Dynamics of Torsional and Axial Vibrations in Indexable Drills

Amir Parsian
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Acknowledgments

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Borrning används ofta i tillverkningen av produkter som behöver hål för sin funktionalitet, exempelvis för axlar, skruvhål eller stift. Vändskärsborrar är en typ av borr som underlättar tillverkningen av sådana hål. Denna typ av borr kan orsaka höga ljudnivåer på grund av vibrationer och i fokus för denna avhandling är att undersöka mekanismen bakom dessa vibrationer i syfte att minska eller eliminera dessa vibrationer i framtida konstruktioner. Den viktigaste mekanismen som leder till detta är regenerativa "chatter" vibrationer på grund av axiella och vridande rörelser hos borkroppen. Det första steget att angripa orsakerna är att ha en god simuleringsmodell, regenerativa "chatter" vibrationerna i borden genom att modellera de statiska skärkrafterna på ett tillförlitligt sätt. Den framtagna modellen klarar av att förutsöga de totala statiska skärkrafterna som uppstår genom segmentuppdelning av skäreggarna. Modellen klarar av att hantera skillnader i geometri hos skären för beräkning av skärkraften.

De erhållna lasterna används sedan till en vibrationssimuleringsmodell. Denna simuleringsmodell kan simulerar kopplade "chatter" vibrationer genom att inkludera både axiella och vinkel deformationer.

Dynamiken bestäms av ett system bestående av fördröjningsdifferentialekvationer med en variabel för fördröjningen.

Variationer i denna tidsfördröjning sker då verktyget rör sig genom att hoppa ut och bakåt under ingrepp. Dessa rörelser har inkluderats i den framtagna tidsdomänsimuleringen. En uppsättning experiment utfördes för att verifiera modellen.
Abstract

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Drilling is widely used in manufacturing of products which need holes, for example for fluid channels, screws or pins. Depending on application, workpiece material, cutting parameters and economic considerations, different types of drills are employed. Indexable insert drills are types of drills which facilitate inserts to make holes. These types of drills can make high pitch noises due to vibrations. The focus of this thesis is to investigate the mechanism behind these vibrations in order to help reducing the generated noise in the future designs. Primary investigations show that the main mechanism which results the mentioned noise is regenerative chatter vibrations due to axial and torsional flexibilities. There is a gap in modeling of chatter vibrations in indexable drills where loadings and geometries are asymmetrical and due to torsional vibrations, delay terms are variable. The first step of simulating regenerative chatter vibrations in the drill is to model static cutting forces in a reliable way. In this thesis, a model is proposed which is capable of predicting static cutting forces through segmentation of cutting edges. Since, using this model, forces can be calculated separately on each insert, it is possible to consider differences of inserts in estimation of the cutting loads. The obtained loads are used in the chatter simulation. A model is proposed to simulate chatter vibrations by considering axial and angular deflections and the coupling between them. The resulted model is a system of delay differential equations with variable delays. Variations in time delays, tool jump-outs and backward motions of inserts have been included in the proposed time-domain simulation. A set of experiments is conducted to verify the model.
Contents

Acknowledgments i

Populärvetenskaplig Sammanfattning iii

Abstract v

Appended Papers ix

1 Introduction 1
  1.1 Literature Survey and State of the Art 4
  1.2 Aim of the Project and Research Questions 8
  1.3 Research Methodology 8

2 Static Cutting Forces 11
  2.1 Mechanistic Modeling 12
  2.2 Segmentation 13
  2.3 Total Forces 14
  2.4 Applications of the Model 16

3 Chatter Vibrations in Drilling 17
  3.1 Chatter Mechanism 17
  3.2 Variable Delay 18
  3.3 Tool Jumping Out 19
  3.4 Backward Rotations and Modified Force Model 19

4 Identifying the Type of the Vibration 21

5 Dynamic Parameters 25
  5.1 Frequency Response Functions 26
  5.2 Asymmetries in Indexable Drills 26

6 Forced Response 31
  6.1 Solving Equation of Motion 31
  6.2 Using Transfer Functions 32
Appended Papers


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List of Figures

1.1 A typical insert of an indexable drill ................................. 3
1.2 A typical indexable drill with two inserts ............................. 4
1.3 Normal equal-loudness-level contour corresponding to 75 phon .... 5
1.4 Outline of the work .................................................... 9

2.1 An example of an experimentally measured thrust force ........... 12
2.2 Cutting edge of central and peripheral insert .......................... 13
2.3 Segmentation of the insert ............................................. 14
2.4 Segmental friction and normal forces ($\Delta F_i^u$ and $\Delta F_i^v$) ....... 15
2.5 Segmental forces in global coordinates ($\Delta F_i^x$, $\Delta F_i^y$ and $\Delta F_i^z$) .... 15

3.1 Chatter marks at the end of the hole .................................. 18
3.2 (a) Waves in phase; (b) Waves out of phase ........................... 18
3.3 The chatter loop in drilling operation ................................. 19
3.4 The delay term in governing differential equations .................... 20

4.1 Measured sound pressure versus time. Feed rate=0.1 mm/rev, cutting speed=200 m/min, workpiece material= SS2244 .................... 22
4.2 Classification of vibrations in drilling ................................... 24

5.1 Deflections of the drill at its third mode shape .......................... 26
5.2 Typical shapes of the chips of central insert (top) and peripheral insert (down) ........................ 27
5.3 Axial deflection over the top surface of the tool when the tool is loaded by a torque ..................... 28
5.4 Axial deflection of the drill at its third mode shape. Darker areas represent less deflections .......... 29

7.1 Generated axial force by central and peripheral inserts ............ 34
7.2 Generated torques by central and peripheral inserts ................ 34
7.3 The Flowchart of the simulation ........................................ 36
7.4 The Flowchart of the simulation with iterations [80] ............... 37
7.5 Simulated axial vibration of the central insert, $\Delta z^C$ ............... 38
7.6 Simulated axial vibration of the peripheral insert, $\Delta z^P$ ............ 38
7.7 Simulated torsional vibration of the central insert, $\Delta \theta^C$ .......... 39
7.8 Simulated torsional vibration of the peripheral insert, $\Delta \theta^P$ ....... 39
7.9 Simulated angular speed of the central insert, $\Delta \dot{\theta}^C + \Omega$ ......... 40
LIST OF FIGURES

7.10 Simulated angular speed of the peripheral insert, $\Delta \dot{\theta}^p + \Omega$ ......... 40
7.11 Spectrum of the simulated torque ................................................. 41
7.12 Spectrum of the measured sound .................................................. 41

8.1 The chain of causes and effects behind the unwanted noise ............... 43
Chapter 1

Introduction

Modern societies are highly dependent on industrial products and manufacturing of goods. According to the World Bank, in the last decade, around 15.5-17.5 percent of the world’s GDP was generated by manufacturing. In 2012, around ninety million jobs were provided directly and indirectly by manufacturing sector in the European Union. Growing demand of human societies for having a higher level of welfare through employing new technologies, along with eco-friendly and energy-efficiency obligations, push the manufacturing sector to be more innovative and efficient and at the same time more responsive to changes.

