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Computer Aided Design of Involute Gear Shaper Cutters

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Computer Aided Design of Involute Gear Shaper Cutters

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1. J. Butans, A. Tiwari, Computer Aided Design of Involute Gear Shaper Cutters. Submitted to: Mechanism and Machine Theory.

2. J. Butans, A. Tiwari, Gear Shaper Cutter Design. Submitted to: Decision Engineering Report Series.

3. J. Butans, A. Tiwari, Web-based design of gear cutting tools. Submitted to: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science.

List of acronyms

AJAX Asynchronous JavaScript and XML

API Application Programming Interface

CAD Computer-Aided Design

CAM Computer-Aided Manufacturing

CNC Computer Numerical Control

DP Diametral pitch

DXF Drawing Exchange Format

JSON JavaScript Object Notation

MOD Module

NumPy Numerical Python

PA Pressure angle

PDF Portable Document Format

SRS Software Requirements Specification

SVG Scalable Vector Graphics

TCO Total Cost of Ownership

XML eXtensible Markup Language

Abstract

The global market competition has put a pressure on the industry to reduce lead time and increase quality of parts. In particular, the area of gear cutting tool design requires capability to rapidly produce tool designs with increased tool geometry precision. The aim of this research is to explore the field of gear shaper cutter design and produce a model and software that would enable creation of more precise cutter designs, faster.

A literature survey of involute cylindrical gearing geometry highlights deficiencies in addressing industry requirements of tool manufacturing, as most of the research in the area is focused on problems of gear design, but not tool design. This research, therefore, focuses on the process of gear manufacturing using the gear shaper cutters. It attempts to develop an analytical model and a set of tools that are able to aid the design process of gear shaper cutter.

With cylindrical gear being essentially "flat" and therefore easier to express analytically, the focus of recent papers has shifted to non-cylindrical and non-involute gear trains. Yet the geometry of the tools used to produce cylindrical gears remains largely untapped area, in particular the geometry of gear shaper cutters. The knowledge about the profile of the cutter teeth and the profile cut by the cutter in the gear blank are essential for high precision gear manufacturing.

The gear shaper cutter is a metal cutting tool and therefore should be re-sharpened on a regular basis. These re-sharpening operations change the profile

of the tool and, consequently, the profile of the gear it cuts. The changes in the cutter and gear geometry are analysed in this thesis and a way to calculate the life span of the tool is suggested.

Gear shaper cutter profiles usually have one or more modifications to the theoretical ideal involute profile applied. Some of these modifications are used to produce a better cutter profile, while other should in turn produce modifications to the gear profile, and, finally, some are used to overcome generated gear profile constraints. Computer-Aided Design (CAD) software for gear shaper cutter design should be able to show the profile of the cutter and the profile cut by the cutter with arbitrary modifications applied. The analysis and visualisation of gear shaper cutters profiles cut by these cutters is impossible without a clear understanding of the principles of operation of gear generation hardware, generating motion and different machine geometry, all being covered in this thesis.

In order to verify the analytical model and the CAD software case studies of the real-life gear shaper cutter designs were performed.

Chapter 1

Introduction

Looking around one can see that many mechanisms starting from alarm clock to Airbus A380 jet plane use gears of various kinds. Among those the most widely used are cylindrical gears with involute (refer to Section 1.1.5) tooth profile. Cylindrical gears with straight teeth are called 'spur' gears while ones that have teeth inclined at an angle to the gear rotation axis are referred to as 'helical' gears.

While gears and especially combinations of gears working together in gear trains (transmissions) are interesting study objects by themselves, the special interest of this thesis is how gears are being manufactured. In particular, the author looks at the process of cylindrical gear manufacturing by means of generating cutting with gear shaper cutters and applies CAD methods to improve the process.

1.1 Nomenclature, conventions and definitions

This section gives the nomenclature, conventions and definitions created to cover all aspects of gear geometry, conjugate gear-tooth motion and gear manufacturing. The classification in the following section is based on the one presented by Merritt

in [3]. Definitions are taken from the relevant British and international standards. In particular, extended definitions could be obtained from [4] and [5].

The importance of consistent nomenclature that covers the entire scope of this thesis has been recognised by the author, and every care was taken to ensure that this thesis adheres to it. To show the dimensions of a same nature but different in application or magnitude small and capital letters are used for the cutter and gear respectively, further aided by suffixes. For example, d is used to represent the pitch diameter for the cutter, while the pitch diameter for the gear bears D symbol. Base diameters of cutter and gear are represented by d_0 and D_0 respectively.

All calculations and figures in this thesis use polar coordinate system, unless explicitly stated otherwise. Greek letters are used to indicate angular dimensions, except the letter π that stands for the numerical value of the ratio of the circumference of a full circle to its diameter. Distinctions between gear and cutter are made using suffixes, where necessary.

1.1.1   General definitions and nomenclature

The analysis of cylindrical gear teeth starts with defining pitch surfaces and relative shaft position of conjugate members. The *pitch surfaces* of gears that have parallel axes are imaginary rotational surfaces concentric with axes of respective gears. The pitch surfaces roll without slip when the gears rotate with angular velocities reciprocal to the number of teeth in each gear. Pitch surfaces of gears connecting parallel shafts are cylinders, so the name *pitch cylinders* may be used as well. Two pitch surfaces make contact along a straight line termed as *pitch-surface generator,* as this line when rotated round the axes of conjugate gears produces respective pitch surfaces.
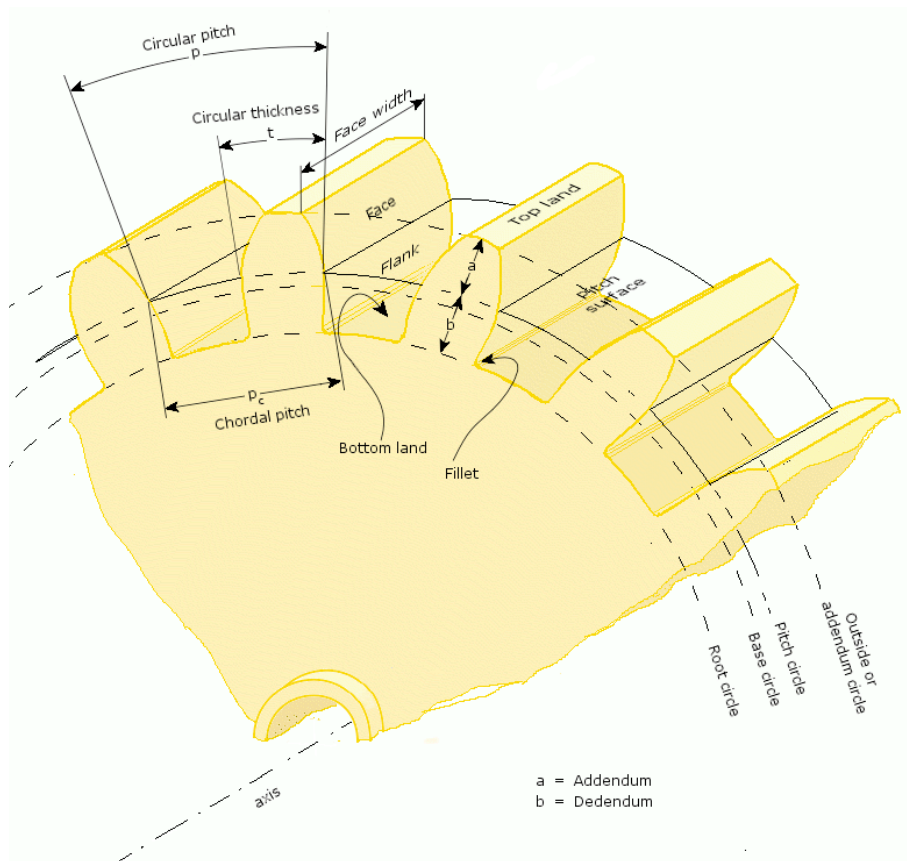
Figure 1.1: Common gear terms, as presented in [1]

The gear will be examined in the following three major planes.

- An *axial plane* is a plane that contains the axis of a gear and intersects with the pitch surface along pitch-surface generator.

- A *transverse plane* is a plane perpendicular to the axis of a gear. Intersection of the transverse plane with the pitch surface gives the pitch circle of a gear.

- A *normal plane* is a plane to which the tooth spiral is normal at pitch point.

Proceeding to describe definitions and nomenclature relating to the pitch surfaces of gears, the two pitch surfaces in a transverse plane make contact at a point termed

as *pitch point.* The circle formed by intersecting pitch surface with a transverse plane is called *pitch circle* of the gear. The *pitch diameter* is the diameter of the pitch circle.

The dimensions described in this section use the following notation throughout the thesis.

d - Pitch diameter of cutter.

D - Pitch diameter of gear.

t - Number of teeth in cutter.

T - Number of teeth in gear.

C - *Centre distance.* The shortest distance between the axes of gears.

Considering the contact of two toothed bodies, one of them being substantially larger then the other and having more teeth, the former will be called wheel, while the later will be called pinion. Consequently, internal gear is always a wheel, while smaller mating gear or cutter is always a pinion.

1.1.2   Tooth spiral and pitch

A *tooth spiral* is the curve of intersection between the tooth flank and the pitch surface. The tooth spiral of a gear having helical teeth is called *tooth helix.*

A *normal helix* of a gear having helical teeth is a tooth spiral lying in the pitch cylinder and having its spiral angle complementary to the spiral angle of the tooth helix. In other words, tangents drawn through the point of intersection between the tooth helix and normal helix cross at right angle.

σ - *Spiral angle.* The angle between a tangent to a tooth spiral at any point and the pitch-surface generator passing through the same point.

σ_p - *Helix angle.* The angle between a tangent to a tooth helix at pitch point and the pitch-surface generator passing through the pitch point.

Pitch is the measure of the spacing between successive tooth spirals on tooth faces of the same orientation.

p - The *circular pitch* is the distance measured along the pitch circle between two immediately following tooth faces of the same orientation.

P - *Diametral pitch.* The diametral pitch is the expression of pitch by quotient obtained by dividing the number of teeth in gear by the pitch diameter.

m - *Module.* The module is the expression of pitch obtained by dividing the circular pitch by π. One can note that the module is reciprocal to the diametral pitch.

1.1.3   Tooth parts

The profile of gears is a combination of 'tooth' and 'space' profiles repeated many times. In fact, tooth and space profiles overlay each other, thus two adjacent space profiles make up for one full tooth profile and two half tooth profiles.

The *tooth* is a part of a gear used to transmit the rotary motion. The teeth extend beyond the pitch surface of a gear.

t - Index of a tooth dimension used where distinction from similar space dimension is necessary.

The *space* is the absence of material between adjacent gear teeth.

s - Index of a space dimension used where distinction from similar tooth dimension is necessary.

In the context of this thesis it is important to distinguish between gear and tooth profiles. The tooth profile starts from the centre of immediately preceding space profile and ends at the centre of immediately following space profile. In turn, space profile lies between centres of adjacent tooth profiles.

The *blank* is a plain metal cylinder from which a gear is made by cutting teeth in it.

The *crest* is part of the original outside cylinder of the blank remaining on the gear after tooth generation process.

The *addendum circle* is the circle containing tooth crests.

The *dedendum circle* is the circle tangent to bottom of tooth spaces.

The tooth *face* is the portion of active tooth profile above the pitch circle.

The *flank* is the portion of active tooth profile below the pitch circle.

The *tip* of the tooth is the edge between the tooth face and tooth crest or the portion of the tooth profile immediately adjacent to that edge.

The *root* is the bottom part of the tooth.

The *clearance curve* is the bottom portion of the space profile, joining two adjacent tooth flanks.

The *fillet* is a part of the clearance between the tooth flank and the bottom of tooth space.

Some gears have arbitrary modifications to the tooth profile whereby small amounts of material are removed from profile portions close to tooth tip or (and) root. Such modifications are called *tip relief* and *root relief,* respectively. Cutters designed to cut these gears will have complementary profile modifications termed *root rise* and *tip rise.* It is important to note that tip modification on gear results in root modification on cutter and *vice versa*.

A profile modification termed *chamfer* is used to enable sliding gears engage more smoothly. It puts a sloping involute surface at the tip of the gear tooth. Consequently, on the cutter chamfer occurs near the root of the tooth.

After being cut by a gear shaper cutter most gears are thermally treated and afterwards have to be finished by grinding. The operation removes small amounts of material along the involute profile of the gear tooth. This may leave a sharp 'step' between the fillet and the involute profile, which is undesirable. To avoid finishing step on the gear the cutter profile should be modified by offsetting a portion of the

involute profile at the tip of the cutter tooth. The offset portion undercuts the gear tooth in such a way that after finishing no sharp step appears. This modification to the cutter tooth is termed as *protuberance.*

The *top rake angle* is the angle between pitch-surface generator and the crest of the tooth in axial plane of the cutter.

The *front rake angle* is the angle between front surface of the tooth and transverse plane of the cutter.

1.1.4   Tooth dimensions

This section lists the dimensions of the tooth with the following definitions and symbols: ψ - *Pressure angle.* The acute angle between the common pitch plane and the common normal to the profiles of meshing gear teeth at the point of contact, measured in arbitrary plane. By default this angle is understood to be measured in transverse plane.

Addendum. The distance between the pitch circle and the tooth crest measured in radial direction.

a - Addendum of cutter.

A - Addendum of gear.

Dedendum. The distance between the pitch circle and the bottom of the tooth space measured in radial direction.

b - Dedendum of cutter.

B - Dedendum of gear.

c - *Clearance.* The amount of space between the bottom of the cutter space and the crest of the gear tooth.

Outside diameter. The diameter of the addendum circle.

Root diameter. The diameter of the dedendum circle.

Circular thickness. The distance between two adjacent tooth flanks measured round the circle of a given diameter. Unless explicitly stated otherwise, this quantity is understood to be the thickness of the tooth measured at the pitch circle in transverse plane.

g_t - Circular thickness of cutter tooth. This quantity is measured between the flanks of the same tooth.

G_t - Circular thickness of gear tooth. This quantity is measured between the flanks of the same tooth.

g_s - Circular thickness of cutter space. This quantity is measured between the flanks of two adjacent teeth joined by the clearance curve.

G_s - Circular thickness of gear space. This quantity is measured between the flanks of two adjacent teeth joined by the clearance curve.

l - Cutter life. The length of the tooth crest measured in the axial plane of the cutter.

1.1.5   Involute surfaces

The dimensions and definitions related to the involute part of the tooth profile are listed in the following section:

The *involute* is the locus of points made by the end of a tightly pulled string as it being unwound from a circle in the plane of that circle. That circle is being termed as the *base circle* of the involute. The point lying on the base circle at which the involute starts is called *origin* of that involute. Considering the involute as the surface being unwound from the cylinder, that cylinder is termed as *base cylinder*. Refer to Figure 5.1 for involute-related definitions.

Base diameter. The diameter of a base circle or base cylinder.

d_0 - Base diameter of cutter.

D_0 - Base diameter of gear.

p_0 - *Base pitch.* The base pitch is the distance between two immediately successive involutes forming tooth flanks measured along a common normal.

Circular base thickness. The distance between two involutes forming adjacent tooth flanks measured round the base circle. By default, this quantity is understood to be measured between the involutes forming the flanks of the same tooth.

g_{0t} - Circular base thickness of cutter tooth. This quantity is measured between the involutes forming the flanks of the same tooth.

G_{0t} - Circular base thickness of gear tooth. This quantity is measured between the involutes forming the flanks of the same tooth.

g_{0s} - Circular base thickness of cutter space. This quantity is measured between the involutes forming the flanks of two adjacent teeth joined by the clearance curve.

G_{0s} - Circular base thickness of gear space. This quantity is measured between the involutes forming the flanks of two adjacent teeth joined by the clearance curve.

The *basic rack* is a gear with infinite base diameter. On the basic rack the involutes constituting tooth flanks are straight lines.

1.2 Introduction to generating cutting

Generating cutting is a standard manufacturing technique widely used for spur and helical gear manufacturing. Without going into details at this stage it can be noted that the form produced in a gear blank by the generating cutting process is different from the inverse form of a cutter.

Knowing the principles underlying the process of gear manufacturing is essential for the study and design of a gear profile. It has been often staited that if a gear profile is designed with certain involute dimensions, the particular way of how it will be produced is irrelevant to the designer. This assumption caused (and causes) a good deal of trouble to the people responsible for producing and maintaining tools for

cutting gears. The mere fact that the tooth profile of the involute gear is relatively simple does not suggest that any arbitrary involute profile can be produced [3]. Many otherwise perfect gear profiles are either completely impossible to produce, or the process is too complicated and expensive. Accounting for the exact manufacturing technique used to produce the gear brings a number of "foreign" considerations to the gear design, such as the requirement for a tool to have a possibly longer life span and yet to produce gears within finite tolerances.

One should bear in mind that the tooth profile is not limited by the portion that comes into engagement, but extend all the way down to the bottom of the tooth space, producing what is known as the "clearance curve". The form of the clearance curve produced on the gear blank depends on a number of factors, including the manufacturing technique [6] and cutter parameters [7], [8].

Looking closely at the tooth profile of a gear shaper cutter presented in Figure 1.2, it is apparent that the active involute profile comprises only a small part of the tooth flank curve, tooth tip and fillet profiles being non-involute. A cutter like that will have a short life span and can be easily damaged because of heavily undercut fragile teeth.

The importance of knowing the correct clearance curve can not be underestimated as it affects tooth strength and gear train meshing characteristics. Additionally, clearance curve may limit the active profile or interfere with it under specific meshing conditions as presented in [9] and [10].

