique.
4. The developed models and implementation of the chatter control system in the manufacturing industry could lead to the following benefits:
    a. Higher dimensional accuracy and improved surface finish of machined parts.
    b. Greater material removal rate and production efficiency.
    c. Increased process predictability and reliability which could facilitate automation.

d. Significantly longer tool life and better machine tool performance which would lead to better process economics.
e. Avoidance of catastrophic tool or machine tool failure, hence increase in process safety.
f. Reduction of reworks and wastages.
g. Cancelation of loud high pitched noise associated with chatter during machining operations.
h. Elimination of the need for using cutting fluid making turning of stainless steel more environmentally friendly.

1.4 RESEARCH PHILOSOPHY

This research study is designed based on the historical roots of the physical phenomenon of chatter formation in machine tools. Different hypotheses, employing both theoretical and empirical approaches, were evaluated in depth based on their merits and limitations. The philosophical assumption of this research is made based on the experimental findings of previous and current research on: the discreet nature of chip formation, vibration spectral analysis and cutting force during turning. Past research works have used quantitative, qualitative and mixed-method approaches to explain chatter formation (Patwari, 2010).

The current research employed a positivist philosophical approach to address the research questions. This philosophy dictates that vital and relevant information is obtained by adopting a precise, programmed approach when gathering data. This mode of thinking preaches an objective approach to understanding reality where emphasis is put on quantitative precision and the collection of relevant factual data in order to build knowledge and obtain a closer estimation of reality without any