Machining processes are manufacturing methods that are widely used to make high quality products with close tolerances. While different manufacturing methods have been developed to cope with the constant growing complexities of the industrial products, the machining keeps playing an indispensable role in producing many manufactured components. At the end of the last century Merchant highlighted the importance of machining by mentioning that 15 percent of all product values are due to the machining and in producing of mechanical products, the machining process is used more than any other manufacturing process. It is predicted that machining will continue to play its important role in the coming decades. Due to their important roles, machining processes have been subject of many projects and academic studies around the world and as it was predicted by Merchant in 1993 there is a focus in research to increase autonomy and quality in these processes.

Although a large variety of machining processes have been developed over time, it is possible to categorize them into two main types namely conventional, or traditional, and non-conventional machining. While conventional machining processes e.g. turning, drilling and milling are processes which cutting edges cut the material from workpieces through movements of tools relative to workpieces, the term non-conventional machining refers to other cutting processes for example water jet, electrochemical machining, electrical discharge machining, etc. In a recent review paper written by Arra-

\footnote{Advancing Manufacturing paves way for future of industry in Europe; European Commission-MEMO/14/193, 19 March 2014}
CHAPTER 1. INTRODUCTION

zoia et al. it has been mentioned that conventional machining represents a large fraction of manufacturing processes [4], which emphasizes the importance of this category of operations and its key role despite of advancements in non-conventional machining processes.

Hole making with drills as a conventional machining operation is widely used in manufacturing of products. Holes are made in manufactured parts for different reasons for example where screws or pins are needed or channels must be made for fluids. Making holes consumes more than a third of machining time [5] which represents the importance of drilling processes in the machining industry and the effect of its efficiency on manufacturing costs. Depending on cutting parameters, workpiece material, quality requirements and economic considerations, different types of drills might be used such as solid carbide, exchangeable tip and indexable insert drill. Despite the differences in designs, the common feature of drilling process with these drills is that materials are removed in simultaneous angular and axial motions of the cutting edges of drills.

Indexable insert drills, also called endrills in the literature [6–9], facilitate indexable inserts to make holes. A typical insert is shown in Figure 1.1. Due to exchangeability of the inserts, using them improves the economy of machining. Inserts are made of more durable materials in comparison to drill-body which makes it possible to this type of drills to tolerate sever cutting conditions. In most cases each insert has several cutting edges that are used in turn by rotating (indexing) the inserts. Having edges as a part of inserts, rather than the tool-body, makes it possible to use the tool-body for a longer time simply by indexing the inserts until all cutting edges are worn out and then replacing the insert. As shown in Figure 1.2 different inserts are usually mounted at different radial distances to the drill rotation axis and each insert cuts a part of the hole. Depending on the radial distance of the insert from the drill rotation axis the average cutting speeds are different for inserts and therefore their geometry, coating and produced chip might differ. In most cases these lead to asymmetric geometries and asymmetric cutting loads.

Although, drills with helical flutes, including indexable insert drills, show reasonable performance in making holes, they can make a high pitched noise that can be very unpleasant in workshops. To address this issue and to obtain a less noisy drilling operation, one needs to investigate the mechanism which is leading to vibrations and consequently the generated noise.

Vibrations are induced into machine-tool-work system due to dynamic loads. Removing the material from the workpiece generates cutting forces on the drill which cause deflections; the deflections can be static, if the forces are constant over the time, or dynamic and vibrational, if forces are varying over the time.

In general, vibrations are usually unwanted phenomena in machining, because they cause noise, poor surface quality, unacceptable tolerances and shorten the tool life. Therefore, except cases such as vibration assisted machining [10–12] where vibrations
are used to break the chips and reduce cutting forces, there are efforts in machining industry to have cutting processes which are less prone to vibrations. Different mechanisms lead to vibrations in machining and cause free, forced or self-induced vibrations [13]. Technical definitions of these types of vibrations are found in ISO-2041-2009 [14]. In spite of recent achievements in avoiding and controlling self-induced vibrations, they still challenge machining processes and reduce the quality of the operations. In self-induced vibrations, also called self-excited vibrations, the vibration itself affects the dynamic forces in such a way which sustains the vibration, which gives the reason for their names. This family of vibrations can be generated due to different mechanisms such as mode coupling and regenerative chatter mechanism [13].

Regenerative chatter vibrations lead to excessive noise which is troublesome in many workshops. They cause poor surface finish and less accuracy and reduces the tool life [15]. As the relative distance between the tool and the workpiece varies due to dynamic forces, a wavy surface is left on the workpiece. During the next cut, these waves in combination to current motions of the tool-workpiece system cause variations in uncut chip thickness and therefore cutting forces which consequently affect the dynamic motions of the system. This interaction and reciprocal influences between forces and deflections can lead to development of regenerative chatter vibrations. Details about the mechanism of regenerative chatter can be found in the literature [16, 17].

Axial, angular and lateral flexibilities can cause regenerative chatter in drilling operations. Regenerative chatter vibrations in drilling cause noise, holes with large tolerances, wavy surfaces on the walls of the holes and even the breakage of tools. The generated noise in torsional and axial chatter vibrations, usually is a high-pitched noise. In many cases in current designs of indexable drills, the frequency of this noise is in the range of 2-6 kHz. The normal equal-loudness-level contours, provided in ISO 226:2003 [18], shows the human hearing system is more sensitive in this frequency range; which
means a sound is perceived as a louder sound when the dominant frequencies are in range of 2-6 kHz. Figure 1.3 shows the normal equal-loadness-level contour of 75 phon which is produced based on formulas provided in [18]. Because of the negative effects of the noise generated by torsional and axial chatter vibrations in drilling with indexable drills, the subject of this thesis is to investigate these types of vibrations to help decreasing the resulted noise.

1.1 Literature Survey and State of the Art

Despite being a very old manufacturing technique, dating back to early civilizations, the drilling operation is still a limiting process in many manufacturing workshops [5]. Causing a better chip evacuations, introducing of helical flues in 1863 by Morse, U.S. Patent 38,119 [5, 19], was a breakthrough in the drill design [20]. In parallel to indus-
trial innovations in drilling technology such as indexable insert drill and exchangeable
tips which have helped with having a better drilling process, academic studies have been
conducted to support the future designs and to increase the performance of drilling op-
erations.

As a metal cutting operation, developments in drilling is tightly connected to research
conducted in metal cutting field. Although the studies in metal machining have been
done as early as 19th century, such as the study by Mallock in 1881 [21], the inher-ent complexities in multi-physic nature of machining process are still challenging the
academia and the industry. One important goal of many metal cutting studies is to ob-
tain predictive models. Such models can reduce the trial and errors, improve the quality
and increase the productivity [4]. Modeling in machining is done using experimental,
analytical, numerical, artificial intelligence techniques and combination of these tech-
niques, according to a survey conducted by CIRP [22]. Among the different aspects
of metal cutting research, prediction of cutting forces and dynamic behaviors are in the
scope of this thesis. Ehmann et al. have categorized approaches that have been applied
to model the dynamic cutting process and static cutting as a special case of it, into four
categories, analytical, experimental, mechanistic and numerical [23]. It is worth not-
ing that the mechanistic modeling can be seen as a combination of experimental and
analytical models [22]. Adding the fact that artificial intelligence techniques has been
used in modeling dynamics of metal cutting for example the work done by Tarng et al. [24] and Lee et al. [25], the same categories as mentioned by Luttervelt et al. in
[22] for metal cutting in general can be used in cases of modeling of dynamic and static

\[ \text{Figure 1.3: Normal equal-loudness-level contour corresponding to 75 phon}\]^[2]

\[\text{For description of phon, refer to ISO 226:2004}\]
CHAPTER 1. INTRODUCTION

cuttings. Among the mentioned approach for modeling, i.e. experimental, analytical, numerical and artificial intelligence techniques, the last one has the disadvantage of not being a physics-based approach.