Among the great variety of gear manufacturing processes the generating cutting stands out as the most widely used process, with the ability to mass-produce high performance internal and external gears of different sizes. The generating cutting is based on the relatively simple principles discussed in the following part of the section.
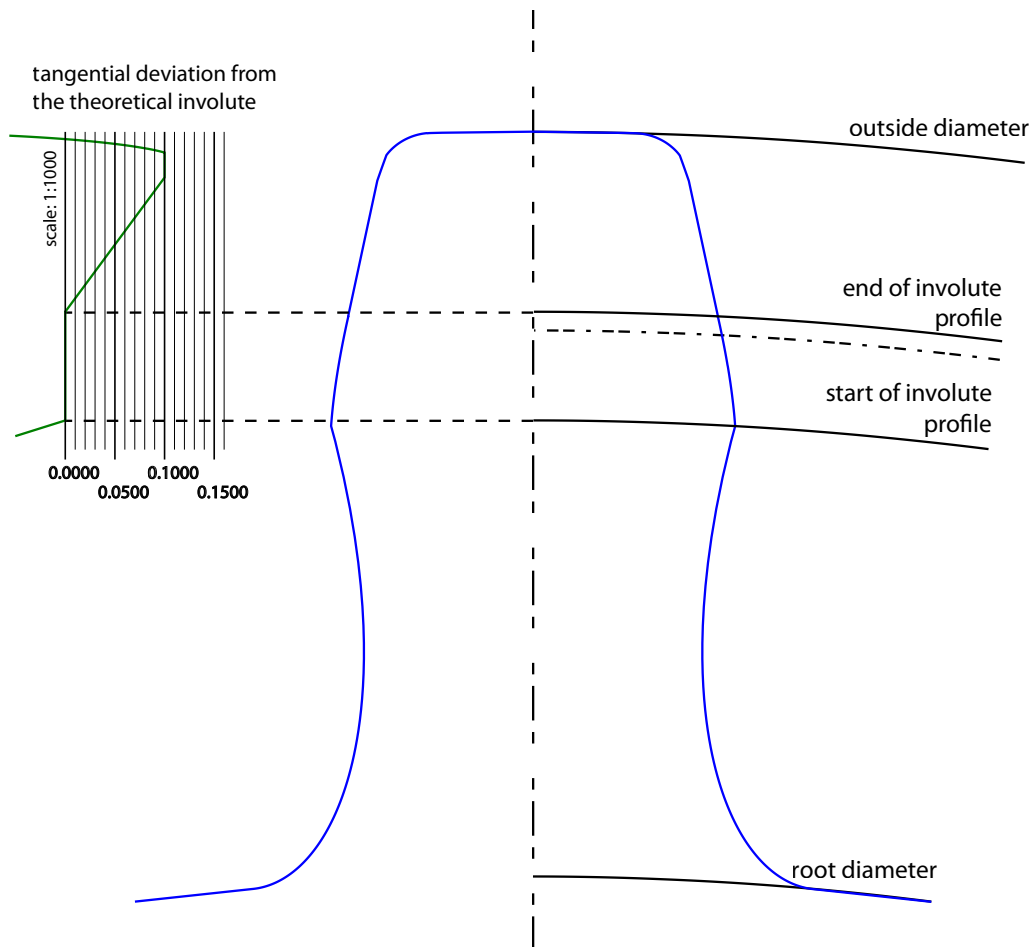
Figure 1.2: Gear shaper cutter tooth with severe undercut (8.47 DP, 14.5 PA, 25 teeth)

The underlying principle of gear design is the fact that two toothed bodies moving relative to each other in constant mesh have their conjugate profiles in determined relationship. Many books and papers, such as [11], [12], [13] discuss the rules governing that relationship, such as the relative position of the point of contact, relative motion of two toothed bodies participating in the contact and geometry of conjugate profiles.

If the geometry of one of the conjugate profiles is given along with the relative motion of both profiles, the geometry of the second profile could be obtained by either analytical, numerical or graphical means. Although this thesis mainly deals with the former two, a brief description of the graphical solution was deemed helpful by the author for the reader to aid his (or her) imagination.

Consider Figure 1.3 that illustrates a gear during the generation process. The cutter profile "A" is mounted in a determined position to the gear blank "B". The determined position means that the pitch circle of the cutter is tangent to the pitch circle of the gear to be produced from the blank. Both parts rotate at angular velocities that are inversely proportional to their pitch diameters. If the profile "A" is given cutting properties and moved reciprocally in the axial plane (a plane perpendicular to the plane of the drawing), it will produce the conjugate gear profile on the gear blank.

A number of different mechanical devices exist to help the gear designer in the problem of obtaining the conjugate profile. One of them is presented in Figure 1.4. The device consists of two major parts, one being the embodiment of a portion of the gear's pitch circle with a piece of card **A** secured on it and the other being the representation of the pitch line of the basic rack. The basic rack part has a template of the rack's space **B** attached in a proper relation to the pitch line. The basic rack part is able to rotate round the gear part without slip. To get the profile of the gear, one would trace the space profile of the rack at different roll angles on the piece of card (lines marked **C**). The resulting envelope line **D** (thicker line) would be the gear profile conjugate to the given basic rack profile.

Actual gear production by generating process presents a solution to the problem of determining the conjugate profile by employing purely mechanical means. A gear shaper cutter and a blank are mounted in the same relative positions and subjected
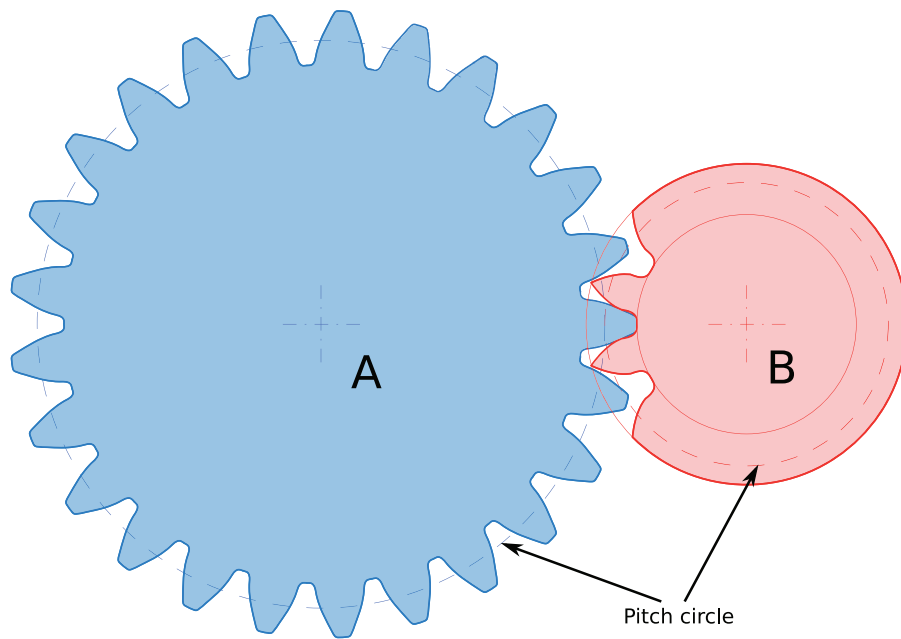
Figure 1.3: A graphical solution to the conjugate profile problem. Cutter profile **A**, gear profile **B**.
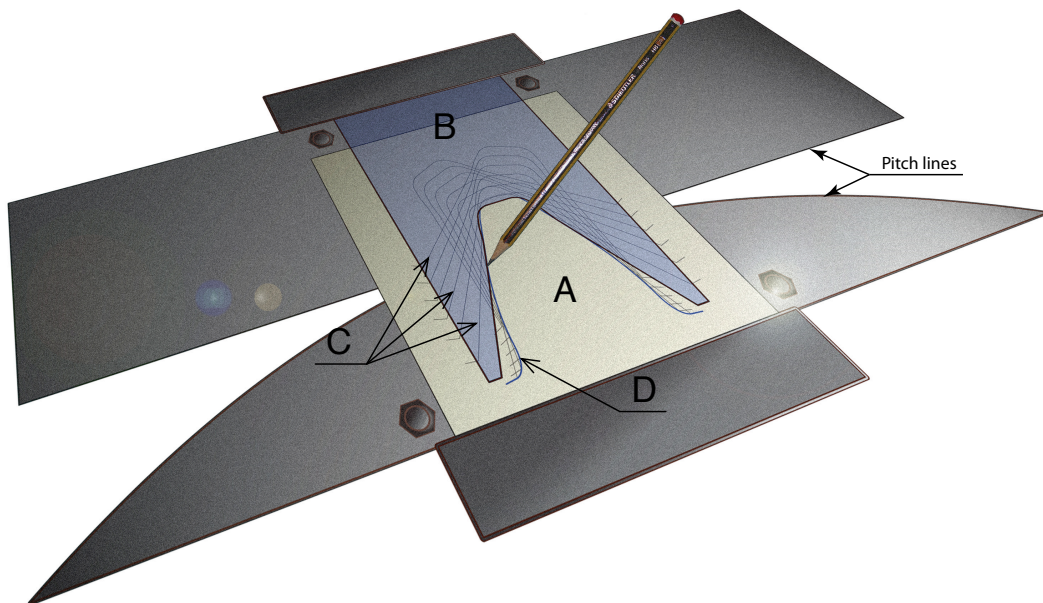
Figure 1.4: A mechanical device used to obtain the conjugate profile

to the same rolling motion as the two gears in a gear train. A general idea of the
process is based on two principles:

- the cutter is subjected to the motion along the axis perpendicular to the
  transverse plane of the gear that makes the cutting edge of the tool to cast off
  metal from the gear blank;

- the blank is mounted in a determined relationship with the cutter and both
  tool and blank are given a relative rolling motion equal to the motion between
  conjugate profiles represented by the cutter and gear that should be produced.

1.2.1   Generation with a rack type cutter

Previous examples assumed gear generation by a gear shaper cutter, however, the
property of the involute line to mesh in a uniform manner with any involute of the
same base pitch allows to use a cutter with any pitch diameter. In particular, if
the pitch diameter of the cutter is infinitely large, it becomes a rack type cutter.
Figure 1.5 illustrates a configuration, where a reciprocal motion given to the rack
type cutter "A" along the axial plane of the blank "B" makes its cutting edge to cast
off small pieces of metal from the blank. In addition to this reciprocating motion,
the cutter advances along its pitch line with the speed equal to the linear velocity
of the gear blank at pitch diameter. The two aforementioned motions, combined,
make cutter to produce an involute profile in the gear blank.

To obtain continuous generating action, the length of the rack needs to be mod-
erately larger than the pitch circumference of a blank. Because this is not practical,
the rack type cutters employ indexing action, that disengages the cutter after it
has advanced by a number of pitches from the blank and returns it to the initial
position, the blank remaining static during the indexing cycle.
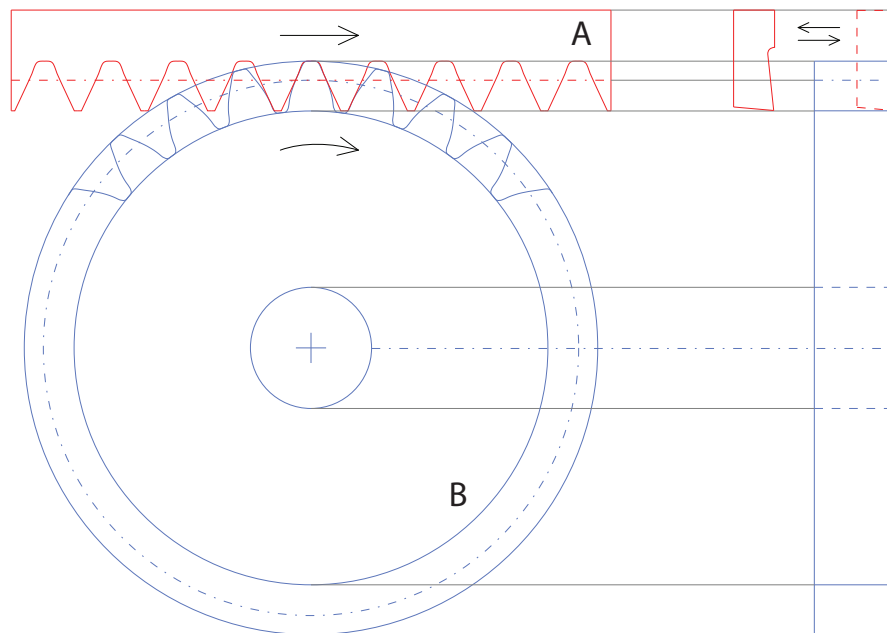
Figure 1.5: Gear generation with a rack type cutter

1.2.2 Generation with a grinding wheel

In a particular case of gear generation with a rack type cutter the rack can be substituted by a grinding wheel. The profile of the wheel should match the one of the rack tooth. The required geometry is applied to the wheel with an industrial diamond following the rack tooth template. Referring to Figure 1.6, the wheel is given a reciprocal motion in a plane inclined to the axial plane of the work at an angle σ_p (the helix angle of the gear shaper cutter being produced) that makes it act as a tooth of the rack. Additionally, the gear blank is given a rolling motion that makes the wheel generate an involute profile on the gear blank.

Figure 1.6: Generation of a helical gear shaper cutter with a grinding wheel

1.3 Introduction to gear shaper cutters

A gear shaper cutter is a mechanical tool used to produce gears of various kinds. Owing to the property of the involute profile to mesh correctly with a gear of any pitch diameter under certain conditions, a rack type cutter may be substituted with any gear derived from it. Simply put, a gear shaper cutter is a gear having its teeth suitably relieved to cut the material of blank without rubbing it. On a closer look, it turns out that the gear shaper cutter is somewhat different from the typical gear, because it might have profile modifications required to produce gear with certain special properties.

A gear might have a chamfer to remove sharp end between tooth face and crest. To aid gear in engagement, their teeth can have root and tip reliefs of different configurations. Some gears require optimisation to the fillet profile. Finally, a gear that is subject to a finishing operation after, for example, a heat treatment, should have an appropriate modification to remove the sharp step between the finished profile and the fillet. Generally, it is desirable to put all aforementioned modifications with the same tool that generates the active involute profile, as this reduces time required to produce gear and the manufacturing costs associated with a number of tools and appropriate machinery.

Considering that a gear shaper cutter might have to produce all of the aforementioned modifications simultaneously, plus additional modifications to the cutter itself to get a better tool life or better manufacturability, the geometry of the cutter and gear may become very complex.

1.4 Problem statement and motivation

A question that should be answered as a necessary precondition to defining the problems encountered in the course of gear shaper cutter design is 'what makes

gear shaper cutters worth using for gear manufacturing'. The gear shaper cutters are reliable tools for high-volume production of external gears. What makes them special, is the ability to cut internal gears, because neither hob type cutters nor rack type cutters are able to produce internal gears. Additionally, machines employing gear shaper cutters do not require indexing cycles that are inherent to the machines that use rack type cutters.

A quick look at the literature available in the area of cylindrical gearing (see Chapter 2 for details) shows vast number of papers and books about topics such as design of gears and gear trains, various gear profile modifications and CAD techniques. There is a decent number of software CAD packages aimed to ease the life of gear designer. At the same time the amount of research on topics of gear shaper cutter design process, profile modifications, tool life and interaction between the cutter and gear is comparatively low. Likewise, CAD packages for gear design are difficult to use for gear shaper cutter design due to some functionality missing.

Based on the observations presented above, the following problems can be defined to be addressed in the present thesis:

- the exact nature and scope of the gear shaper cutter design process is not defined in the current literature;

- no analytical model exists that is suited in an unmodified form for the analysis of the gear profile generated by the gear shaper cutter, includes provisions for all necessary gear shaper cutter profile modifications and accounts for the changes in the cutting tool profile geometry throughout its life;

- there is no software suite readily available to aid a gear shaper cutter designer in his / her job, making what should be a simple and quick operation a craft that requires lots of manual work.

1.5 Thesis layout

This thesis is organised into eight chapters with *References* and *Appendices* counting separately. The chapter are in the order they appear in the thesis: the *Introduction, Literature review, Research aim, objectives and methodology, Gear shaper cutter design process, Analytical model of involute cylindrical gearing, Computer-Aided Design software for gear shaper cutter design, Real life case studies* and *Discussion and conclusions.*

The first chapter, *Introduction,* contains information of a general kind about generating process used to manufacture gears as a whole and gear shaper cutters in particular. A major portion of the first chapter is devoted to describing the nomenclature, conventions and definitions that are used throughout the rest of the work. In the final pages a problem definition is given along with the current portion, the *Thesis layout.*

The second chapter is dedicated to a review of the current literature. First the literature about the features of a gear shaper that make it different from the gear are discussed; those are the few papers existing about the gear shaper cutter design. Afterwards the sources concerned with profile modifications on the gear are analysed in the hope to get a foundation for a similar analysis of a cutter. Finally, a brief analysis of current approaches to dealing with the gears in motion is attempted resulting in a summary and identification of the research gap.

Chapter 3 defines the aim of this research and establishes research objectives and scope. Subsequently, the research methodology gets outlined, based on the specifics of the research field. Following sections provide the reader with details about the industrial context of the research and industrial focus for the development of better gear shaper cutter design techniques.

In the fourth chapter the author attempts to analyse and document the gear shaper cutter design process. Namely, real gear shaper cutter designers were asked

about their workflow, challenges in tool design and specific requirements that might not be obvious to an outside observer. An analysis revealed three major design cases with separate design processes with computations and input parameters required for each of them. That resulted in three separate sections entitled *Cutter design case, Gear and cutter design case* and *Redesign case.* Auxiliary design operations are summarised in the *Manufacturing requirements* and *Body selection* sections. At the end a short summary is provided. It is important to keep in mind, that cutter and gear geometry do not get discussed within this chapter. Instead, it focusses on the process of design and definition of the requirements for the analytical model and software package.