Cutting forces cause structural deflections which affect the cutting zone and consequently the surface of the workpiece. Furthermore, these forces affect the design of the tool and selection of the machine and the fixture. Therefore, prediction of cutting forces play a crucial role in metal cutting. One common technique in metal cutting field for modeling static cutting forces is to divide the cutting edge into smaller segments and use experimental, analytical or numerical approach to calculate segmental forces and combine the forces to obtain total forces. Armarego and Cheng in [26, 27] proposed an elemental approach to calculate cutting force in drilling by dividing the cutting edge into smaller segments. The segmenting approach also was used by Watson in [28] to predict cutting forces produced by drill lips in twist drills. The model did not include the chisel edge and therefore in the experimental part the center of the holes where removed by pilot holes. However, the author of the paper mentioned that the prediction was not good enough because the chip was assumed as a collection of individual element rather than an integrated piece. In another work [29], Watson reviewed the model and considered the effect of integrity between the elements and obtained better results for modeling forces on the lips of the twist drills. However, the model did not include the effect of chisel edge and therefore it was modeled in a separate paper [30] where a model is presented which uses a process similar to wear process in combination to extrusion and oblique cutting to predict the chisel edge forces. Finally the proposed models for lips and chisel edges were compared by a series of experiment in [31] and it was shown that the offered model for predicting the cutting force generated by lips is more accurate than the model which tries to predict the whole force generated by lips and chisel edge. Therefore, revealing that the modeling of the chisel edge, where the cutting edge more plows into the workpiece than cuts it, can be more complicated in comparison to modeling only the lips. Predicting cutting forces by dividing cutting edges into smaller segments gives the possibility of modeling a wide range of cutting shapes and therefore it is a common practice in metal cutting and has been used in other applications such as turning, milling and boring. Kaymakci et al. in [32] presented a unified model which uses the cutting edge segmenting idea to predict cutting forces in several metal cutting operations including drilling. Later this model is used in [33] by Parsian et al. to propose a matrix equation which relates the geometries of cutting edges, workpiece material and cutting forces in drilling with indexable insert drills. The proposed relationship can be used to predict cutting forces by using a set of cutting coefficients. Using this model, cutting coefficients can be obtained from a small set of drilling operations by using the fact that in most indexable inserts, due to their asymmetric design, the radial force is not zero in contrary to symmetric drills. Therefore, the model uses the radial force in combination to the thrust force and the torque to obtain required coefficients.

In a general usage chatter refers to a quick and repeated high pitched noise. In the field of metal cutting the term of chatter refers to noisy vibrations made by different
1.1. Literature Survey and State of the Art

mechanisms. While some authors use the term of chatter to refer to vibrations made by both self-excited and forced vibrations [34–38], others have used chatter for self-excited vibrations [13, 15, 39–55]. Throughout this thesis the term of chatter only refers to the vibrations made by self-excited mechanisms. This phenomenon has been investigated for different metal cutting operations such as turning, milling, boring and drilling. Taylor who is referred as “the father of metal cutting science” [22], gave one of the earliest explanations for the chatter problem in his book on metal cutting [56] which indicates the importance of chatter since the early age of metal cutting research. Taylor in [56] explained the chatter as a result of changes in cutting pressure which is exciting one of the resonance frequency of the system. However, as it is mentioned by Chen [38] there was a little research about the metal cutting vibrations before the work done by Arnold [57] in 1940’s. Other pioneering studies on chatter vibrations in machining were done by Hahn [58] and Doi and Kato [59] in 1950’s. In fact 1940’s and 1950’s are sometimes referred as the “golden age” for the research in the metal cutting field [3]. A comprehensive review on chatter vibrations is given by Quintana et al. in [60] which presents the state of the research in chatter before 2011.

Surveying the literature shows that studies on chatter vibrations in drilling have been done by considering torsional, axial and lateral flexibilities. A drill with helical flutes represent a twisted bar, and since the torque changes the length of a twisted bar [61], therefore the drill structure has a coupling between torsion and axial deflections. Bayly et al. in [62] have considered this coupling effect in the study of chatter vibrations in drilling. They proposed a single degree of freedom model which can predict the onset of chatter. In [62] the dynamic of the system is presented in form of a delay differential equation, DDE, which can be used to predict the occurrence of the chatter due to torsional-axial flexibility. Although the torsional-axial chatter is very common in drilling, lateral chatters can happen as well. Arvajeh et al. in [63] presented an approach to model the lateral chatter in drilling. Later, they combined this model with the one proposed in [62] to present a model which is capable of predicting chatter in torsional-axial and lateral directions [64]. Due to variations of the torque during the chatter, the drill vibrates in angular direction which affects the dynamics of the chatter. This effect has been considered in the model proposed by Roukema et al. in [65] and it has been discussed that torsional vibrations affect how the amplitude of the vibration increases. Later, lateral vibrations were added to the model to obtain a model which can predict torsional, axial and lateral chatters in drilling operations [66, 67]. Process damping which occurs as a result of forces from friction between cut surface and flank face and plastic/elastic deformations due to this contact [17, 68], has not been included in the proposed model by Roukema et al. in [66, 67]. The process damping affects the dynamics of chatter vibration and causes higher stabilities in lower cutting speeds [68]. Although models proposed by Ahmadi et al. in [69, 70] considers the effect of the process damping in drilling operations, the time delay in governing equations is considered to be constant.

At the current state of research, there is a lack of modeling chatter vibrations in drilling when the drill structure is asymmetric as it is in case of indexable drills, the drill has
low damping ratio and the torsional vibrations cause backward rotations in the drill. This work tries to fill this gap by purposing a model which cover the mentioned features. Such a model can be very useful in designing a more efficient and more silent indexable drills.

1.2 Aim of the Project and Research Questions

The main goal of this project is to understand underlying mechanisms that cause structural vibrations and unacceptable noise levels in indexable drills. The obtained knowledge is intended to be used to model the relationship between mechanics of cutting process and generated noise levels and vibrations in drilling with indexable drills with focus on drilling in steel. The generated sound in drilling is caused by vibrations which is shown to be dominated by one specific frequency and higher harmonics of that. More investigations showed that the dominant frequency is very close to a natural frequency of the drill structure. The corresponding mode shape is a torsional-axial mode in drill which is the third mode shape of the current design of most indexable drills. This relationship between dominant frequency of the noise and natural frequency of the structure might be a sign of a type of vibrations known as regenerative chatter vibrations. Therefore, it is intended to provide a better understanding on mechanisms which are leading to regenerative chatter problem in indexable insert drills. The obtained knowledge, in form of mathematical models, helps to create a design space which suppresses the noise and unwanted vibrations. Such a model provides a relationship between design parameters and drill dynamic behaviors and therefore saves a lot of time and cost in the designing phase. The work is limited to modeling of torsional and axial chatters since they are dominant chatter mechanisms in the current design of indexable insert drills.

Although this study is focusing on indexable insert drill, the presented approach can be extended to other types of drill such as exchangeable tip or solid carbide drills.

1.3 Research Methodology

In this thesis, a combination of experimental, analytical and numerical techniques are used to model the dynamic behavior of the indexable insert drills. Prediction of steady-state (static) forces in drilling was the first step in this work because of their important effects on dynamic behaviors of drills. Due to its computational time, finite element is not used for modeling steady state forces in this thesis. However, interested reader may refer to [71–74] for more details on this approach in metal cutting simulation. To predict static forces, a model is developed, which is based on segmentation of cutting edges. Each edge is divided into smaller segments, loads on each segment are calculated using empirical coefficients and summed up to obtain total forces. The method is based on a work by Kaymakci et al. [32], but it is adapted to be used in indexable insert drills and is presented in Paper A [33].
After obtaining a force model, the next requirement for simulating dynamic behaviors of the system is to identify the dynamic parameters which affect the system. These parameters include masses, stiffnesses and damping ratios. A global damping ratio is considered in the model which is obtained from an impact test. The impact test is carried on by clamping the drill in a holder which is mounted on a heavy rigid table. The obtained damping ratio, along with the Young’s moduli, Poisson’s ratios and densities of the materials of the tools are used in a finite element model to obtain frequency response functions. These frequency response functions are used to obtain dynamic parameters by using modal analysis techniques. Another required task for the modeling of chatter vibrations is choosing a force response method which relates the input forces and dynamic parameters to the output displacements. Equations of motions of the system are solved by Runge-Kutta methods to obtain the responses. Furthermore, due to angular vibrations the drill edges rotate backwards in some time intervals, this phenomenon has been considered in modeling the forces and is discussed in Paper B [75]. Having all necessary tools, a model is proposed in paper C to simulate chatter vibrations in the indexable drill. The outline of the project is shown in Figure 1.4.

![Figure 1.4: Outline of the work](image-url)
Chapter 2

Static Cutting Forces

The prediction of cutting forces is important for tool, machine tool and fixture designers and in workshop for selection of right tools and devices. In this work, a model which is capable of predicting static cutting forces is required because it will be used for simulating of chatter vibrations.

Drilling with indexable inserts as a conventional metal cutting operation involves removing a thin layer of workpiece material in each tool revolution. This generates forces known as cutting forces. These forces vary as the tool start penetrating to the workpiece. However, after a complete penetration, in most drilling cases, the average values and RMS values of forces do not change significantly until the drill starts going out of the workpiece. As an example a measured thrust force in drilling with indexable insert is shown in Figure 2.1.

Amplitudes and directions of cutting forces depend on different parameters for example workpiece material, cutting speeds, inserts geometries, uncut chip thicknesses and chip widths. The relationship between these parameters and cutting forces is of interest in machining industry because it helps a better prediction of cutting forces. Prediction of cutting forces are important mainly because cutting forces cause deflections in the machine-tool-workpiece system. Furthermore, they affect the tool life and power consumption. A model which is capable of predicting cutting forces, accelerates the tool design phase via reducing the number of prototypes and helps better drilling operations in workshops through suggesting better parameters for cutting process. Therefore, several studies and research works have been conducted using different approaches such as analytical, mechanistic and finite element methods to obtain a useful model. The choice of method depends on the purpose of the modeling, but in all cases a relationship is made between cutting forces in one hand and geometries, physical properties such as workpiece material, coating of the edge and cutting parameters e.g. feed rate and cutting speed on the other hand.
2.1 Mechanistic Modeling

One approach to model cutting forces is mechanistic approach and can be found in the literature [16]. In this method forces are written as functions of equivalent chip width \((L_e)\) and chip thickness \((h_e)\) using a set of coefficients. By obtaining these values from a set of experiments, it is possible to predict forces in different chip thicknesses and widths. The cutting coefficients are obtained by experimental methods. The first step to estimate these coefficients is to measure cutting forces at different feed rates and then to calculate the average forces at each feed rate and finally to fit a function (usually a linear polynomial) to the discrete points. If a linear polynomial is used, the obtained relationship will have a generic form as shown in Equation 2.1.

\[
F = a \cdot h_e \cdot L_e + b \cdot L_e
\]  

While the equivalent chip width and thickness are dependent on geometries, the cutting coefficients incorporate the effect of many parameters which influence the cutting forces for example workpiece material, coating of the edge and the feed rate. Although using these coefficients is convenient because of the simple relationships between them and cutting forces, they put a lot of restrictions on their applications. Because they have been set to specific cutting cases, if any of the factors which affects these coefficients changes the coefficients must be estimated again using a new set of experimental data. Example of this type of changes includes changing of workpiece material, chang-
ing of the coating or changes in cutting edge geometry. The dependency of cutting coefficients to insert geometries is a drawback in case of using these coefficients in design. The reason is that the coefficients can be calculated only when the physical tool is produced and used to measure cutting forces. This way of modeling is not an efficient way from tool design point of view because a lot of prototyping is required before an optimized design is achieved. To overcome this problem, segmentation approach is used as described in the following section to reduce the dependency of cutting coefficients on geometries and positions of cutting edges.

2.2 Segmentation

Segmentation is an approach to separate the effect of cutting edge profiles from cutting coefficients. As shown in Figure 2.2, the edge of inserts for central insert and peripheral insert can be different and the edges of inserts are not limited to those shown here. Segmentation provides the possibility to deal with variations in edge profiles in a systematic way.

![Figure 2.2: Cutting edge of central and peripheral insert](image)

The aim is to separate the whole geometry of the tool or at least a part of that from cutting coefficients. The method consists of dividing the cutting edges into smaller segments (Figure 2.3 shows an example), computing the forces on each segment and finally combining the segmental forces to obtain the total cutting forces. The method has been widely used in different metal cutting applications.

The forces on each segment are calculated using a set of cutting coefficients which are the same for all segments on a specific edge. Forces in friction and normal directions on segment \(i\) (\(\Delta F_u^i\) and \(\Delta F_v^i\) respectively) are calculated on the surface of the segment using four cutting coefficients as shown in Equations 2.2 and 2.3 [32]. The forces are shown in Figure 2.4.

\[
\Delta F_u^i = K_{uc} \cdot h^i \cdot L^i + K_{ue} \cdot L^i \quad (2.2)
\]

\[
\Delta F_v^i = K_{vc} \cdot h^i \cdot L^i + K_{ve} \cdot L^i \quad (2.3)
\]

When the forces are calculated on each segment, they are transformed into a global coordinate system (\(\Delta F_x^i\), \(\Delta F_y^i\) and \(\Delta F_z^i\) as shown in Figure 2.5) and summed up to make the total cutting force on the tool.
Chapter 2. Static Cutting Forces

Paper A [33] presents a mechanistic approach using segmentation, adapted for indexable insert drills. One of the advantages of using segmentation is that it is possible to use different cutting coefficients at different segments. This has been used by Parsian et al. in [33] to allow using different cutting coefficients for central and peripheral inserts. Since central and peripheral inserts do not have the same cutting conditions, using different cutting coefficients is a necessary part in modeling cutting forces. When the segmental forces on all segments of the edges are calculated it is possible to sum up them and find the total forces which is generated in the drilling process.