Chapter five establishes an analytical model of involute cylindrical gearing. Taking the process model from the previous chapter, the author provides an exact solution to each stage of the design process. Strategies for dealing with variable sets of inputs are given as a separate section. The model is tailored to meet the requirements of the software CAD package that would be discussed in the next chapter entitled *Computer-Aided Design software for gear shaper cutter design.* In particular, the equations required to compute profile deviations from the theoretically perfect ones are discussed.

Successive chapters contain description of the developed CAD package and case studies accomplished with the help of the software package. In particular, chapter six provides a detailed view on the architecture, principles of operation, implementation, interface and usage of the software for cutter design. It starts with the description of the methodology used for the development and proceeds to the identification of the requirements based on the material of Chapter 4. The next section discusses CAD package architecture, i.e. the details of the principles of operation and the software platform. As already stated before, visualisation of the design data is very important for the human designer. The visualisation presents a number of

challenges, such as choosing a drawing format or supporting interactive graphics in the end-user applications, therefore a separate section is dedicated to the problems of visual representation of data.

Next section contains a description of the software interface prototype that was created, based on the interviews and co-operative design work with the practitioners in the field of gear shaper cutter design. The chapter finishes with a portion about the actual CAD package along with usage notes. A summary of the chapter's contents is provided.

Chapter 7 contains a set of three case studies, that cover three different design cases, namely, a case where the cutter is being designed form scratch, a case where the cutter is being designed based on the gear data and also one case with the redesign. Subsequently, the key findings are analysed and documented along with the author's comments and a summary.

The last chapter provides the reader with conclusions and discussion about the accomplished work. In addition, an indication of the future work in the area of the computer aided design of gear shaper cutters is given in a separate section.

Chapter 2

Literature review

Otto von Bismarck once said: *"Nur ein Idiot glaubt, aus den eigenen Erfahrungen zu lernen. Ich ziehe es vor, aus den Erfahrungen anderer zu lernen, um von vornherein eigene Fehler zu vermeiden."* In English translation that would be: "Only an idiot would believe he could learn from his own experience. I prefer learning from others' experience to get rid of own mistakes in the first place." The author could not underestimate the importance of that approach, making a study of the literature a necessary prerequisite for any research.

2.1   Key features of a gear shaper cutter

The initial application of the generating process to the fabrication of gears employed rack type cutters. A rack type cutter is a section of the gear profile with infinite number of teeth. When the number of teeth in a gear approaches infinity, so does the base diameter of the involute that forms the active profile of the gear tooth. An involute curve having infinitely large base diameter becomes a straight line, consequently the flanks of the rack tooth are composed of straight lines. This property makes rack type cutters easy to design, manufacture and inspect [14].
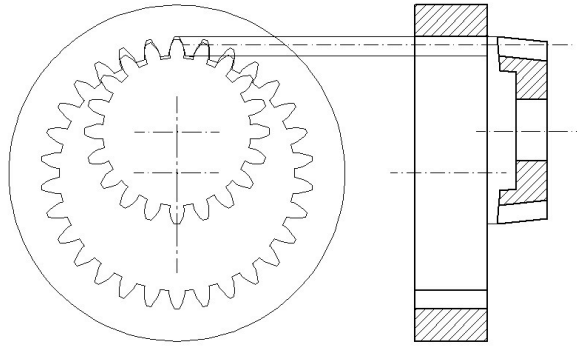
Figure 2.1: Generation of internal gear by shaper cutting process

A rack cutter may be substituted by any gear that may be derived from the same basic rack. This property of the involute is the basis of gear-shaping process or Fellows process, named by the Fellows Corporation founder, Edwin R. Fellows [3]. This cutter is close in appearance to the pinion gear with appropriate profile modifications (Figure 2.1). The spatial position and motion of the cutter and gear blank are the same as the position and motion of two meshing involute profiles.

Reciprocating motion of the cutter along its axis causes cutting edge to cast off severed pieces of metal producing a conjugate profile to the mating gear represented by the cutter. In addition the cutter and the blank are mechanically connected and subject to the relative motion based on the number of teeth. The process is continuous in that it does not require indexing cycle required by the rack-type cutters.

Numerous re-sharpening operations carried out throughout the life of the tool reduce the shaper cutter diameter and therefore the distance between centres of gear and cutter. Because of the special properties of the involute curve two engaging involute surfaces could mesh correctly as the centre distance changes. Consequently,
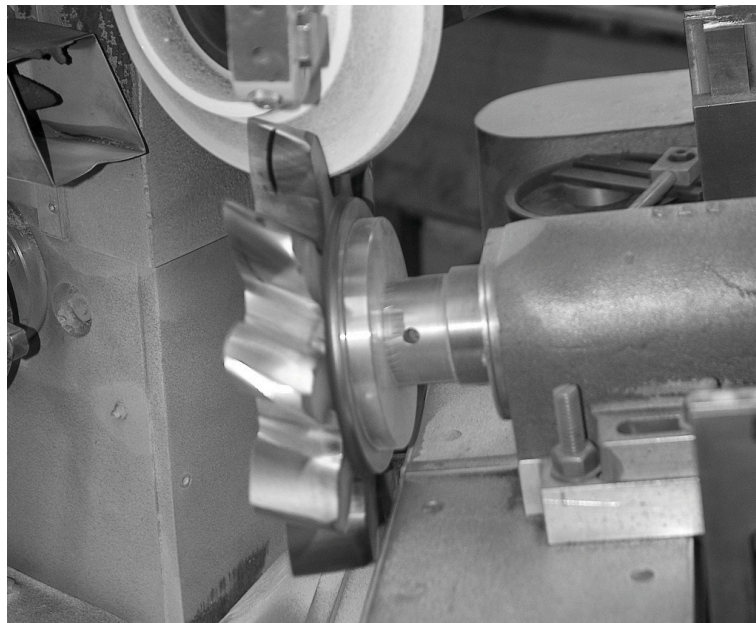
Figure 2.2: Helical gear shaper cutter during generation process

aforementioned changes in the centre distance result only in minor variations of the involute gear profile [15], [16]. Nevertheless, the effects of cutter re-sharpening should be expected and included in the analytical model.

A shaper cutter with appropriate helix angle if given relative helical motion to the blank can cut helical gears. A gear with two opposing helices cut by two similar helical gear shaper cutters that differ only in helix hand (direction of the helix) is basis for the so called Sykes process [3] of manufacturing herringbone gears.

Shaper cutter is manufactured by abrasive wheel, which represents one teeth of the basic rack [3]. The process of producing helical shaper cutter is presented in Figure 2.2. Spur shaper cutters are not different in production with the exception of helix angle that is not set in the machine. The wheel itself is formed with industrial diamonds based on the basic rack template of the cutter corrected for the machine geometry.
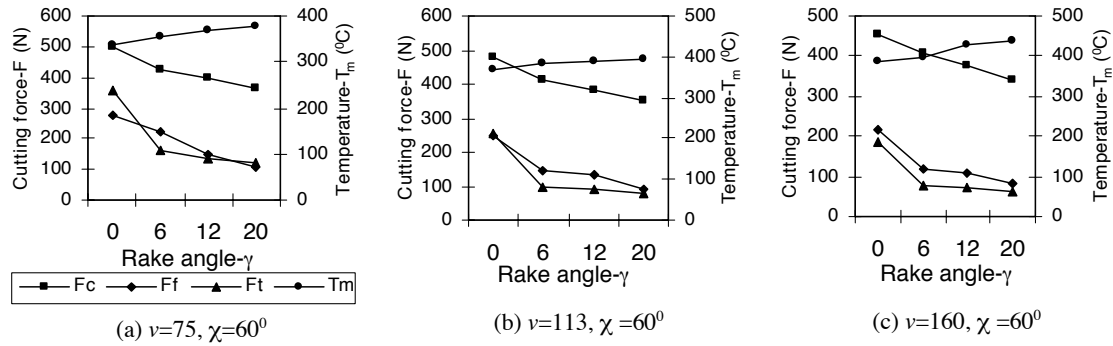
Figure 2.3: The effect of rake angle on cutting force, as presented by Saglam et al. in [2]

2.1.1   Differences between gear shaper cutter and gear

A gear shaper cutter is a tool that closely resembles mating gear in appearance. However, there are a number of significant differences between gear shaper cutter and gear because of the fact that the cutter is a cutting tool.

To produce desired chip and reduce cutting force the tool has to have rake angles. A tool with a positive rake (sharp) will lead to lower cutting forces but to less cutting edge strength [2]. A tool with negative or neutral rake will lead to higher cutting forces, as shown in the Figure 2.3 but increased edge strength.

The flanks of gear shaper cutter tooth must be suitably raised to provide relief on the gear blank. Relief is a discretionary modification of the tooth edge shape to eliminate interference between mating gear profiles. Root rise on the cutter provides tip relief on the gear blank and tip rise on the cutter provides root relief on the gear blank. In addition, the cutter must possess correct clearance. If the gear is intended to be finished after cutting, the cutter should have protuberance to avoid finishing step. Some cutters may have so-called semi-topping to produce gears with a finished tooth top.

2.1.2 Design problems

Despite the relative simplicity of cylindrical involute gear geometry, the high quality of gear shaper cutters produced today is mainly attributed to many years of experience and a large amount of empirical design data. This emerges due to the spatial nature of the shaper cutter and the complex geometry involved in the analysis of spatial gearing.

Design of a gear shaper cutter is mostly parametric, i.e. it requires a number of equations to be solved at the design stage. Therefore the choice of a suitable analytical model that takes into consideration the manifold requirements of the shaper cutter production process is critical [17].

There are a number of ways to design a shaper cutter and the process does depend upon the manufacturing techniques employed. The two main methods are single flank grinding and full form generation. The tooth generation process is performed on various types of machines that may differ in geometry but produce the same tool. The core difference between the different types of machines is how the top rake is positioned in relation to the helix angle. Some machines put the top rake on first then twist for the helix while others twist for helix and then put the top rake on.

Figure 2.4 depicts two different types of machines used for the production of helical gear shaper cutters. The machine in 2.4(a) first twists the cutter axis for helix angle and then lifts it up for top rake angle. The machine in 2.4(b) does the opposite: first lifts the cutter axis to give it top rake angle and then twists to put helix angle.

(a)   (b)

Figure 2.4: Fabrication of helical gear shaper cutters using different types of machines. (a) - cutter axis is first twisted for helix angle and then lifted for top rake angle, (b) - cutter axis is lifted for top rake angle and then twisted for helix angle.

Both the machines produce the same tool, but it is presented to the grinding wheel in a different plane so the grinding template and the wheel have to be slightly different in both cases. These differences do not change the way the basic rack of the shaper cutter is designed but they change the way the rack is corrected into the grinding plane for use as a wheel template.

2.1.3   Basic rack

Basic rack is the shape produced by taking a circular cutter or gear and straightening it out or giving it an infinite number of teeth. Because of the special properties of the involute curve, the basic rack could substitute any gear derived from it (a gear
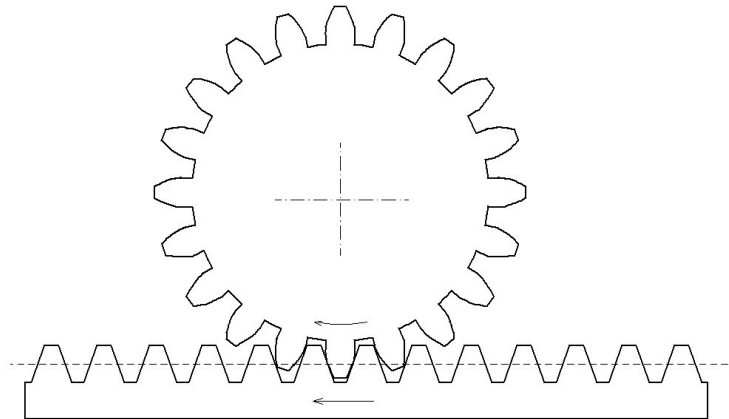
Figure 2.5: Spur gear and equivalent basic rack

that has the same diametral pitch and pressure angle). It is the basis of gear shaper cutter design as the tool is usually produced by grinding the cutter template with an abrasive wheel. As the basic rack is the only part of the cutter that does not change in shape as the cutter diameter varies, it is often better to define the tool by means of its basic rack.

Because of the properties of the involute curve the active involute profile on the rack becomes a straight line. This can be seen in Figure 2.5. This property makes the basic rack easier to correct for different machine geometry, cutter rake and sharpening angles than the gear shaper cutter itself.

The aim of gear shaper cutter design is to produce a basic rack which is corrected for top rake, front rake, helix angle and sharpening angle to form the grinding wheel template to generate the cutter.

2.2   Profile modifications

Some gears are impossible to manufacture, while being a perfectly good design. In other cases the gear would have undercut tooth and therefore unable to handle the designed load. This follows from the properties of the generating process.

Profile modifications are discretionary tooth shape changes to achieve various desirable effects in the gear train or to enable production of gears with the specified parameters. Profile modifications used in common practice for gear shaper cutter fabrication are: tip and root relief, chamfer, front and top rake angles, semi-topping, protuberance and sharpening angles. All these modifications change the profile produced on the gear blank, so the analytical model of a gear shaper cutter must include these modifications.

2.2.1   Rake angle

Most existing analytical models consider gear generation by shaper cutters as a two dimensional problem [18]. In the following section the author claims that design of the shaper cutter should be considered only within three dimensional space because of the specific properties of the cutter as a metal cutting tool.

For a gear shaper cutter to cut involute profile on a gear, the tooth edge projection on the transverse plane should also be involute. The projected curve is the same as the meshing curve between the cutter and the gear. For gear shaper cutters designed using traditional approaches, tooth flanks are involute surfaces and the projection of the tooth edge to the transverse plane is also an involute curve.

Gear shaper cutter, being a practical machining tool, usually has tooth face positioned at an angle to the transverse plane, called front rake angle. The cutter also should have side and top clearance so that it can cut without rubbing. This is achieved by orienting tooth profile in the axial direction so that the top land
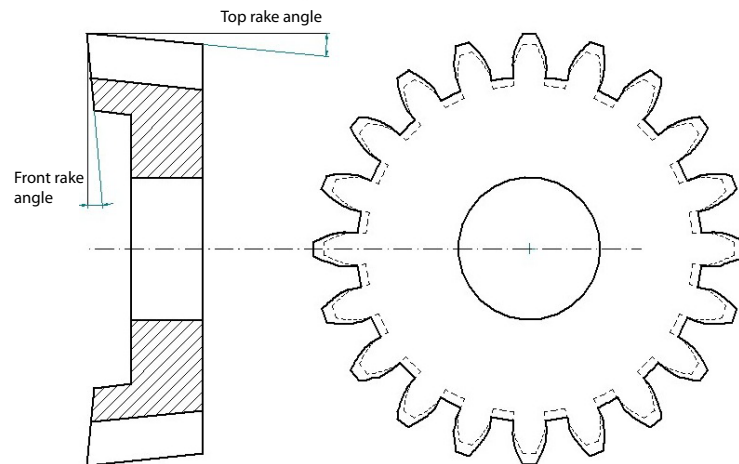
Figure 2.6: Spur gear shaper cutter rake angles

of a tooth would create an angle to the cutter main axis, called top rake angle. In order to produce these rakes the tool is ground at a top rake with the basic rack corrected to produce the correct shape of the tool in the cutting plane. Front rake is put on the cutter blank before grinding and is also accounted for during basic rack correction. The crucial point is that although the diameter of the cutter and the shape of the tooth are changing it is being produced by a constant basic rack so producing true involute on the gear at all times. Taking into account the cutter rake angle and clearance, the projected curve of the cutting edge (designed using traditional methods) to the transverse plane is no longer an involute curve. Therefore the shape of the gear produced by a cutter will deviate from the required dimensions [15], Figure 2.6 shows spur involute cutter with applied top and front rake angles.

Existing studies of the mathematical models in gearing taking into account rake angles generally consider rack type or hob cutters [19], [20]. A recent paper about gear shaper cutter design provides an analytical model for spur gear shaper cutters

only [15]. However, [15] assumes different profile of the gear shaper cutter tooth then presented in this paper.

2.2.2 Tip and root rise

Tip rise on the cutter produces root relief on the gear blank. Likewise, root rise on the cutter produces tip relief on the gear. Tip and root relieves are used to minimise static transmission errors in gear train and avoid interference between meshing profiles. The effects of tip relief on gears were studied by many researchers, among these Tavakoli [21] and Mao [22] were studying spur gears while Guilbault [23] was considering helical gears. However, none of these studies considered necessary modifications of relief/rise profiles for producing correct cutter grinding template.

Apart from widely known elliptical, radial and linear forms of relief curve some researchers proposed different forms, such as linear-parabolic as proposed in [24]. However, the effects of non-standard relief curve profiles should be further investigated.

2.2.3 Protuberance

A gear manufactured by gear shaper cutter is usually finished by shaving to achieve improved precision. The shaving operation removes a small amount of material from the gear tooth flank. The gear tooth cut by an unmodified cutter leads to a step between the fillet and the active involute profile. The step may adversely affect noise, wear and kinematic characteristics of a gear train.

To remove the shaving step, the gear is treated with a protuberance pre-shaving cutter to produce a controlled amount of undercut. A gear cut without protuberance always has sharp shaving step near the end of the involute profile. Adequately chosen protuberance parameters ensure that the shaving tool is able to cut full tooth depth without damaging itself. The finished gear will have smooth transition

between involute profile and fillet. Protuberance parameters depend upon both the dimensions of the cutter and gear. A study on parameters of protuberance pre-shaving cutters and their effect on the generated gear profile using Litvin's tooth generation method was performed by Kuang and Chen [25]. An alternative method that, although being simpler, is only applicable to standard spur gears, was presented in [7].