2.3 Total Forces

As shown by Parsian et al. [33], in case of using an indexable drill with two inserts, the process of summing of segmental forces to obtain total forces can be summarized in a matrix equation as shown in Equation 2.4.

$$
\begin{align*}
C_{8 \times 8} \times A_{8 \times 1} & = B_{8 \times 1} \\
\end{align*}
$$

(2.4)

C is a square matrix which contains geometric information about the edge profiles. A is a vector representing cutting coefficients of inserts ($K_{uc}$, $K_{ue}$, $K_{vc}$ and $K_{ve}$) and B is a vector representing linear coefficients of the forces.

Over cutting edges of an insert, the four cutting coefficients ($K_{uc}$, $K_{ue}$, $K_{vc}$ and $K_{ve}$)
are assumed to be invariants. These coefficients are depended on the workpiece material, coatings of edges, and some geometric features of cutting edges such as roundnesses of edges and relief angles. However, they are assumed to be independent from orientations of segments which gives the possibility of predicting cutting forces in different edge profile designs without requiring of physical prototypes.
2.4 Applications of the Model

Using the proposed model, contributions of each insert to cutting loads are estimated which is required for a better dynamic simulation. Helping with a better chatter simulation is the main reason for developing of this force model. However, other benefits of the model are,

- It gives the distributions of cutting forces on the edges. This helps a better simulation of deflections on the drill.
- It makes it possible to find the contribution of each insert and using it in designing insert seats.
- The calculated forces can be used in choosing appropriate machine, fixture, adapters, etc.
- Forces can be used for power consumption estimations.
- Forces at the entry and exit can be estimated.

Due to asymmetry in indexable drill design, in most cases radial forces in drilling with this type of drill is not zero. This radial force causes deflection in the drill which can cause a larger or smaller hole than the nominal value, depending on the direction of the radial force. In some cases this radial force can be so large that the produced hole becomes out of acceptable tolerances. Therefore, calculation of this force, which can be done using the proposed model, is beneficial in tool design process.

As mentioned above another advantage of the model is that it makes it possible to calculate the forces at entry and exit of the hole. How the drill enters the hole plays an important role in drilling operation and its quality. Usually these drills are designed in a way to have small radial forces in case of full edge cutting. However, this does not mean that the radial forces are small in the entry and the exit. In the entry and the exit, inserts are partially engaged which in some cases results in large unbalanced forces. Therefore, a good estimation of magnitude of these forces is crucial in designing of this type of drill.

Even though, balancing of the tool or estimation of radial forces at the entry and the exit are not the main aims in this study, but the developed model can be used for these purposes as well. Because of mentioned benefits, the proposed model in this chapter and Paper A [33] has been implemented in a computer package (Indexable Insert Drill Simulator), to be used as an assistant for the drill design.
Chapter 3

Chatter Vibrations in Drilling

Axial vibration of the drill affects the chip thicknesses and in presence of axial vibrations, torsional vibrations affect the chatter dynamics as well. Therefore, the deflections of the drill in axial and angular directions need to be considered in the chatter simulation.

Helical flutes, used in the design of indexable insert drills, improve chip evacuation; and therefore they are very common features in current design of indexable drills. However, these geometrical features cause a coupling between angular and axial deflections of the drill structure. This coupling has a significant effect on the dynamic behavior of the drill which will be explained in this chapter and Chapter 7.

3.1 Chatter Mechanism

In this section the basic mechanism underlying torsional-axial chatter in drilling is described. Chatter vibration is a self-induced vibration [13] which arises due to feedback effect of previous cuts and its combination to current relative motions between the workpiece and cutting edges [13, 16]. The chatter produces noise and marks on the surface of the workpiece known as chatter marks. An instance of such a chatter marks is shown in Figure 3.1. This pattern is generated at the end of the hole by vibration of drill-workpiece system and is a sign of chatter.

In drilling operations, each infinitesimal segment on the cutting edge go through a helical path due to simultaneous axial and angular motions of the edges. Assuming the length of the drill is varying sinusoidally due to vibrations, each segment leaves a wavy surface when it is cutting the material. In the next cut, another wavy surface is generated and if these two waves are in phase as it is shown in Figure 3.2a, the thickness of uncut chip remains constant. On the other hand, if these waves are not in phase as shown in Figure 3.2 b, the uncut chip thicknesses vary which cause variations in cutting forces and induce more vibrations.

In the above explanation, the vibration was assumed to be a pure sinusoidal motion in
3.2 Variable Delay

In case of drilling, due to torsional vibrations, delay terms in governing equations change over time. As it will be discussed in Chapter 7, this variable delay reduces the amplitudes of vibrations by affecting the chatter mechanism. This has been discussed
3.3 Tool Jumping Out

In chatter, amplitude of vibrations can grow such that the tool jumps out of the cut which causes a non-linearity in the system [76]. This phenomenon has a stabilizing effect on the chatter as mentioned by Tlusty et al. in [76]. As mentioned in [76] forces in case of tool out of the cut are zero which is a source of significant nonlinearity in the system.

3.4 Backward Rotations and Modified Force Model

Beside causing variable delay, angular vibrations cause another phenomenon which is the backward rotation. The incremental relative rotation between the cutting edge and workpiece at each time interval is the summation of the rigid body motion and the torsional vibration. In some intervals the amount of backward rotation due to the torsional vibration is larger than the forward rigid body motion and therefore the edge experiences a backward angular motion. This backward motions in drilling have been mentioned in previous studies [66]. In such moments the cutting edge does not cut by its rake face. Instead the flank face might touch the surface which has been cut [66]. The method proposed in [75] is used in this work to simulate the forces in those conditions.
To simulate the regenerative chatter vibration made by the loop shown in Figure 3.3, a force model is needed to calculate the cutting forces, dynamic parameters of the system are needed and finally a method is required to calculate the response of the system to dynamic cutting forces. The force model was introduced in Chapter 2, dynamic parameters are estimated in Chapter 5 and force response calculation is presented in Chapter 6. Finally, these tools are used in Chapter 7 to simulate regenerative chatter vibrations caused by axial and angular flexibilities.
Chapter 4

Identifying the Type of the Vibration

Vibrations in machining can be classified into three main categories, free, periodic forced or self-induced vibrations [13]. The vibration might be dominated by one of these types or a combination of them. Identifying the dominant mechanism or mechanisms in dynamics of the system is a crucial measure to take. To do the mentioned identification, a series of sound measurements are conducted at different conditions to see how the vibrations are affected. Sound measurements are done at different feed rates, cutting speeds and tool lengths.

The free vibrations are generated by transient forces and disappear over time due to the damping. An example of time domain measurement of the sound generated in a typical drilling process is shown in Figure 4.1. The measurement is divided into nine one-second-intervals and root means square, RMS, value is calculated over each interval. As shown in Table 4.1 the RMS values increase as the tool engage and after that changes between 0.7 and 0.96 Pascals. These variations are the effect of transient forces and can be generated by chip evacuation and defects in the workpiece material.