It is desirable to combine generating cutting and pre-shaving operations by using a gear shaper cutter with protuberance. This eliminates the need for a separate pre-shaving cutter and reduces the time to fabricate a gear, however the shape of the resulting fillet should be determined precisely.

A comprehensive study of gear tooth fillet generated by rack type cutters was presented in [26]. The same approach appears to be useful for the determination of fillet shape of gears generated by gear shaper cutters.

2.2.4   Chamfer

Gear teeth manufacturing process is not limited to rough tooth surface forming. Other processes may be required for a particular gear, for example, chamfering. Chamfer is a bevelled edge at the intersection of gear tooth face and top land (crest) surfaces [27]. This typically requires additional roughing process with different tools and machinery. A chamfer tool usually has the form of mating gear with additional tooth profile modifications near the fillet. As chamfer tool and the gear engage, they start to rotate in unison and the modified profile displaces metal on the edge of the gear tooth forming the chamfer. As with the protuberance, it is desirable to put chamfer on the gear with the same tool as used for generation.

2.2.5   Tool life optimisation

As the tool is being re-sharpened during day-to-day use and the tool diameter reduces the centre distance between gear blank and cutter on the gear-shaping machine is changing. This change of generating action and centre distance causes variation in true involute form (T.I.F.), root diameter, chamfer diameter etc. All these variations need to be considered and the variations kept within the tolerances required on the component. This gives the cutter a definite life, reflected in the length of tooth that can be re-sharpened. To enhance this life the cutter can be enlarged from its initial design diameter defined by the basic rack, reducing the variation in tooth length being cut during tool life cycle. The author proposes to call this concept oversize.

2.2.6   Sharpening angle

Helical gear shaper cutters have one more cutting angle usually not present on spur cutting tools. The angle between transverse plane of the cutter and the plane in which individual tooth of the cutter is sharpened is called sharpening angle.

Sharpening angle influences the projected tooth surface to both the transverse and normal plane of the cutter, and therefore cutter grinding template should be corrected for sharpening angle as well.

2.2.7   Meshing of internal gears

Teeth of the wheel may be cut on the internal surface of the annulus, producing an internal gear. The internal gears are largely similar to the external gears except that the shafts rotate in the same direction and the teeth engage external to the line of centres. Pinions for external and internal wheels have the same tooth profiles.

Although internal gears closely resemble external ones, there are a number of additional constraints that should be considered at the design stage of the internal gear shaper cutter. In particular, the interference between conjugate profiles in internal gears could occur not only at the contact point, but in other parts of the gear tooth profile too [28]. In addition, the teeth of internal gears could be trimmed during backoff, infeed, and rotary feed cycles of the tool [29]; so analysis of various forms of interference is of a great importance.

Internal pinions tend to have small number of teeth to avoid backoff interference, worsening problems of tip interference and undercut [30].

2.3 Relationship between cutter and gear profiles

Existing literature provides many methods for analysing the curvature of engaging gear profiles. These methods can be divided into three main categories: the classic approach not involving differential geometry as presented by the works of Buckingham [11], Colbourne [31] and Merrit [3], an approach developed by Litvin [32] together with numerous later improvements, and finally the one proposed by Di Puccio, Gabiccini and Guiggiani in [13] and [33] (an earlier preliminary work exists by the same authors [34]).

The classical approach to curvature analysis of gears considers them as two dimensional objects that are represented by two dimensional involute profiles. All analytical models developed by these approaches heavily rely on transformations between gear and basic rack, as the involute profile of the gear tooth becomes a straight line on the basic rack, therefore enabling the use of conventional trigonometric equations to describe tooth profile modifications. In particular, these models perform gear to rack conversion to account for both top and front rake angles of gear shaper cutters. The classical approach is characterised by using manifold of

different reference systems tied to various significant points in the gear train, e.g., point of contact and centres of gear wheel and pinion. A number of studies have been carried out on this theory to develop CAD models and software; among these particularly interesting results were obtained by [17] who used solid modelling procedure to simulate tooth fabrication process and [35], where tooth undercut conditions are investigated in detail.

The approach developed by Litvin [32] carries on the tradition of using multiple reference systems but considers the gear as a three dimensional object. This approach presents an important step in gear curvature analysis as it moves from profile curve analysis to tooth surface analysis. The ability to represent gear as a whole is very important for gear shaper cutter design as the shaper cutter is not a cylindrical body and therefore requires surface modelling. The surface of the gear to be generated by a shaper cutter is considered to be generated by the envelope of surfaces of the cutter [36]. This idea allows for strict analytical determination of undercut conditions. A singularity of the envelope surface presents the condition for the undercut; this was investigated in a number of papers [37], [38] and [39].

Despite the novelty and importance of Litvin's theory [32], it contained some limiting ties to legacy approaches. The main disadvantage was how the approach was dealing with vectors representing gear teeth surfaces. The common practice at the time was to work with vectors by means of their components, thus creating a number of reference system to express these components. All that led to complications (usually a set of formulae is provided for each reference system) and confusion among practitioners.

A novel approach was developed by Di Puccio, Gabiccini and Guiggiani in [13] and further developed in [33] and [40]. The proposed theory aimed to create analytical model of gearing without any reference systems. This was achieved by using

vectors without expressing them through their components. Overall the approach leads to more compact and understandable equations of the gearing theory.

One important difference between the two latter methods is how they obtain relationships between two conjugate gear profiles. Litvin's method derives surface curvature equations by studying the motion of the contact point between two gears. In this way Litvin's approach can be regarded as indirect. Also the approach does not consider generating motion, focusing, as mentioned above, on meshing conditions.

In contrast, the new approach [13] obtains equations for the normal surface curvature and geodesic torsion of surfaces by directly applying their definitions to the enveloping process [41].

A number of other less known approaches exists for gearing analysis, for example, Argyris developed an original approach to rotation analysis that uses matrix calculus [42]. One more recent development is the use of special geometric objects known as dynamic blocking contours in gear design and modelling [43].

2.4 Existing software systems for gear shaper cutter design

Gear shaper cutters profiles contain portions with complex geometry that is not possible to create without extensive calculations. Therefore, general purpose CAD packages are of a limited use for gear shaper cutter design. It can be argued that considering the expenses associated with the licensing costs of proprietary CAD packages and compatibility problems among different software versions, it is more efficient either to use a purpose-built software or to develop one. The following section contains a survey of existing gear design software and its applicability to gear shaper cutter design.

The target systems were selected by doing extensive web search using Google Internet search engine [44], which has been proven to have the largest index size among currently available search engines [45]. Four systems for gear design (CONFORMS, Gear C.A.M., Gear Factory, HyGears) [46, 47, 48, 49] were selected and subjected to a set of criteria to determine their usefulness for cutter design.

Consider Figure 2.7 that outlines the criteria used in the survey of existing software systems. Ultimately, a system might fit into one of three main categories, namely it can solve the problem of gear shaper cutter design completely, require minor modifications to solve it or be used as a part of the new system. It is clear that a system that completely solves the problem of gear shaper cutter design should be designed for that task. Notably, it should be able to perform simulation of cutter action on the component, match required sets of input and output values (refer to Appendix B) and generate appropriate drawings and Computer Numerical Control (CNC) code. If the system is not able to solve the problem fully, it may still be better to modify it instead of producing a completely new system. However, the system should meet the following conditions in order to be considered for modification. First, it should have an active community which in turn implies that the system should use current software technologies. And second, either the source code should be open or a well-documented Application Programming Interface (API) should be available.

Table 2.1 shows exiting gearing CAD systems evaluated using the criteria defined previously in Figure 2.7. Columns 2 and 4 show implementation quality of a given criteria as a percentage of the theoretical maximum. The evaluation is based on the view of the experts from the industrial sponsor ("Dathan Tools").

Analysing the data from the Table 2.1, the two most capable systems are CONFORMS and HyGears. Unfortunately, both could not be extended with new features because no source or API are available to the general public. In addition, both sys-
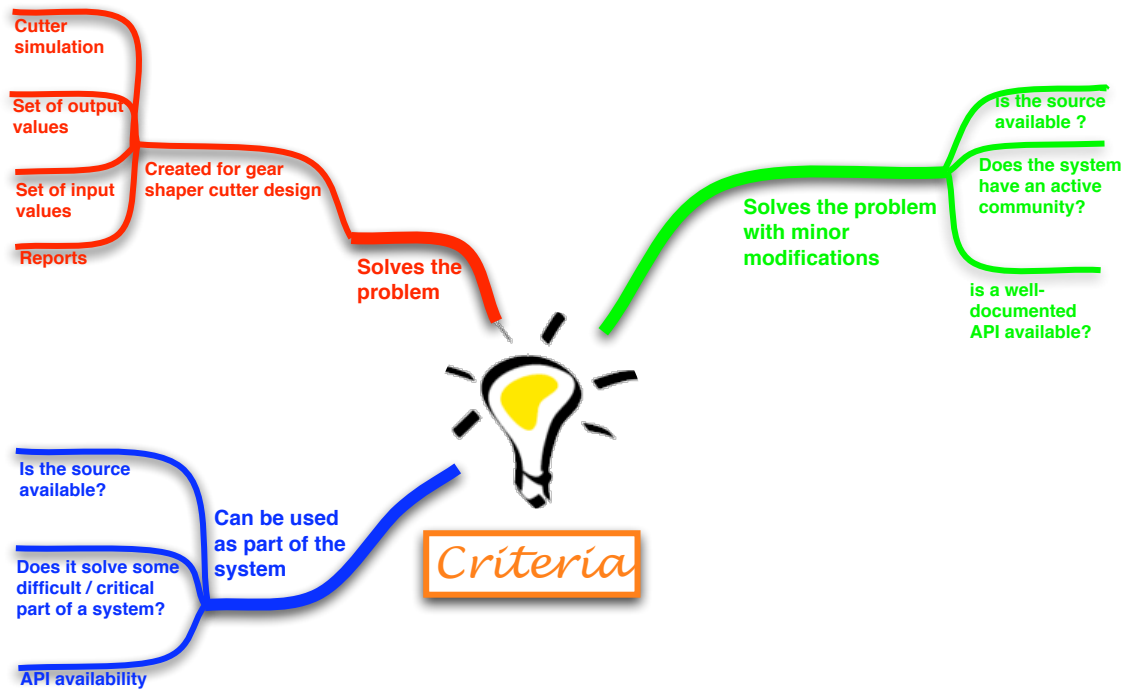
Figure 2.7: Criteria used to assess available CAD systems

	Required inputs & outputs	Simulation of cutter action	Reports	Source availability	API availability	Active community	Comments
CONFORMS	60%; 85% with additional software	present	75%	not available	not available	no	Capable, but built using obsoleted technologies
Gear C.A.M.	40%	not present	30%	not available	not available	no	built using obsoleted technologies, lots of functionality missing
Gear Factory	10%	not present	10%	not available	AutoCAD API	yes	Requires AutoCAD, works with standard gears only
HyGears	70%	not present	50%	not available	not available	no	built using obsoleted technologies, lots of functionality missing

Table 2.1: Assessment of existing gear design systems

tems are built using proprietary software technologies and their use may involve
significant integration and maintenance problems. However, it should be noted that
the output of these systems could be used to verify the results of a new one. Gear
C.A.M. has the same drawbacks as the two former systems, and is able to accom-
plish less then half of the required functionality. The last system left, Gear Factory,
is limited because it can draw only involute standard gears without profile modifica-
tions. In fact, its usefulness is limited to drawing the involute section of the profile,
which is a trivial task itself. In summary, no existing gearing CAD systems could
fulfil the needs of a gear shaper cutter designer, although the results obtained from
those systems could be used to verify substantial portions of a new system.

2.5   Summary

Most prominent research in the area is attributed to gear design not considering
special requirements of gear shaper cutters. The gears are assumed to be produced
either by rack type cutters or by hobs, that are essentially the same as racks. Con-
sequently, most existing models fail to address gear profile geometry changes due to
rake angles of the tool.

Another area that is not sufficiently discussed in current literature is the design of
helical tools. As mentioned above, helical cutters have one more distinctive feature,
called sharpening angle, when compared to spur cutters. The pattern used for
grinding the cutter should be corrected for sharpening angle to produce proper
gear geometry. Furthermore, helical cutters could be defined in different reference
systems, that considerably complicate their design.

One objective of the gear shaper design is to create grinding template with correct
geometry, the other is to achieve maximum possible tool life. The latter task needs

to be formalised. i.e., there should be a formal way to calculate the period during which the tool produces gears within given tolerances.

The correct design of gear cutting tools is impossible without proper and rigourous verification of results obtained by the means of analytical model. The objectives of verification would be to measure deviations of the produced tool from the theoretical one, determine machine settings used for tool production and provide a way to superimpose geometry of the produced tool on the geometry of the theoretical one. Existing papers in the area of tool measurement, such as the study published by Litvin [50], provide foundation that should be reconsidered and adopted for analytical model verification.

Most existing analytical models for gear and gear shaper cutter designs are applicable either to spur or to helical profiles, but not both. However, both spur and helical profiles have many common features and characteristics. One can prove that a helical involute gear shaper cutter with zero helix angle is essentially a spur cutter. The tooth profile in the normal plane of a helical gear is the same as the transverse profile of a spur gear.

For practical reasons it is desirable to have one common model both for spur and helical gears. This provides code reuse during CAD system development. Unified model also reduces the possibility of error due to a significantly lower amount of code and allows for common interface for spur and helical tool design.

However, latest research in the area of gear shaper cutter design is limited to spur shaper cutters. The approach proposed by Lai and Wu [15] could be enhanced with methods developed by Di Puccio, Gabiccini and Guiggiani [13], [33], leading to more compact and universal models.

An overview of gear generating was presented together with the description of one of the cutting tools used in the process, namely the gear shaper cutter. Main principles of the generating motion, tool and machine specifics were covered.

Main problems faced during shaper cutter design stages were listed, leading to the discussion about necessary profile modifications of the basic rack.

Profile modifications commonly used in gear manufacturing were identified and described. The studies concerning each modification were also given.

Major existing approaches to gear surface curvature analysis were presented and categorised. Where appropriate the deficiencies in the scope of current research are noted.

2.6   Research gap

Due to their widespread usage in gear manufacturing the gear shaper cutters have received a lot of attention, with substantial number of papers in the area of gear shaper cutter geometry and design, such as [15], [18], [6] and [51] to name a few. Still, there is no sufficient description of the gear shaper cutter design process found in the literature produced to date. The *design process* is understood to be a comprehensive description of the following topics and concepts:

- *Design workflow.* A report on the necessary and sufficient steps one should take to design a gear shaper cutter suitable for manufacturing. All process inputs and outputs should be included in the description.

- *Requirements for the cutter as a cutting tool.* A list of the requirements and constraints that are specific to gear shaper cutters as metal cutting tools. Such requirements are usually ignored in the papers devoted to gear design and manufacturing.

- *Input parameters.* The complete list of input parameters required by the design workflow with the variations required by the manufacturing process. All

parameters should have their meaning described along with their effect on the gear.

Notwithstanding the amount of research put into the study of the conjugate profiles produced by shaper cutters with various modifications performed by [16], [32], [51] and others, these studies usually consider a small number of modifications applied simultaneously to the cutter tooth. Furthermore, the application of developed techniques to building a CAD software might be difficult. A straightforward and simple model, yet one that is able to obtain the conjugate profile from the cutter with any number of arbitrary modifications and that can be easily adopted by CAD software writers is what the current research lacks.

Chapter 3

Research aim, objectives and methodology

3.1 Research aim

The research aim is to develop an analytical model and a set of tools that are able to aid the design process of a gear shaper cutter.

3.2 Research objectives

In order to fulfil the aim of this research, the following research objectives are set forth below:

- study and describe the nature and scope of the gear shaper cutter design process;

- establish an analytical model:

  - to obtain the geometry of the cutter based on what gear it has to produce;

– to assess the changes in the profile of the gear as the cutter geometry changes during its life;

- produce a software suite that would draw on the aforementioned analytical model to enable rapid gear shaper cutter design according to a documented design process;

- produce a set of case studies to verify the model and the software.

3.3   Research scope

This research is concerned with the design stage of gear shaper cutters used to cut cylindrical gears having involute active profile. However, the results of this research may be applicable with alterations to non-involute profiles as well because of the way the conjugate profile is obtained.

3.4   Research methodology

In dealing with something that one had a limited or no experience with before, a wise approach would be to get acquainted with the subject matter by studying the works of others having more exposure to the problem. The author's modus operandi is no different in that regard, so the first step is to find a treatise on the gear design and geometry. A number of good books were found, including the ones of Buckingham [11], Merritt [3] and Colbourne [31].

After a sufficient understanding of the subject area is gained, the literature search expanded to cover recent papers about involute cylindrical gears in general and gear shaper cutters in particular. For the purposes of obtaining the initial list of

papers a script in the Python language[1] was created with the ability to search the Scopus database using predefined set of keywords, and obtain list of references for each paper. This allowed to include the papers not directly contained within Scopus database. For the papers where the Portable Document Format (PDF) source was present in Scopus, it was retrieved and examined with an extended set of keywords. The results were put into a relational database for further analysis. Iterative reduction of the initial input set resulted in a set of 73 papers and books, with most of them subjected to a detailed study. This resulted in the material presented in Chapter 2 and identification of the research gap. The aim and the objectives of this research were set based on the review of the literature and the research gap. The remainder of this section describes the methodology used to achieve each of the stated research objectives.

3.4.1 Describe the gear shaper cutter design process

Semi-structured interviews with three practitioners in the domain of gear shaper cutter design were carried out at the industrial sponsor to extract knowledge required to understand and document the design process. The semi-structured interview approach was chosen because it combines high validity of the results and ability to clarify complex questions because the interviewed people are able to talk about the subject in greater depth and detail. Additionally, semi-structured interviews resolve the problem of "pre-judgement" where the interviewer predetermined set of topics to cover. All questions are open-ended to facilitate dialogue-like conversation between the researcher and the interviewee.

The interview questions are attached in Appendix A. Due to the unique nature of the process (only a few companies in the world produce gear shaper cutters) it

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[1]Python was used due to the power and ease of use of text processing functions and excellent code readability.

was not possible to include more than one company in the data collection activities. During the interviews the existing gear shaper cutter design workflow was documented in the form of photographs, which later turned out to be an invaluable data source.

The interview data was analysed and resulted in the description of the design process accompanied by the process model drawn using a standard diagramming software, list of cutter profile modifications commonly used in gear shaper cutter design, and the functional or user requirements for the CAD software. The requirements were captured in the form of the interface prototype drawn using a standard diagramming software and the software requirements specification document written in a text processor. The findings were presented to the interviewed people for comments and refinement.

3.4.2   Establish an analytical model

With the understanding of the subject matter, the list of industrial requirements and knowledge about the state of the art in the research of cutter and gear geometry, the analytical model of interaction between the gear and the cutter was developed. The primary tools being used for this purpose remain unchanged for centuries. There are no better tools than a pencil, ruler and a sheet of paper. The model creation process was greatly assisted by the Python Numerical Python (NumPy) software library that provided means for fast numerical verification of the results. It was chosen because of its availability for the Mac platform and open-source nature.

3.4.3   Produce CAD software

The software was developed alongside the analytical model using Python programming language. Refer to Section 6.1 for in-depth description of the methodology used to develop the software package.

3.4.4 Produce a set of case studies to verify the model and the software

The case studies used to verify the analytical model and the CAD software were given by the industrial sponsor and reflect real requirements of gear shaper cutter designers. The case studies were chosen to be representative of the different cases of gear shaper cutter design. Additionally, a set of requirements for the cases themselves was established (refer to Section 7.1 for more details).

The verification process used the profiles obtained by other means (i.e., not full form generated) to compare with the profiles obtained with the help of the CAD software. The profiles were also verified by rolling the conjugate profile around the pitch circle. Additionally, the design lead times using the new system and the existing one are compared.

3.5 Industrial context

The present research is industry-oriented in its nature and therefore impossible without close contact with the industry. For purposes of staying in touch with industry needs, a company called "Dathan Tools and Gauge Co. Ltd" based in the United Kingdom was selected that specialises in gear shaper cutter design and manufacturing. Dathan Tools are manufacturing a variety of precision cutters for automotive, aerospace and defence industries. The special property that makes this company a good target for research is that it is doing both manufacturing of the tools and through-the-life service (re-sharpening and re-coating), so the effects of the variations in the tool geometry as it goes through numerous re-sharpening cycles could be observed.

Special attention was paid to ensure that analytical model and the software developed in the course of this research could be used in real life to design a gear

shaper cutter. In fact, the output of the CAD package could be directly used by a Computer-Aided Manufacturing (CAM) system to drive a CNC grinding machine that produces disk cutters, although currently there is an intermediate stage of producing paper drawings.

3.6   Industrial focus for development of gear shaper cutter design techniques

Gears and, consequently, gear cutting tools are manufactured for more than a century already. The question that might be nagging to the reader is what is the incentive for further development of gear shaper cutter design techniques. There are two main reasons for this. Firstly, the improved cutter design techniques allow for increased precision in gear manufacturing. In particular, a better analytical model would allow for tight control over such gear parameters as root, chamfer, root and tip relief diameters and root and tip relief profiles produced throughout the life of the tool. Secondly, and perhaps even more important is that the gear shaper design process nowadays is time consuming craft that requires a highly skilled workforce. The specifics of the modern cutter tool industry, namely, the use of the special wear-resistant coatings that considerably prolong the life of the tool, shifted the tool orders into low-volume category. This means that instead of ordering hundreds of the same tool now companies order only a number of the same tool. The time required for the design should be reduced accordingly, and that is not possible with the old design techniques. So there is a constant pressure to reduce the time required to design a tool without sacrificing (and even improving) the precision of the component and the degree of control over parameters of gears produced by that tool.

3.7 Summary

This chapter defines the aim, objectives and methodology of the research. The aim of the research establishes a general direction to proceed while the objectives provide a set of milestones to achieve. The analytical model, while being a purely abstract thing, should be tailored to the requirements of the application software. Both are impossible to master without a clear understanding of the background process. For an applied research it is very important to keep the balance between the theoretical and the applied parts. And this balance is reflected in the objectives defined herein.

The research guidelines ensure quality of the research and reduce project risks. In addition, methodology plays an important role in obtaining repeatable results.

Chapter 4

Gear shaper cutter design process

To build an analytical model and a software that would enable rapid design of gear shaper cutters is a complex task that requires a solid knowledge of the geometry of gearing and programming skills. Assuming it is successfully accomplished, the result might be, however, useless without the knowledge of the actual gear shaper cutter design process. In other words, one would get a perfect tool that would not do the job, because it was not designed with that particular job in mind. To avoid such pitfalls, this chapter attempts to study and document the detailed nature and scope of the gear shaper cutter design process.

Figure 4.1 provides the reader with the design process model, which will be discussed in subsequent sections. Note that decision points are shown in yellow, activities related to data collection and processing are shown in green, while the portions related to geometry processing and visualisation are in pink colour. The decision points are presented in the form of question to be answered at that point with the respective answers placed above the arrows coming out from the boxes. The blue box highlights the special *Redesign* activity. The parts that are outside the scope of the design process have white background (e.g., the CNC code is produced by a CAM system).
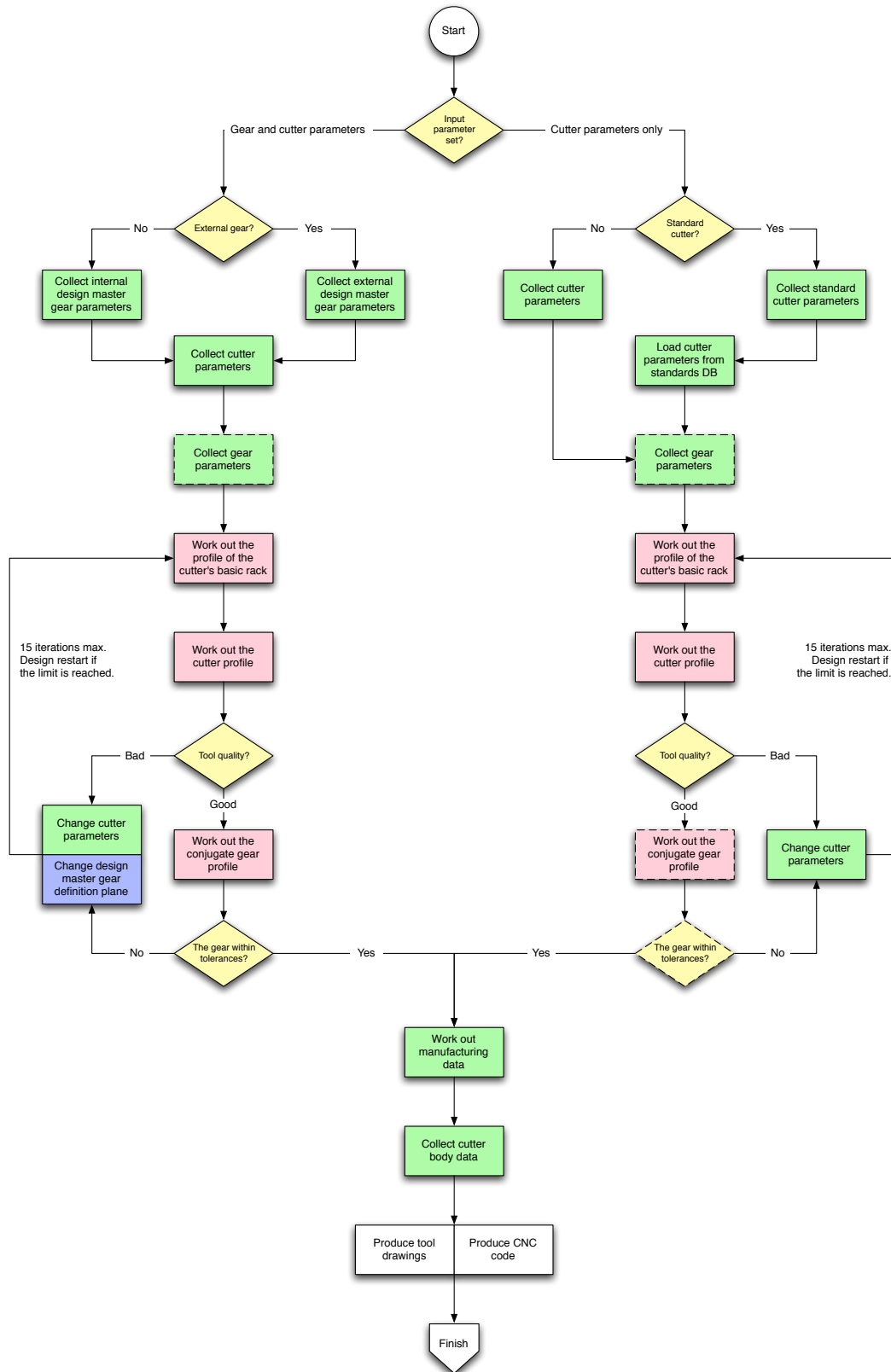
Figure 4.1: Gear shaper cutter design process model

4.1 Challenges in defining the gear shaper cutter design process

The main challenge in the study of the gear shaper cutter design process is the scarcity of written sources dealing with the subject matter. Much has been written about design of gears, much less about the design of the tools that cut gears and almost nothing about the process of designing such tools. Yet the clear understanding of the process is an essential precondition to any further research in the gear shaper cutter design area. The knowledge of the process would provide with such important information as process input and output parameters, functional or user requirements and use cases. Following the analogy presented in the previous section, one would know what the tool is supposed to do and what it is supposed to look like.

The other challenge observed after a brief study of the actual design process is that there are in fact three different workflows each with its different set of inputs and slightly different processing. Those three cases are reviewed in separate sections below.

4.2 Methodology for modelling the gear shaper cutter design process

To get the knowledge about the actual design process an opportunity was given to study a live design department of a gear shaper cutter manufacturing company (Dathan Tools). First step was gaining an initial understanding of the process using semi-structured interviews with three practitioners. The list of the interview questions is attached in Appendix A. To provide additional information needed

for detailed analysis, the existing design process was documented in the form of photographs.

Based on the preliminary information, the three different workflows were identified with the help of Venn diagrams. Each workflow was accompanied by the respective sets of input parameters (see Appendix B). A common set of output parameters was identified for all workflows. In the course of repeated sessions with the designers those initial sketches were refined to obtain the process definition and the process model as it is formulated in this chapter. The software for gear shaper cutter design based on the process model presented herein was tested with the help of the actual tool designers for the purposes of verifying the process model. Namely, the designers were using the software to perform the actual design of gear shaper cutters.

4.3   Cutter design case

The design case that allows to define the tool directly is the basis for the gear shaper cutter design process. Here, no knowledge of the gear is necessary to design a cutter, however, the gear parameters can be optionally collected to see what the actual gear produced by the cutter looks like. Referring to Figure 4.1, it is the right branch of the *Input parameter set* decision point. The input parameter collection stage depends on the cutter being either standard or a custom one. For standard cutters some of the parameters are taken from the respective standard while for the custom cutters those can be entered directly. In addition, standard cutters are restricted to have some of the profile modifications that the custom cutters may have. It is worth noting that the geometry processing stage is no different for both custom and standard cutters.

As mentioned before, the gear shaper cutters are produced by the grinding wheel that has the form of a conjugate rack tooth corrected for the machine geometry, as presented in Section 2.1.2. An enlarged basic rack template, called 'former' is used to shape the grinding wheel with an industrial diamond. The former itself, being essentially the rack tooth with geometry corrections to adapt for different machine geometries, is directly obtained from the basic rack. This leads us towards the description of the next major stage, i.e., the construction of the cutter's basic rack. This activity encompasses working out the geometry of the basic rack of the cutter with all requested modifications and visualising the result in the form of the rack's drawing. The basic rack is considered to be in the transverse plane of the cutter for the purpose of visualisation.

Having obtained the profile of the basic rack, the next step is to produce the profile of the cutter tooth. The profile of the cutter tooth is obtained keeping in mind how the cutter is actually produced (refer to Section 2.1.2). Again, the computed profile should be presented in the form of drawing to aid in verification by the human designer. The parameters that would be needed later for the inspection of the actual cutter are also computed at this stage.

The design process of gear shaper cutters imposes many trade-offs that are currently impossible to solve in a fully automated way. An example might be a situation where the tip rise on the cutter completely eliminates the protuberance. Another example might occur if the chamfer modification leaves too little active involute profile on the cutter. Sometimes the otherwise perfect cutter profile might be either undercut or be unacceptable because it does not give the tool a desired longevity. The gear shaper cutter designer must ultimately choose a compromise between many different criteria to arrive at the tool of a "good quality". In order to do so the original cutter parameters should be adjusted.

If the tool quality is acceptable to the designer, one optional step may be taken to see what profile the tool will cut in the actual gear. This step is directly related to the optional step of collecting the gear parameters described above. During this phase the conjugate gear profile to that of the cutter is constructed and visualised. Additionally, the graphs of the root and chamfer (if the cutter has the chamfering modification) diameters cut in the actual gear during the cutter life cycle are computed and plotted. If the cutter and optionally the gear profiles are acceptable, the design proceeds to the manufacturing cutter selection and, later, to the body selection phases.

4.4   Gear and cutter design case

The *gear and cutter* design case is more complex compared to the previous one where the geometry of the cutter was specified directly. In this case the cutter geometry is defined by the geometry of the gear it should produce. The gear that has control over the cutter parameters is called the *design master gear.*

The first step is to collect the data about the gear that control the cutter's geometry. Using Figure 4.1 as the reference, it can be seen that there are two different input sets depending on whether the gear is an external or an internal one. Because the geometry of the cutter is controlled by the gear geometry, the cutter parameter set is accordingly reduced. The remaining parameters mostly control the features that are specific to the cutter as a cutting tool, e.g., top and front rake angles.

In the majority of cases the cutter is designed to cut one particular gear. However, there are cases where it is necessary to optimise the cutter for cutting several different gears. The next optional step entitled *Collecting gear parameters* allows to enter parameters of multiple auxiliary gears. The profile that the cutter cuts in

each of those gears, including design master gear could be constructed and verified independently. The next three steps closely match those of the cutter design case. Namely, the basic rack profile of the cutter gets constructed first. Next stage is to construct the profile of the cutter tooth. The step of producing the conjugate gear profile is mandatory in contrast to the cutter design case. There is always at least the design master gear profile to be produced at that stage. Consequently, both questions about the tool quality and the gear that is being produced by that tool should be answered before advancing to the manufacturing phase. In addition, the graphs of the root and chamfer (if the gear has the chamfering modification) diameters cut in the actual gear by cutter during numerous re-sharpening cycles are computed and plotted. The author deliberately avoids describing the case where either of the aforementioned questions is answered negatively as that description belongs to the next section.

Assuming both the cutter and the design master gear profiles are acceptable, it is required to obtain the manufacturing parameters for the cutter blank as described later on in Section 4.6. In short, the process and cutter must be chosen to remove the excessive metal in the teeth spaces of the cutter blank. Finally, during the body selection step the essential body parameters and the shape are chosen for the cutter.

4.5 Redesign case

This section attempts to answer the question of what happens if either the gear or the cutter profiles are not acceptable to the designer in the gear and cutter design case. As one can remember, in cutter design case the only way to influence the profiles was to change the parameters of the cutter. Consequently, this is reflected in Figure 4.1 by the green boxes entitled *Change cutter parameters.* However, in the gear and cutter design case there is another option to alter the geometry of the gear
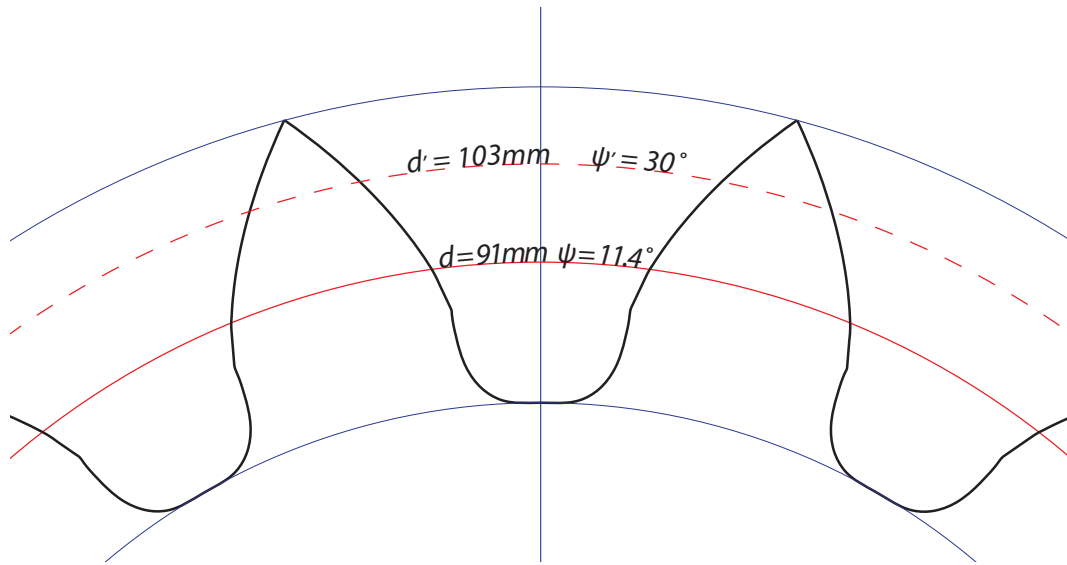
Figure 4.2: Different definition planes of a gear

and cutter profiles, i.e., to change the definition plane of the design master gear. This is what is called the *redesign* of the cutter and gear geometry.