The periodic forced vibrations changes when the spindle speed changes. Therefore, cut-

<table>
<thead>
<tr>
<th>Time interval</th>
<th>RMS value [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1901</td>
</tr>
<tr>
<td>2</td>
<td>0.2023</td>
</tr>
<tr>
<td>3</td>
<td>0.5833</td>
</tr>
<tr>
<td>4</td>
<td>0.8772</td>
</tr>
<tr>
<td>5</td>
<td>0.9552</td>
</tr>
<tr>
<td>6</td>
<td>0.8922</td>
</tr>
<tr>
<td>7</td>
<td>0.7014</td>
</tr>
<tr>
<td>8</td>
<td>0.7716</td>
</tr>
<tr>
<td>9</td>
<td>0.6483</td>
</tr>
</tbody>
</table>

Table 4.1: RMS values over the time
Figure 4.1: Measured sound pressure versus time. Feed rate=0.1 mm/rev, cutting speed=200 m/min, workpiece material= SS2244

One initial finding is that in all cases the vibrations are highly dominated by one specific frequency and its higher harmonics. The dominant frequency in the sound and corresponding resonance frequencies of the one end clamped drill structure are shown in Table 4.2. Comparing the mentioned frequency to the resonance frequencies of the clamped drill, reveals that the dominant frequency is very close to one of the natural frequencies of the structure which is typical in regenerative chatter vibrations.

The chatter is a self-induced vibration [13] which can be divided in two types, the primary and the secondary chatter [77]. Regenerative chatter is the secondary chatter [77] which can be categorized into lateral, axial and torsional chatters in case of drills. This classification is shown in Figure 4.2. One specific feature of regenerative chatter vibration is that it always occur close to a natural frequency of the system. The frequency of chatter is far from resonance frequency associated to bending modes, therefore it seems logical to conclude that the chatter vibration which this work is dealing with is not a lateral chatter.

Change in chip thickness is the driving cause behind chatter vibrations. Axial deflection
Table 4.2: Dominant frequency in the sound and third resonance frequency of drills with clamped boundary conditions

<table>
<thead>
<tr>
<th>$L/D$</th>
<th>$f_n$ [mm/rev]</th>
<th>$v_c$ [m/min]</th>
<th>$f_{dominant}$ [Hz]</th>
<th>$f_3$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.18</td>
<td>190</td>
<td>3785</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>200</td>
<td>3785</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>210</td>
<td>3825</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>220</td>
<td>3825</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>230</td>
<td>3785</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>240</td>
<td>3805</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.18</td>
<td>250</td>
<td>3846</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>190</td>
<td>3825</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>200</td>
<td>3805</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>210</td>
<td>3825</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>220</td>
<td>3805</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>230</td>
<td>3846</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>240</td>
<td>3846</td>
<td>3996</td>
</tr>
<tr>
<td>4</td>
<td>0.13</td>
<td>250</td>
<td>3846</td>
<td>3996</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td>190</td>
<td>2950</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td>200</td>
<td>2971</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td>210</td>
<td>2951</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td>220</td>
<td>2930</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td>230</td>
<td>2930</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td>240</td>
<td>2951</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td>250</td>
<td>2910</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>190</td>
<td>2991</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>200</td>
<td>2971</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>210</td>
<td>2930</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>220</td>
<td>2991</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>230</td>
<td>2971</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>240</td>
<td>2951</td>
<td>3245</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
<td>250</td>
<td>3012</td>
<td>3245</td>
</tr>
</tbody>
</table>
changes the chip thickness which can develop chatter vibrations. When it is accompa-
nied by axial vibrations, angular deflection affects the chip thickness. Due to helical
chip flutes, the axial and angular deflections of the drill are coupled and therefore an-
gular displacement can affect the chatter.

Based on what mentioned above, a hypothesis is that the main reason for the noise
problem in the current design of indexable drills is chatter due to torsional and axial
flexibilities. The assumption is that a good modeling of these regenerative chatter vi-
brations will help to capture the important characteristics of generated noise.

![Figure 4.2: Classification of vibrations in drilling](image)

**Figure 4.2: Classification of vibrations in drilling**
Chapter 5

Dynamic Parameters

When a mechanical system is loaded by dynamic forces, it responses in form of dynamic motions. The response is a function of the loading and dynamic parameters of the system. Identification of these dynamic parameters is a prerequisite in simulation of dynamic behaviors of the system. In this work, frequency response functions of the system are used to estimate the required dynamic parameters.

If a linear dynamic system is subjected to a pure sinusoidal force, the responses of the system are sinusoidal motions which have the same frequencies as the input signal but might have different amplitudes and phases [78]. For a pair of excitation and response, at each frequency of excitation, the difference between phases and the ratio between amplitudes of output and input signals can be represented in form of a complex number. A frequency response function, abbreviated as FRF, is these complex numbers as a function of the excitation frequency. Each frequency response function is associated to an input (excitation) and an output (measurement). One advantage of frequency response function is that it is measurable in most cases [79].

A basic assumption in using frequency response functions is that the system is time-invariant which means its characteristics remain constant over time. In drilling, due to chips which are carried in drill flutes, the system dynamics varies over time, but because of marginal mass of the chips compared to the mass of the drill, it is assumed that these variations are not significant and the system is assumed to be time-invariant.

As it was discussed in Chapter 4, the dynamics of the system is highly dominated by the vibrations of the drill structure in axial and angular directions. This means that the effect of machine tool, workpiece and bending of the drill is assumed to be negligible.

The next sections and Paper C [80] describe more details on obtaining the dynamic parameters which are required in this project.
5.1 Frequency Response Functions

Usually more than one frequency response functions are required to describe the dynamics of a system. Therefore, a starting point for identification of dynamic parameters is to decide how many frequency response functions are required and what are their inputs and outputs. The number of required FRFs depends on the nature of vibrations, demanded accuracy and computational cost. The aim is to choose the frequency response functions which are enough for describing the chatter problem in the drill at a low computational cost and an acceptable accuracy.

As described in Chapter 4, investigation on the sound spectrum of the noise revealed that the vibration is very dominated by a frequency component very close to third natural frequency of the one end clamped drill. When a system is vibrating at a specific resonance frequency, the effect of other modes are marginal and it can be concluded that drill is mainly vibrating at its third mode shape; which consequently explains how the drill is deflecting and this can be used as a guide in determining which frequency response functions are needed. Figure 5.1 shows the deflections of the drill at its third mode shape. As it is observed from the figure, the deflection of drill in this mode is a combination of angular and axial deflections. Therefore, the system is assumed to be flexible in these directions.

![Figure 5.1: Deflections of the drill at its third mode shape.](image)

5.2 Asymmetries in Indexable Drills

Most indexable insert drills are designed in asymmetric geometries. One reason for this asymmetry is that the flutes are not similar for different inserts of the drill. The main
reason that flutes are not designed with the same geometry is that they carry chips with different shapes. Typical chips for central and peripheral inserts are shown in Figure 5.2. This does not mean the shapes are limited to the ones shown in Figure 5.2, but it shows that in the same cutting process the inserts generate different forms of chips and therefore their flutes need to be designed in dissimilar geometries.

Figure 5.2: Typical shapes of the chips of central insert (top) and peripheral insert (down).

In addition to the asymmetry due to the flutes, the second reason of having an asymmetric geometry is that the inserts are mounted at different locations on the drill. Because of this, the inserts have different axial displacements when the drill is subjected to a torque. This is due to two displacements: Helical flutes and warping of cross section. Since the cross section is not circular, it warps in twisting and therefore different parts on the cross section will have different axial displacements. These effects on axial displacements can be seen in Figure 5.3.