The properties of the involute profile enable it to engage in uniform motion with any involute profile of the same base pitch. Meshing with different gears of the same base pitch changes such parameters as the pitch diameter, pressure angle and circular tooth thickness, but the profile itself remains essentially the same. For any given involute gear profile it allows to pick any arbitrary pitch diameter, obtain the pressure angle and circular thickness and use this data to define the cutter.

Figure 4.2 illustrates a gear initially defined at the pitch diameter $d = 91mm$ with the corresponding pressure angle $\psi = 11.4°$. If one is to use this gear directly to define a cutter this would result in the cutter being severely undercut, as shown in Figure 4.3(a). To get the cutter geometry that is more suitable for production, the gear is redefined at a new pitch diameter $d' = 103mm$. Consequently, the new pressure angle is $\psi' = 30°$. The cutter profile constructed using the redesigned gear data is presented in Figure 4.3(b).
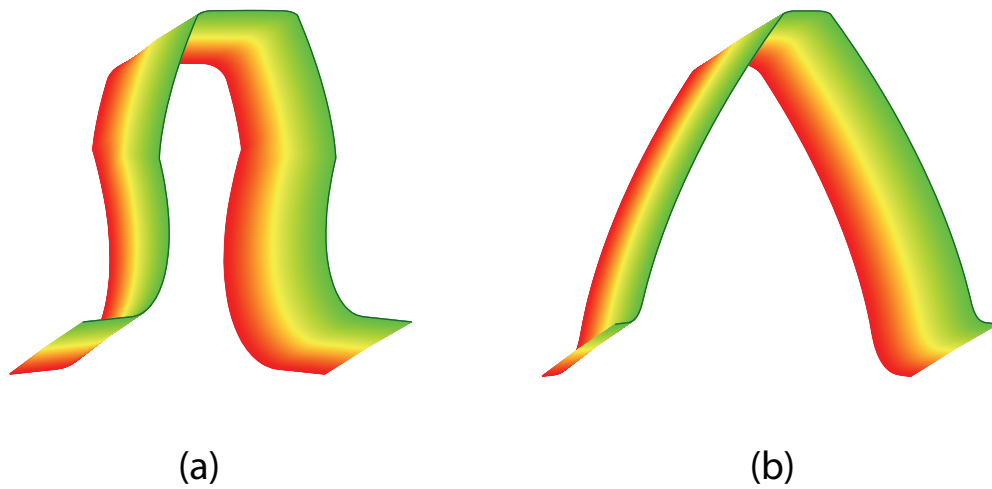
Figure 4.3: Cutter profiles that are obtained from the same gear at different pitch diameters. (a) - design master gear profile was not redesigned, (b) - design master gear profile was redesigned

4.6 Manufacturing requirements

Before finishing the cutter profile with the grinding wheel, it is desirable to remove the excessive metal in the teeth spaces of the cutter blank by using hob, rack or gear shaper cutter or a milling cutter. The reason behind this is that the grinding is slow and expensive but allows high precision finishing. So the task of a cutter designer at the manufacturing phase is to choose a cutter that would cut the closest possible profile to the required one on the cutter blank. Referring to Figure 4.4, the theoretical cutter profile is drawn to a proper scale and compared to the traces of various available manufacturing cutters. The profile cut by the manufacturing cutter is a conjugate profile in the case of a gear shaper cutter or the inverse profile in the case of the milling cutter. The profile can be moved along the line OO_1 to adjust the amount of metal left in the root and in the tip of the cutter blank. The
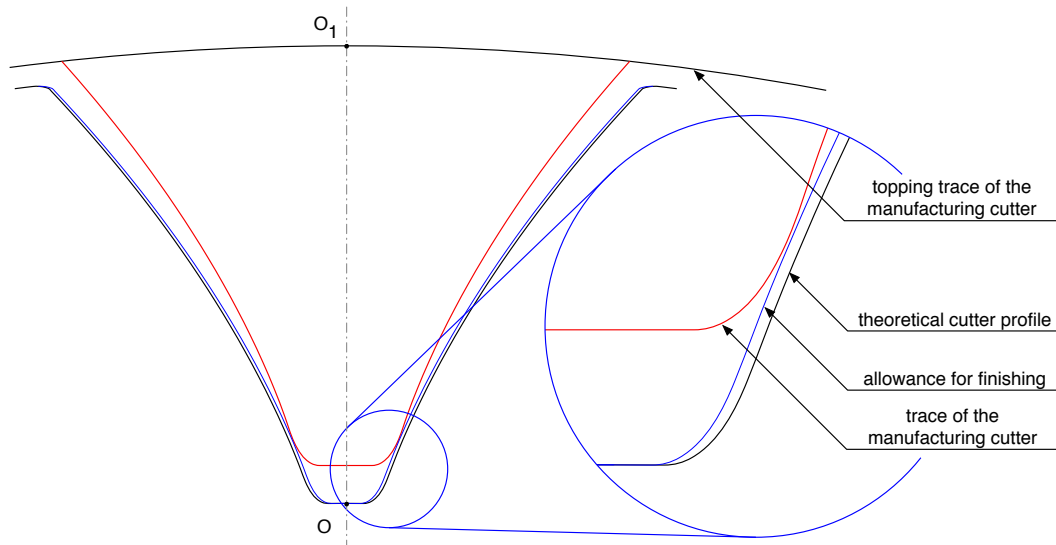
Figure 4.4: Manufactured cutter trace is superimposed on the theoretical cutter profile with grinding allowances

theoretical profile of the cutter space has grinding allowances drawn alongside it to aid the process of choosing the manufacturing cutter.

4.7   Body selection

The final stage of the gear shaper cutter design process is to select the parameters and shape of cutter body. Usually, those parameters are obtained from the database of readily available standard bodies by selecting the body shape, bore size and the body type, alternatively, the body can be parametrically constructed from the user input data.

Figure 4.5 contains a drawing of the gear shaper cutter body and the actual tool photograph. The cut-out in the right hand side of the body is a key slot to secure the tool on the machine shaft. One can see that the cutter has its tooth crests
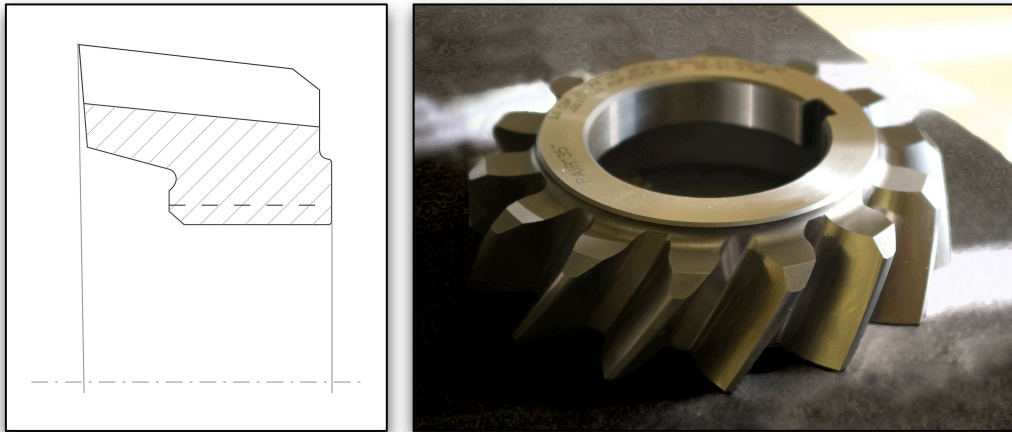
Figure 4.5: Gear shaper cutter body drawing and its embodiment in metal

inclined in the axial plane. Consequently, the outside diameter of the tool changes during re-sharpening cycles.

4.8 Summary

This chapter defines the gear shaper cutter design process. Three distinctive workflows were identified and documented. Namely, the cutter only workflow allows to input the cutter parameters directly. In contrast, the gear and cutter workflow defines the cutter through the gear it should cut. Finally, the redesign workflow uses the same gear data as the gear and cutter case, but this time the gear is redefined at a different pitch diameter. The process model of the gear shaper cutter design process that encompasses all three aforementioned workflows was presented.

Chapter 5

Analytical model of involute cylindrical gearing

The gear shaper cutter is specified by a set of key parameters describing its geometry. In order to obtain the complete profile of the cutter tooth, it is necessary to follow some geometry rules that would be described in the present chapter in Section 5.1. Likewise, the theoretical profile of the gear cut by the cutter is obtained by the same set of rules.

Knowing the theoretical ideal profiles of the gear and cutter is not enough for a good design. As stated earlier in Section 1.2, the process that is used to produce both the cutter and the gear does not merely produce the inverse form of the tool in the blank. Instead, the profile is being generated and depending on the exact proportions of the tool and the blank along with the rolling motion they are subjected to, the results may be different from the ideal theoretical involute tooth surface. The equations that allow to obtain the profile cut in the blank knowing the profile of the tool and the motion both members are given are presented in Sections 5.2 and 5.3.
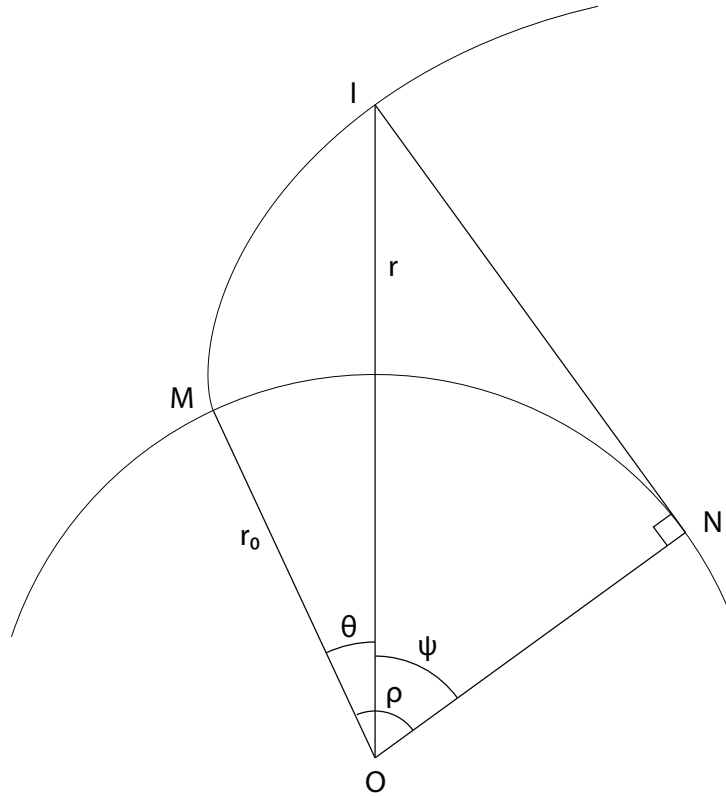
Figure 5.1: The involute line, base circle, radius vector, polar and pressure angles. θ - polar angle, ψ - pressure angle, ρ - angle between the radius vector to the origin of the involute and the tangent to the involute profile, r_0 - base radius of the involute

5.1   Cutter tooth geometry

The gear shaper cutter is manufactured by the grinding wheel, that represents a portion of the cutter basic rack. So the first step to obtain the profile of the cutter tooth is to construct the basic rack of the cutter. But even before that some basic properties of the involute curve and the cylindrical gears in general [11] should be discussed.

Figure 5.1 illustrates the basic symbols that define the involute line. Let I be the pitch point. Then from the first principles of trigonometry the tangent of the

angle ψ is equal to the ratio of the opposite side to the adjacent side in the triangle OIN:

$$\tan \psi = \frac{IN}{ON}. \qquad (5.1)$$

The angle ρ between the origin of the involute line and the tangent to the base circle drawn from the pitch point is equal to the ratio of the portion of circumference enclosed between two radii to the length of the radius, that is:

$$\rho = \frac{MN}{r_0}, \qquad (5.2)$$

where MN is the length of the arc between M and N. From the definition of the involute line as the locus of points formed by the end of unwinding rope, it follows that $MN = IN$. Knowing, that ON is r_0, the angle ρ can be expressed as follows:

$$\rho = \tan \psi. \qquad (5.3)$$

From the geometrical conditions presented in the Figure 5.1, the radius vector r and the vectorial angle θ are, respectively:

$$r = \frac{r_0}{\cos \psi} \qquad (5.4)$$

$$\theta = \rho - \psi. \qquad (5.5)$$

Substituting the angle ρ in (5.5) with (5.3) results in the following equation:

$$\theta = \tan \psi - \psi. \qquad (5.6)$$

The equation (5.6) is called the *involute function* [3] of the angle ψ or simply inv ψ. Together with equation (5.4) it allows to obtain the coordinates of the involute profile at any value of the pressure angle ψ.

5.1.1 Circular thickness

The circular thickness of the cutter tooth g_t is the width of the tooth along the circumference of a circle with the centre on the axis of the cutter. The input data for the cutter usually contains the circular thickness at pitch diameter d. Various calculations presented further in this chapter require the ability to calculate the circular tooth thickness at an arbitrary diameter.

Consider Figure 5.2, that shows the circular tooth thickness at two different radii r and r'. From the geometrical conditions presented in the drawing, the angle α is:

$$\alpha = \frac{g_t}{2r} = \frac{g_t}{d}. \tag{5.7}$$

The sum of the vectorial angle θ and the angle α stays constant for all possible values of θ, resulting in the following equation:

$$\alpha + \theta = \alpha' + \theta'$$
$$\alpha' = \alpha + \theta - \theta'. \tag{5.8}$$

Bearing in mind (5.6) and (5.7), the equation (5.8) could be expressed as:

$$\alpha = \frac{g_t}{d} + \operatorname{inv} \psi - \operatorname{inv} \psi', \tag{5.9}$$

that leads to the expression for the new circular tooth thickness as:

$$g_t' = d' \left(\frac{g_t}{d} + \operatorname{inv} \psi - \operatorname{inv} \psi' \right). \tag{5.10}$$

One can prove that for internal gears the equation (5.8) has the form of:

$$\alpha' = \alpha - \theta + \theta', \tag{5.11}$$

that gives the following expression for the new circular thickness for internal gears:

$$g_t' = d'(\frac{g_t}{d} - \text{inv }\psi + \text{inv }\psi'). \tag{5.12}$$

5.1.2 Centre distance

The outside diameter of the cutter changes as the cutter gets used more and more because of the re-sharpening. In order to cut gears of constant thickness the centre distance between two toothed bodies has to be adjusted for different outside diameters of the cutter.

The equations (5.13) and (5.14) give the expressions for the circular thickness of the cutter and the circular thickness of the gear, respectively, at an arbitrary pitch diameters d_c' and d_g' and corresponding pressure angles.

$$g_{t_c}' = d_c'(\frac{g_{t_c}}{d_c} + \text{inv }\psi_c - \text{inv }\psi_c'). \tag{5.13}$$

$$g_{t_g}' = d_g'(\frac{g_{t_g}}{d_g} + \text{inv }\psi_g - \text{inv }\psi_g'). \tag{5.14}$$

Bearing in mind that $\psi_c' = \psi_g'$ and substituting ψ using equation (5.4), the following expression can be obtained for the new pitch diameter of the cutter:

$$d_c' = \frac{d_{o_c} d_g'}{d_{o_g}}, \tag{5.15}$$

where d_{o_c} and d_{o_g} are outside diameters of cutter and gear, respectively. At the same time, $g_{t_c}' = g_{s_g}'$, and

$$g_{s_g}' = \frac{\pi d_g'}{T} - g_{t_g}', \tag{5.16}$$

therefore

$$g_{t_c}' = \frac{\pi d_g'}{T} - g_{t_g}'. \tag{5.17}$$
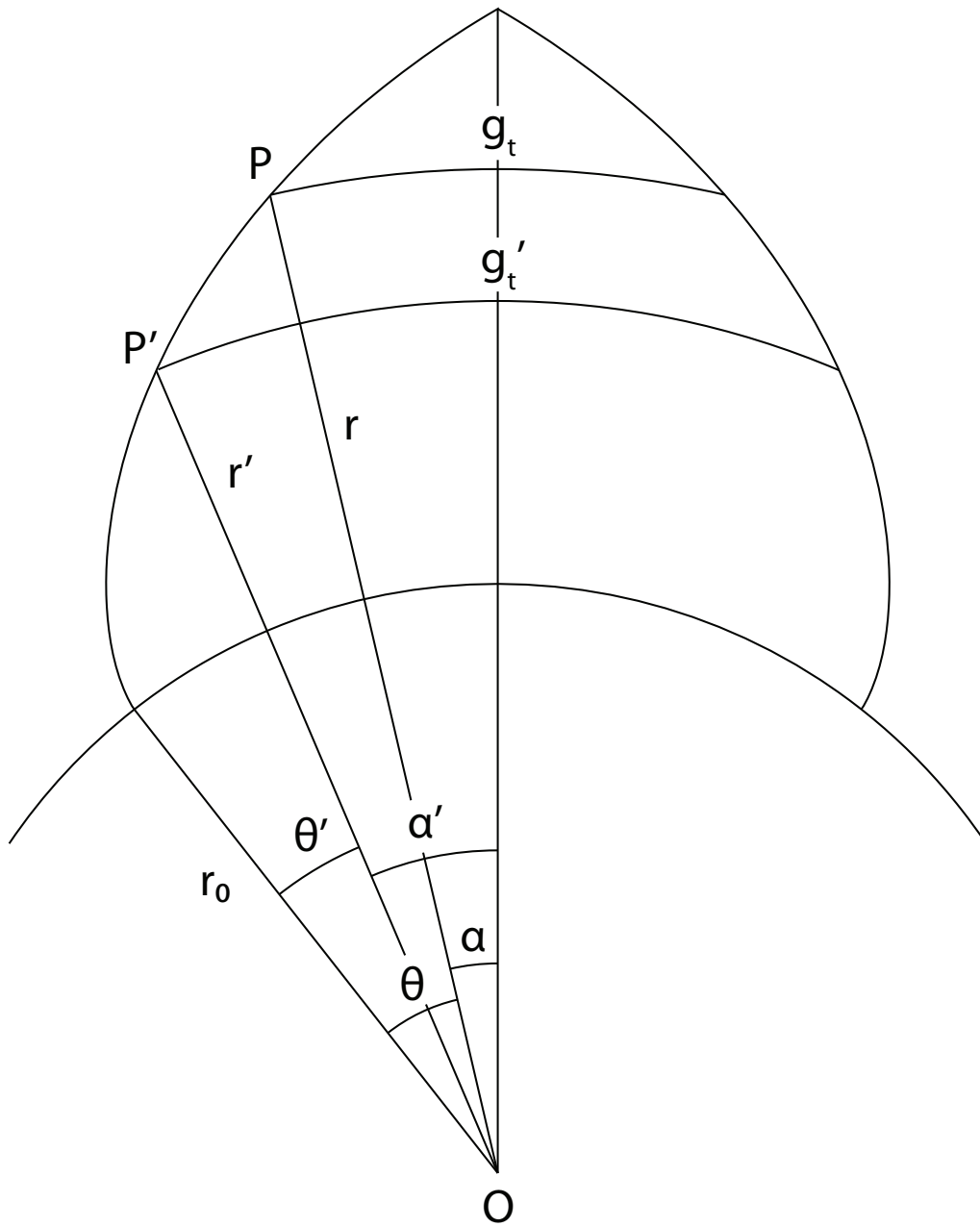
Figure 5.2: Circular thickness of the cutter

From (5.17), (5.13) and (5.14) follows, that

$$d'_c(\frac{g_{t_c}}{d_c} + \text{inv}\,\psi - \text{inv}\,\psi') = \frac{\pi d'_g}{T} - d'_g(\frac{g_{t_g}}{d_g} + \text{inv}\,\psi - \text{inv}\,\psi'). \tag{5.18}$$

Substituting d'_c with (5.15), the expression (5.19) for the new pressure angle ψ' is obtained

$$\psi' = \text{ainv}\,\frac{\frac{g_{t_c}}{d_{og}}\cos\psi + \frac{d_{o_c}}{d_{og}}\text{inv}\,\psi - \frac{\pi}{T} + \frac{g_{t_g}}{d_g} - \text{inv}\,\psi}{\frac{d_{o_c}}{d_{og}} - 1}. \tag{5.19}$$

It should be noted, that the ainv function is calculated using numerical means.

New gear and cutter pitch diameters are calculated using equation (5.4). The centre distance between the two toothed bodies is equal to the half of the sum of the pitch diameters

$$C = \frac{d'_g + d'_c}{2}. \tag{5.20}$$

5.1.3 Tool life

Authors define tool life L as a measure of the extent to which the tool can be re-sharpened while maintaining the component profile within given tolerances. The life is the length of the useful portion of the cutter tooth crest measured in the axial plane of the cutter. Typically for the gear generation process with gear shaper cutters, tolerances are specified as border conditions for the gear root diameter d_{r_g}.

The changing outside diameter of the cutter can be expressed as

$$d'_{o_c} = d_{o_c} + 2\Delta d_{o_c}, \tag{5.21}$$

where the quantity Δd_{o_c} is the *radial oversize* of the cutter tooth. The relationship between the oversize and tool life is represented as:

$$L = \frac{d_{o_c}}{\sin\alpha}, \tag{5.22}$$

where α is the top rake angle of the cutter.

Using the equation (5.21), the root diameter of the gear, consequently, is

$$d'_{r_g} = C - d'_{o_c}. \tag{5.23}$$

In order to stay within tolerances, the root diameter of the gear should be between the specified minimum and maximum root diameters.

5.2   Relationship between cutter and rack profiles

Previous sections explained how to produce the profile of the basic rack from the input data for the gear shaper cutter design process. But knowing the profile of the basic rack is not enough to manufacture a good cutter. It is desirable to obtain the profile the grinding wheel would produce in the cutter blank prior to the manufacturing stage to be able to apply profile corrections if needed.

As the cutter is always an external component, i.e., its teeth are on the external side of the annulus, the only case of meshing that is presented in Figure 5.3 should be considered. The basic rack advances in the direction AA' that causes the cutter blank to rotate around its centre O. Because of this motion the point of contact between the profiles moves from the position I to the new position I'.

The primary coordinate system in Figure 5.3 is a polar coordinate system with the centre at the point O. The vectorial angle is zero at the point of contact I. Adhering to the standard conventions of the polar coordinate system, the author assumes that all angles are positive when measuring in the counterclockwise direction. Knowing the coordinates of the profile of the basic rack (x_r, y_r), the length of the radius vector to the new point of contact I' is:

$$r' = \sqrt{(r + y_r)^2 + x^2}. \tag{5.24}$$

The angle of rotation of the cutter blank δ, considering that the cuter and the basic rack are rolling without slip with their respective pitch surfaces is:

$$-\delta = \frac{x - x_r}{r} \tag{5.25}$$

$$\delta = \frac{x_r - x}{r}.$$

Note, that this angle is negative because the blank rotates in the clockwise direction as the rack moves in the AA' direction. The vectorial angle θ of the radius vector r' to the new point of contact, assuming the blank remains stationary, is:

$$\theta = \arctan \frac{x}{r + y_r} - \delta. \tag{5.26}$$

Using the value of the $-\delta$ from the equation 5.25, the expression of the vectorial angle takes the following form:

$$\theta = \frac{x - x_r}{r} + \arctan \frac{x}{r + y_r}. \tag{5.27}$$

The equations 5.24 and 5.27 allow to determine the conjugate profile of the cutter if the profile of the basic rack is known.

The only question remaining unanswered is how to find the abscissa x of the new point of contact I'. The instantaneous pressure angle at the point of contact must be found first. From the definition of the pressure angle as the acute angle between the common pitch plane and the common normal to the profiles of meshing toothed bodies and the geometrical conditions presented in Figure 5.3 follows:

$$\tan \psi = \frac{dx_r}{dy_r}. \tag{5.28}$$

The abscissa of the new point of contact is, therefore:

$$x = \frac{-y_r}{\tan \psi}. \tag{5.29}$$

5.3   Relationship between cutter and gear profiles

The analysis of the conjugate action between the cutter and the gear is in essence similar to the one of the cutter and the basic rack. However, this analysis requires more effort mainly attributed to the possibilities of both internal and external contact between the toothed bodies.

5.3.1   External gear case

The analysis of the conjugate action between the cutter and the gear profile is started by considering the case of external meshing. Figure 5.4 contains the transverse section of the cutter above the gear blank both engaged into an appropriate rolling motion.

The figure contains two primary polar coordinate systems with the centres on the axes of the respective toothed bodies. The polar angle is assumed to be zero at the pitch point. Following the standard conventions for the polar coordinate system, all angles are positive when measured in the counterclockwise direction.

To get the coordinates of the conjugate gear profile, assuming the cutter profile is given by a series of points $(\theta, r^{'})$, the expressions for the radius vector $R^{'}$ and the polar angle Θ should be obtained. From the geometrical conditions illustrated in Figure 5.4, the radius vector of the gear profile can be expressed in the following form:

$$R^{'} = \sqrt{(R + y_c)^2 + x^2}. \tag{5.30}$$

The value of x, i.e., the abscissa of the point of contact, can be readily expressed as:

$$x = r^{'} \sin(\delta + \theta). \tag{5.31}$$

The value of the angle δ, which is the angle of cutter rotation from the zero position, can be in turn expressed as:

$$\delta = \psi - \lambda - \theta. \tag{5.32}$$

The instantaneous pressure angle at the point of contact can be calculated using the following equation:

$$\psi = \arccos \frac{r' \cos \lambda}{r} \tag{5.33}$$

Finally, the angle λ between the common tangent to the tooth profiles at the pitch point and the radius vector is:

$$\lambda = \arctan(r' \frac{d\theta}{dr'}) \tag{5.34}$$

The polar angle Θ is equal to the difference between the sum of the pressure angle ψ and the angle of gear rotation from the zero position $-\Delta$ and the angle between the common tangent to the tooth profiles and the radius vector Λ:

$$\Theta = \psi - \Delta - \Lambda. \tag{5.35}$$

The angle Δ can be obtained by multiplying the angle δ by the ratio of cutter and gear pitch radii:

$$-\Delta = \delta \frac{r}{R} \tag{5.36}$$
$$\Delta = -\delta \frac{r}{R}.$$

Following the same considerations as in the equation 5.33, the angle Λ can be calculated as:

$$\Lambda = \arccos \frac{R \cos \psi}{R'}. \tag{5.37}$$

5.3.2   Internal gear case

In the internal gear case the reasoning logic is the same as with the external gear, however the arrangement of the cutter and gear is different, namely, the centres of both toothed bodies lie on the same side of the common normal to the tooth profiles at the pitch point. Additionally, the cutter and the gear rotate in the same direction. That causes some differences in the equations.

In particular, the length of the radius vector of the gear profile will be:

$$R' = \sqrt{(R - y_c)^2 + x^2}. \tag{5.38}$$

Because both toothed bodies rotate in the same direction, the angles of rotation from the zero position would have the same sign:

$$\Delta = \delta \frac{r}{R}. \tag{5.39}$$

Carrying out the calculations for the internal gears, one should remember that the angles δ and θ have their signs swapped compared to the external gear case.

5.4   Summary

This chapter establishes the analytical base for the full form technique that is used obtain the conjugate profile. By full form the author understands that the initial profile is considered as a whole regardless of the number and type of the profile modifications applied. Therefore, it is sufficient to construct the profile of the basic rack in order to obtain the profile of the cutter tooth.

The major precondition of the full form generation technique is the ability to remove crossed over sections from the conjugate profile. For this purpose the algorithm developed by Shamos and Hoey [52] is used. This will be discussed in detail in the following chapter.

Figure 5.3: Meshing between the cutter blank and the basic rack
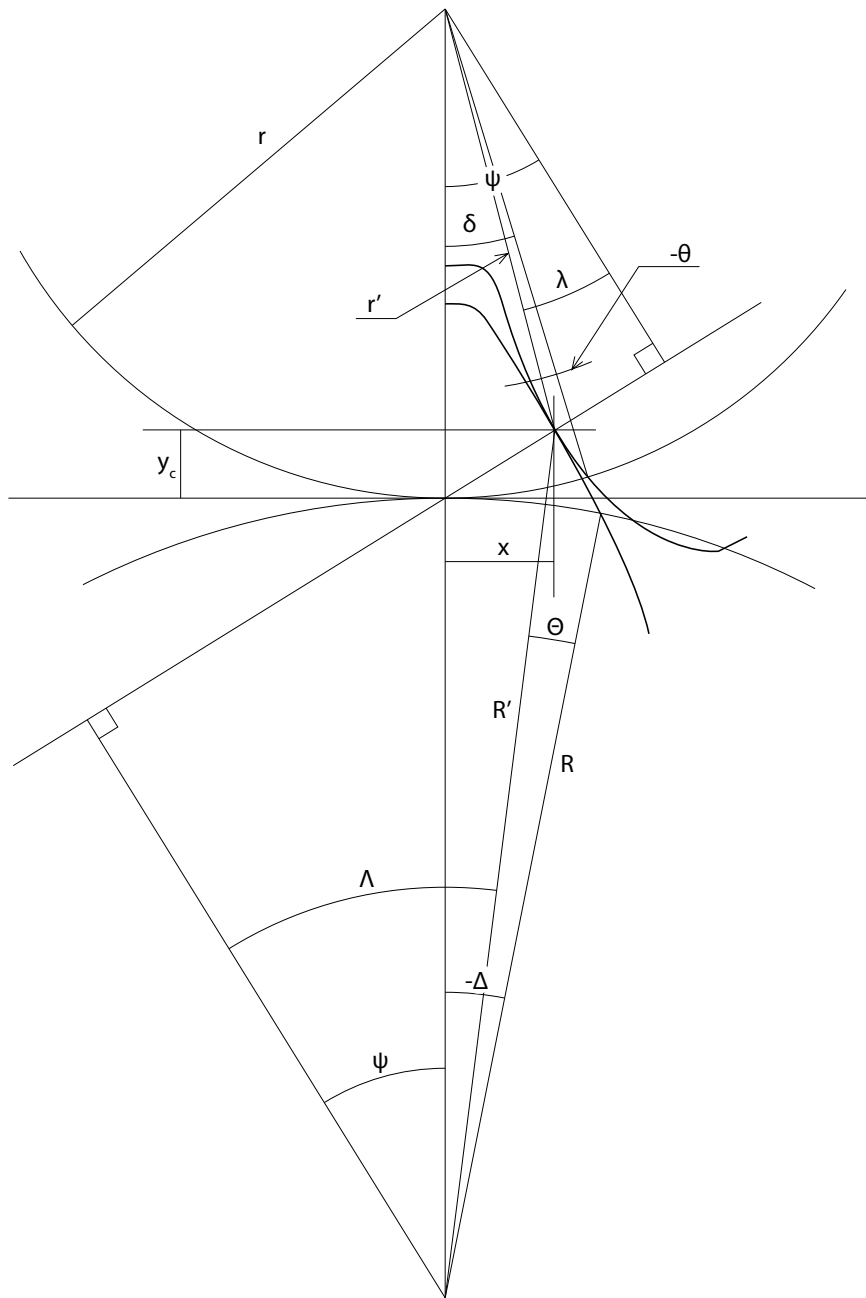
Figure 5.4: Meshing between the gear blank (below) and the cutter (above)

Chapter 6

Computer-Aided Design software for gear shaper cutter design

As noted in Sections 2.6 and 3.1 the results of the analysis of gear generation by gear shaper cutters should be in a useable form to build a package for computer aided design of the gear shaper cutters. It can be argued that there is no better way to ensure that the model is suitable as a base for the CAD software than to actually write the software. That decision is further supported by the fact that no software for gear shaper cutter design is hitherto available. The current CAD packages could not be used for gear shaper cutter design because the cutter design is a highly parametric task that requires extensive computations.

One added advantage of the CAD package readily available is the ability to verify the real industry requirements for both the gear shaper cutter design process and the analytical model. Thus the software becomes an important verification tool for the findings of the present research.

6.1   Methodology for CAD package development

The development of the CAD package for gear shaper cutter design is a project where both the functional or user requirements and the added requirements are not clearly known initially and are continuously refined during the development process. Another important aspect of the project is that the development team is very small, i.e., the author. The choice among the methodologies suggested by the literature yielded the *Rapid Prototyping* [53], [54] as the ultimate choice for the project.

The rapid prototyping methodology suggests to develop a prototype that implements the major or best-known requirements and continuously refine it as the new requirements are revealed in the development process. That approach allows to develop the software alongside the analytical model, the importance of which can not be underestimated. The iteration time was chosen to be two weeks.

In the course of adopting the methodology for the project requirements, it was enhanced with techniques acquired from the *Extreme Programming* approach [55], [56] and [57]. In hope to produce code of a better quality and reduce the number of errors peer reviews of the source code were adopted. Namely, the changes in each new revision of the code were reviewed by a fellow researcher. Automated regression tests were implemented where possible to reduce the time required for testing on each iteration.

6.2   Identification of the software requirements

The semi-structured interview with gear shaper cutter designers at the industrial sponsor provided initial material for requirements analysis. The interface prototype was jointly developed with the practitioners at Dathan based on initial functional requirements (attached in Appendix C).

The lists of inputs for each of the design cases from Chapter 4 aided in the process of interface prototype refinement. Alongside the interface prototype, a Software Requirements Specification (SRS) document was developed and approved by Dathan. The SRS document can be found in the Appendix D.

6.3 Architecture of the software package

The design of the gear shaper cutter is parametric and therefore does nor require a lot of interactive graphical information. It is based on a set of textual inputs and a set of textual outputs accompanied by the drawings of the basic rack, cutter and gear profiles. Additional requirement imposed was to make the software platform independent and based on the freely available components and standards.

Considering the aforementioned requirements, the software was chosen to be web-based implementing client-server architecture. The main idea underlying that choice was the ability of the client portion of the software to work in any modern browser[1] on any computing platform, be it an IA-32 PC running MS Windows or GNU/Linux or Macintosh running OS X or GNU/Linux.

The client portion of the software is based on the templates written in a specially created language and uses the Scalable Vector Graphics (SVG) format for the graphical data interchange and representation. The interactive features of the user interface are supported by the MochiKit JavaScript library that provides an abstraction layer from the browser-specific implementation of the JavaScript runtime. A desktop-like experience when using the software is implemented using the Asynchronous JavaScript and XML (AJAX) technology that uses JavaScript Object Notation (JSON) as the data interchange format between the client and the server.

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[1]Currently, both the Mozilla Firefox 2.0+ and Safari 3.0+ are fully compatible. Other browsers that use either WebKit or Gecko are compatible, such as Shiira and Camino. Microsoft Internet Explorer was never tested in the absence of it.

The server portion of the software is written using Python programming language and the TurboGears programming framework. The framework helps to process web requests and provides the authentication and deployment services. The PostgreSQL database was chosen as the database back end for its reliability and speed. The top level architecture of the system is illustrated in the Figure 6.1.