Due to the mentioned asymmetries, the axial deflection of the drill at the third mode shape is not the same over the top surface of the drill as shown in Figure 5.4. Because of this asymmetry in deflections, for different inserts, different dynamic parameters are used.

The frequency response functions as listed in Table 5.1 are considered in modeling of the chatter vibration. The type of drill used throughout this study has two inserts and each insert has two degrees of freedom (axial and angular). Therefore, the system has four degrees of freedom which results in sixteen FRFs. However, due to reciprocity principle [78] the equalities shown in 5.1 apply which will reduce the number of non-identical FRFs to ten.
Figure 5.3: Axial deflection over the top surface of the tool when the tool is loaded by a torque.

Table 5.1: List of frequency response functions.

<table>
<thead>
<tr>
<th>Load</th>
<th>Axial motion of $i^{th}$ insert</th>
<th>Angular motion of $i^{th}$ insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust force due to $j^{th}$ insert</td>
<td>$H_{zF_j}$</td>
<td>$H_{\theta F_j}$</td>
</tr>
<tr>
<td>Torque due to $j^{th}$ insert</td>
<td>$H_{zT_j}$</td>
<td>$H_{\theta T_j}$</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
H_{zF_j}^i &= H_{zF_j}^i \\
H_{\theta F_j}^i &= H_{\theta F_j}^i \\
H_{zT_j}^i &= H_{zT_j}^i \\
H_{\theta F_j}^i &= H_{\theta F_j}^i \\
H_{zT_j}^i &= H_{zT_j}^i
\end{align*}
\]

(5.1)

The frequency response functions listed in Table 5.1 are obtained using the finite element method\(^1\). Modal analysis methods are used to obtain dynamic parameters, i.e. mass, stiffness and damping and the results are presented in Paper C [80]. The obtained

\(^1\) Ansys was used as the finite element software.
5.2. Asymmetries in Indexable Drills

Figure 5.4: Axial deflection of the drill at its third mode shape. Darker areas represent less deflections.

dynamic parameters can be represented in form of equations of motions as given in Equation 5.2. An alternative is to represent them using transfer functions as shown in Equation 5.3 [78].

\[ M \ddot{u} + C \dot{u} + Ku = f \quad (5.2) \]

\[ H_{pq}^i(s) = \frac{U_p^i(s)}{F_q(s)} = \frac{\omega_n^2 / k_p^{ij}}{s^2 + 2\zeta \omega_n s + \omega_n^2} \quad (5.3) \]
Chapter 6

Forced Response

The dynamic parameters of the system were identified in chapter 5 and a force model was introduced in Chapter 2 to calculate the input force to the system. Now a tool is needed to calculate the output of the system for a given force input. A dynamic system can be represented as a system of differential equations. One method to approximate the response of a dynamic system, is the numerical integration of the corresponding differential equations. A common method is to use fourth order Runge-Kutta method.

6.1 Solving Equation of Motion

To solve the equation of motion, shown in Equation 5.2, a classic way is to use Runge-Kutta family methods, introduced by C. Runge in 1895 [81]. Due to computational advantages of fourth order Runge-Kutta method, known as RK4, it is used in this work for solving the system of equations of motions. To do that a new variable, \( y \), is introduced as shown in Equation 6.1.

\[
y = \begin{bmatrix} \dot{u} \\ \ddot{u} \end{bmatrix}
\]  

(6.1)

Following RK4 scheme, \( y \) is calculated as shown in Equation 6.2.

\[
y[n] = y[n-1] + (k_1 + 2k_2 + 2k_3 + k_4)\Delta t / 6
\]

(6.2)

\( k_1 \)-\( k_4 \) are obtained as shown in Equation 6.3.

\[
k_1 = g(t[n-1], y[n-1])
\]

\[
k_2 = g(t[n-1] + \frac{\Delta t}{2}, y[n-1] + \frac{\Delta t}{2} k_1)
\]

\[
k_3 = g(t[n-1] + \frac{\Delta t}{2}, y[n-1] + \frac{\Delta t}{2} k_2)
\]

\[
k_4 = g(t[n-1] + \Delta t, y[n-1] + \Delta t k_3)
\]

(6.3)

Where

\[
\dot{y} = g(t, y)
\]

(6.4)
6.2 Using Transfer Functions

An alternative approach is to use transfer functions and find their responses to the applied forces. It is possible to calculate the forced response of a system with one pole as shown in Equation 6.5 [82]. The total response can be obtained by combining the response of all poles.

\[
x[nT + T] = x[nT]e^{\lambda T} + \frac{R_{pq}}{\lambda^2 T}(f[nT](1 - e^{\lambda T}(1 - \lambda T)) + f[nT + T](e^{\lambda T} - \lambda T - 1))
\]

In Equation 6.5, \(x[nT]\) is the response of the structure to applied force, \(f\), at \(n^{th}\) time step. Where \(T\) is the time step, \(\lambda\) is the pole and \(R_{pq}\) represents the corresponding residue.
Chapter 7

Simulation of the Dynamic Behaviors

Having all necessary tools, presented in previous chapters, it is possible to simulate the vibrations produced by regenerative chatter vibrations based on the loop presented in Figure 3.3. An indexable insert drill with two inserts is used in this chapter both for simulations and measurements. The specifications of the drill is given in Table 7.1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>24 mm</td>
</tr>
<tr>
<td>Length</td>
<td>96 mm</td>
</tr>
<tr>
<td>Young’s modulus of the body material</td>
<td>210 GPa</td>
</tr>
<tr>
<td>Density of the body material</td>
<td>7800 kg/m³</td>
</tr>
<tr>
<td>Product code of the drill</td>
<td>880 − D2400L25 − 04</td>
</tr>
</tbody>
</table>

The force model, presented in Chapter 2 and Paper A [33], is used to calculate static axial force and torque on each insert for a range of feed rates, after that linear regression is used to fit linear functions to the obtained points as shown in Figures 7.1 and 7.2.

In case of static operations, feed per revolution is equal to chip thickness. Therefore it is reasonable to used the obtained linear regressions to estimate the torques and axial forces generated by inserts for given chip thicknesses. Equations 7.1 to 7.4 are used to express axial forces and torques as functions of chip thicknesses, presented in Paper C [80].

\[
F_C[n] = -1070h^n - 1508 \tag{7.1}
\]

\[
F_P[n] = -2910h^P[n] - 1036 \tag{7.2}
\]

\[
T_C[n] = -37h^C[n] - 0.8 \tag{7.3}
\]

\[
T_P[n] = -100h^P[n] - 5.7 \tag{7.4}
\]

The simulation is done for a drilling operation with the drill shown in Table 7.1 at a

\(^1\)More information about the tool is available in Sandvik Coromant website
feed rate of 0.1 mm/rev and cutting speed equal to 200 m/min. At the beginning of the simulation, chip thicknesses are assumed to be equal to the axial feed rate for central and peripheral inserts. The dynamic system, presented in Chapter 5, Equation 5.2, is loaded by obtained forces. The response of the system to this loading is calculated...
7.1 Modeling Forces in Backward Rotations

Using RK4 as explained in Chapter 6 and Paper C \cite{80}. The resulted response will be added to rigid body motion of the drill to obtain the new positions of the inserts. The rigid body motions refer to motions caused by the axial feed of the drill and the spindle rotation. The new positions of the inserts are compared to the positions of the inserts in previous cuts to estimate the chip thicknesses using Equations 7.5 as presented in Paper C \cite{80}.

\[
b^i[n] = z^i[n] - \max(z^i|\theta = \theta^i[n] - 2k\pi), k = 0, 1, 2, \ldots \quad (7.5)
\]

The superscript \(i\) in the above equation determine the insert. The chip thicknesses are used in the next time step to calculate forces and this process continues until the simulation is ended.

\[\text{In above equations, } \Omega \text{ is angular speed of the spindle in radians per second. The flow chart of the simulation is shown in Figure 7.3.}\]
CHAPTER 7. SIMULATION OF THE DYNAMIC BEHAVIORS

7.2 Nonlinearities

The forces shown in Equations 7.6 to 7.9 are nonlinear functions and this affects the simulations routine. To cope with these nonlinearities, iterating at each time step is a necessary measure. The flowchart of the simulation in a implicit manner is shown in 7.4. The implicit simulation is used to simulate chatter vibration for a drilling process with the parameters given in Table 7.1. The simulated torsional and axial vibrations are presented in Figures 7.5 to 7.8. As was mentioned, the angular speed of inserts become negative in some time intervals which can be seen in Figures 7.9 and 7.10.

Due to limitations in dynamic range of force dynamometer, it was not possible to compare the simulated dynamic forces with the experimental forces. Instead, the spectrum of the simulated torque, Figure 7.11, is compared to the spectrum of the measured sound, Figure 7.12.
7.2. Nonlinearities

\[ n = 1 \]

Initial guess for \( h_P[n] \) and \( h_C[n] \)

Calculate \( F_C[z][n] \), \( F_P[z][n] \), \( T_C[n] \) and \( T_P[n] \)

\[ y[n] = y[n-1] + (k_1 + 2k_2 + 2k_3 + k_4) \Delta t \]

\[ h_i[n] = z_i[n] - \max(z_i'[0, \pi; z_i - 2k_i \pi], k = 1, 2, ...) \]

Converged?

\[ n = n + 1 \]

\[ t[n] > t_{end} \]

End

Figure 7.4: The Flowchart of the simulation with iterations [80]
Figure 7.5: Simulated axial vibration of the central insert, $\Delta z^C$.

Figure 7.6: Simulated axial vibration of the peripheral insert, $\Delta z^P$. 
7.2. **Nonlinearities**

Figure 7.7: Simulated torsional vibration of the central insert, $\Delta \theta^C$.

Figure 7.8: Simulated torsional vibration of the peripheral insert, $\Delta \theta^P$. 

39
Figure 7.9: Simulated angular speed of the central insert, $\Delta \dot{\theta}^C + \Omega$.

Figure 7.10: Simulated angular speed of the peripheral insert, $\Delta \dot{\theta}^P + \Omega$. 
7.2. **Nonlinearities**

![Figure 7.11: Spectrum of the simulated torque](image1)

![Figure 7.12: Spectrum of the measured sound](image2)
Chapter 8

Conclusion

The main goal of this work is to propose a method for modeling generated noise in drilling with indexable inserts. As it was discussed, in indexable drills, the main source of the noise is chatter due to axial and torsional flexibilities. Figure 8.1 presents the chain of causes and effects which results in generating the unwanted noise in drilling with indexable inserts.

![Figure 8.1: The chain of causes and effects behind the unwanted noise.](image)

The mechanism of the torsional and axial chatter was discussed in chapters 3 and 7 and a simulation routine was proposed to predict dynamic behaviors of the drill. The starting point for simulating the chatter is to predict forces for a given uncut chip thickness. A model is proposed Paper A [33] for such a prediction.

The chatter vibrations is discussed and investigated in Paper B [75] and Paper C [80]. Initial steps for simulating of the chatter were taken in Paper B, where the backward rotation of the drill was discussed and a force model was proposed to incorporate this phenomenon. In Paper C, separate degrees of freedom were used for central and peripheral inserts to capture asymmetrical designs and loadings in indexable insert drills.

It was shown that due to angular vibrations, drill might rotate backwards in some time intervals and an approach was discussed to estimate cutting forces in such instants. Angular vibrations cause variations in the delay term in equations which govern dynamic motions of the drill. These variations affects the chatter development and were considered in the model.

As shown in Chapter 7 and Paper C [80], by considering angular and axial flexibilities
of the drill structure, variable delays and backward rotations, it is possible to simulate torsional and axial chatter vibrations in drilling by indexable inserts.
Chapter 9

Future Work

An important step towards achieving a better drill design with less vibrations and noise is to optimize the geometry of the tool. The optimization routine starts by changing geometric features such as cutting edges and the cross section of the tool. After that, based on the proposed model in this work, forces and dynamic parameters are calculated and the dynamics of the cutting is simulated as described in Chapter 7. The output of the simulation is used to assess the quality of the design. Based on the simulation results, new changes are applied to obtain a new geometry for the tool. A new simulation is then run based on the new geometry and the iterations continue until a desired output is achieved. Running the optimization based on the described method in this work is computationally costly; because it uses a 3D finite element model to calculate frequency response functions (FRFs). This finite element model needs to be updated whenever the geometry of the drill body is modified. In addition, a considerable amount of manual adjustments are needed for calculating dynamic parameters which includes obtaining FRFs from the finite element model and estimating of dynamic parameters from FRFs. Because of these challenges, the automated optimization routine is not used today. An automated and fast method to calculate the dynamic parameters is a crucial step to make this optimization feasible. Automated extraction of dynamic parameters will be investigated in future works. Furthermore, before using an optimization routine, it is important to identify the key parameters of the optimization. The key parameters, are the parameters which have the highest impact on the results and at the same time can be varied in economic and practical ways. These parameters will be identified by a sensitivity analysis of the geometry of the drill, as planned for future works.

As discussed in Chapter 4, in the current design, lateral chatter vibrations are not dominant. But they can emerge when a new geometry is generated in an optimization iteration. To ensure that the future designs are not prone to lateral chatter, the presented chatter simulation method in this thesis will be enhanced to be able to simulate such chatter modes in addition to torsional and axial chatter modes.
Chapter 10

References


47
REFERENCES


REFERENCES


REFERENCES


REFERENCES


REFERENCES


REFERENCES


53
REFERENCES


Dynamics of Torsional and Axial Vibrations in Indexable Drills

Drilling is widely used in manufacturing of products which need holes, for example for fluid channels, screws or pins. Indexable insert drills are types of drills which facilitate inserts to make holes. These type of drill can make high pitch noise due to vibrations and the focus of this thesis is to investigate the mechanism behind this vibration in order to help reducing the generated noise in the future designs. The main mechanism which results the mentioned noise is regenerative chatter vibrations due to axial and torsional flexibilities. The first step of having a good simulation of regenerative chatter vibrations in the drill is to model static cutting forces in a reliable way. A model is proposed which is capable of predicting static cutting forces through segmentation of cutting edges. The proposed model considers differences in geometries of the inserts in estimating of cutting loads. The obtained loads are used in the chatter simulation. A model is proposed to simulate chatter vibrations by considering axial and angular deflections and coupling between them. Governing dynamics is a system of delay differential equations with a variable delay. Variations in time delay, tool jump-outs and backward motions of inserts have been included in the proposed time domain simulation. A set of experiment is conducted to verify the model.