During the development a special attention was paid to maintain the server portion of the software as portable as possible. This resulted in the ability of the unmodified server part of the software to run on both the Mac OS X and GNU/Linux operating systems provided the PostgreSQL database and Python with the appropriate modules are installed. MS Windows compatibility is likely though not tested.

The use of a dedicated GNU/Linux server based system resulted in a better connection to other company resources and better uptime compared to traditional CAD systems. Both characteristics were found very important and valuable by the industrial sponsor.

6.4   Visualisation of the design data

Due to the nature of the gear shaper cutter design process where a designer needs to find a compromise between different cutter parameters, such as tooth strength, life and ability to cut gears with different numbers of teeth, the design data should be visualised in some form to aid the decision making. The commonly accepted form of visualising geometry data is a form of drawing of the actual tooth profile.

The problems that are being dealt by the present research could be visualised either in two or in three dimensions. Two dimensional representation was chosen due to its simplicity in both realisation and perception of the actual drawings.

Database

Drawing module

Templates

Data from controllers

HTML page

AJAX requests

CSS

JavaScript
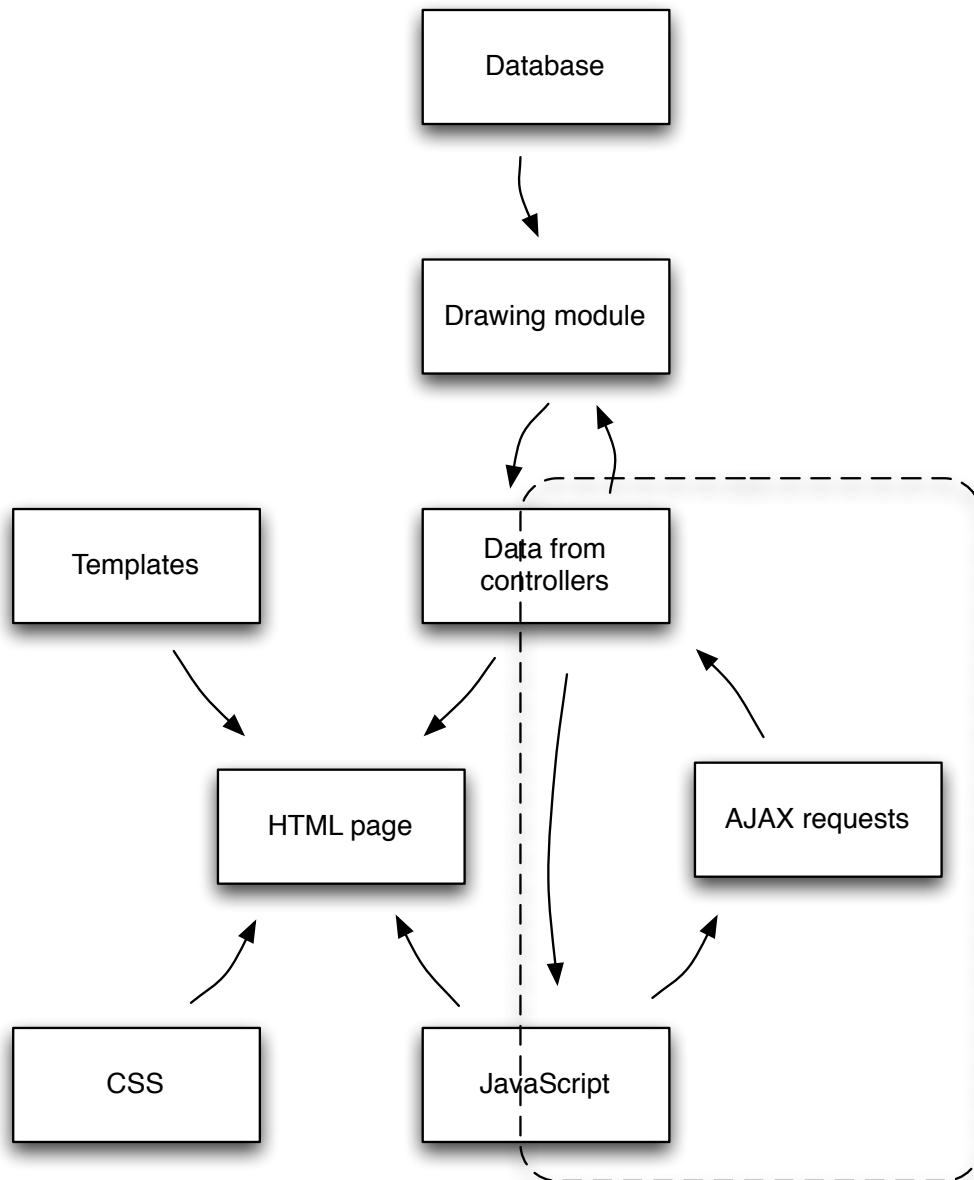
Figure 6.1: Top level architecture of the software package

6.4.1   Requirements for design visualisation

The following requirements for design visualisation were identified:

- The graphics should be interactive, i.e., support drawing the objects on top of the drawing or moving existing ones.

- Drawings must be able to scale within the web interface.

- An obvious requirement for the drawings is to be able to be generated by the program code.

- The drawings should be compatible with external CAD programs.

6.4.2   Challenges in parametric design visualisation

The web based nature of the design software imposed a number of challenges for the design data visualisation. The most important challenge was to make the drawings immediately available to the user within the web browser, without being forced to use supplementary programs. Considering the requirements defined in the previous section, that meant to choose between one of the two widely used vector graphic formats: SVG or Flash. The preference was given to SVG that despite being much less widespread, than Flash, has native support from major browsers and is a World Wide Web consortium Recommendation [58].

As noted earlier, the drawing should be able to be produced as the result of an automated process, and SVG excels in that being essentially an eXtensible Markup Language (XML) [59] subset, i.e., a human-readable text. An SVG file is a set of statements called *tags* that specify geometrical objects, their position, size and other attributes. The size and position are specified by means of *attributes* - text nodes with numerical values. Such text based formats are not only human readable, but also very easy to produce by a program. Another advantage of the SVG format is

that it can be readily translated to the Drawing Exchange Format (DXF) format, which is a standard data interchange format for commercial CAD packages. This enabled the new system to export data to external CAD programs.

A major challenge to the web based CAD is the requirement for an interactive user interface. A "zoom" action is defined to illustrate the most basic interactive operation with a drawing, whereby the user selects a portion of the drawing that should be displayed instead of the entire drawing, magnified to fill the viewport. If this action is to be split into elementary blocks, it would result in a set of elementary requirements that must be supported by the program architecture in order to perform zoom action.

For the user to select a portion of the drawing, the system must be able to detect the coordinates of the pointing device and provide a visual feedback by highlighting the selected area. While a common action on a desktop system, its realisation inside a browser is a complicated task as no standard way of doing that exists. After the selection area is defined, the system should be able to determine the zoom ratio and provide the user with an enlarged portion of the drawing within selection. That requires the system either to be able to retrieve the enlarged portion of the image from the server in real time or to scale and position the image itself.

6.5 Software interface prototype

In the early stages of the present research the industry requirements for the gear shaper cutter analytical model and design software were not fully known. Furthermore, the full set of input parameters for each of the design cases described in Chapter 4 was not defined and, consequently, the modifications of the cutter profile required by the industry were difficult to identify. To refine the initial user requirements and obtain a full set of input parameters for three different gear shaper

cutter design cases in accordance with the course of action suggested by the proto-
type building development methodology, an interface prototype was created.

The interface prototype was created from the images of the actual web interface
elements. Being very close in appearance to the look of the actual software package it
was used to perform user tests. Referring to Figure 6.2 one can see that the interface
consists of four primary parts. Part **A** is the main menu and control portion of the
interface, that allows to go through the design steps, load and save data and choose
global options like the measurement system.

Part **B** contains the actual input parameters that define the geometry of the
cutter. Note, that not all of the parameters are displayed at the same time. Instead,
the input fields are conditionally displayed depending on the chosen design case and
required modifications.

Part **C** displays calculated parameters that are required for the inspection of the
manufactured gear shaper cutters. The values in the block **C** are corrected for the
top and front rake angles of the gear shaper cutter.

Finally, the block **D** displays brief graphical outputs of the software. Those
include a drawing of the cutter profile at three positions, namely when the cutter is
new, at nominal outside diameter and when the cutter is at the end of its life. The
next drawing shows the profile of the cutter's basic rack. Last portion of part **D**
is the gear root diameter graph. It shows variations in the gear root diameter that
occur due to changes in the outside diameter of the cutter caused by re-sharpening
cycles. The drawings, when clicked by a pointing device, display more information
and drawing options. Those additional options will be discussed further in this
section.

For the designs that are based on the gear parameters or where it is necessary
to know the precise shape of the gear being cut by the cutter, the gear parameters
can be input in the gear section. Figure 6.3 illustrates the gear page of the software
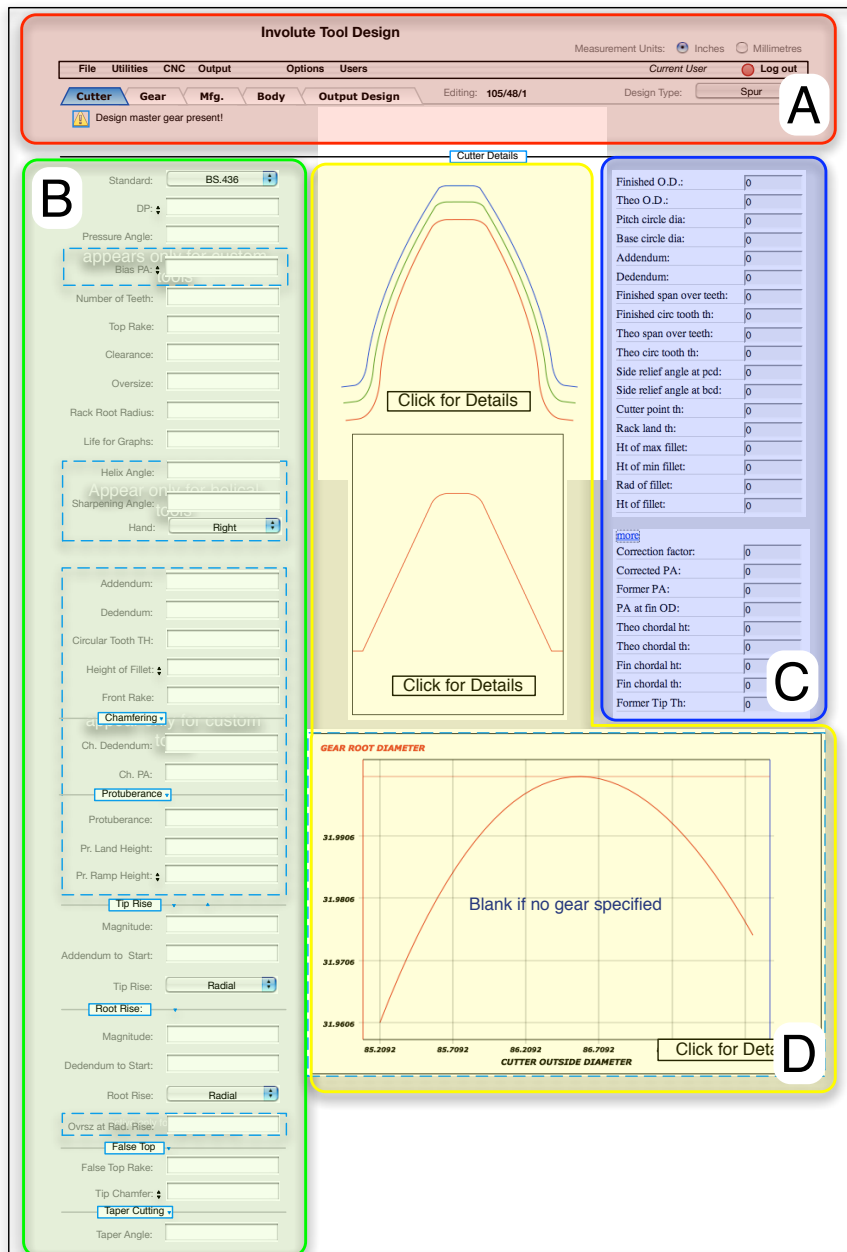
Figure 6.2: CAD software interface prototype: cutter page

interface prototype. Like the cutter page it consists of several parts. Part **A** is identical in functions to one on the cutter page. Part **B** allows the user to input gear parameters. Depending on the value of the *Design Master Gear* switch, the inputs displayed are adjusted, in particular the input fields for the diametral pitch and pressure angle are shown only for the design master gear. There is no part **C** on the gear page, as the parameters in that part are needed only for the inspection of the cutter and, therefore, are not relevant for the gear.

The section **D** contains the drawing of the gear profile cut in the gear blank by the cutter with the gear outside and root diameters labelled. Additionally, it contains the graph of the gear root diameter variation and, optionally if the gear has a chamfer, the chamfer start diameter variation graph.

The crucial part of the gear design software is the so called multigraph pictured in Figure 6.4. It allows to produce drawings of the basic rack, cutter and gear with various supplementary information.

6.6   Implementation details

Building a CAD system is not a trivial task, more so considered that the system is web based. However, the description of full software implementation is outside of the scope of this thesis, so only important details will be given.

It should be clear from the contents of Chapter 5 that in order to obtain the cutter profile one should construct the profile of the basic rack as an array of points with their respective (x_r, y_r) values and the value of angle ψ at each of those points. Each of the points on the basic rack produces a corresponding point on the cutter profile.

One important problem is posed by the points where the change in the gradient of angle ψ is high. In reality, these points roll around the conjugate profile producing
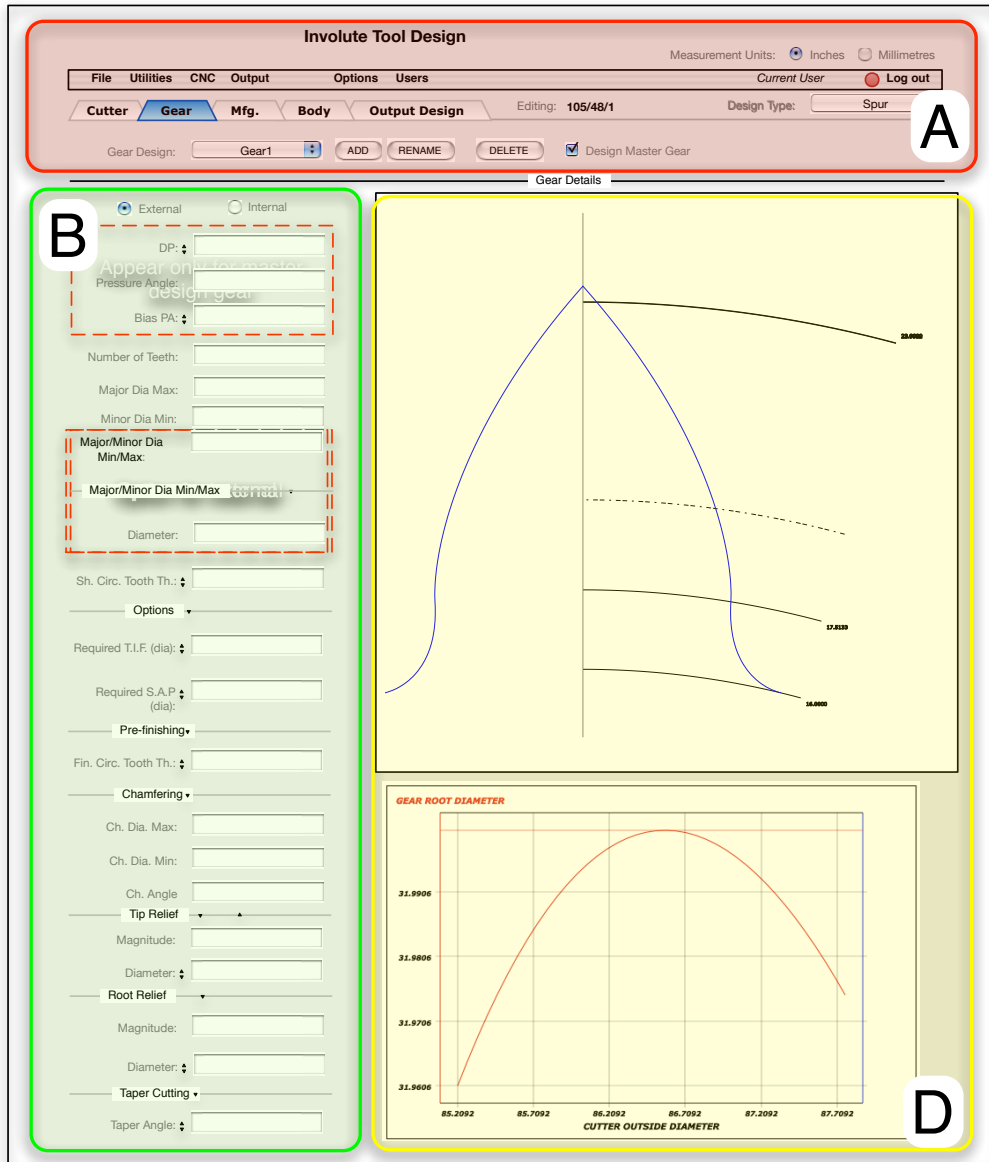
Figure 6.3: CAD software interface prototype: gear page

a curve that is locus of the points with the same coordinates on the basic rack but with different pressure angle. In Figure 6.5 one can see that the point **A** on the basic rack (the point where the crest of the rack join with the tooth face) rolling around the cutter tooth contacts the cutter profile at different pressure angles. In order to obtain correct conjugate profile as seen in Figure 6.5 each point with high change in pressure angle gradient should be substituted with a series of points with the same spatial position and intermediate pressure angle values. The number of intermediate points could be adjusted using angular discretisation threshold and step values.

As noted before, one point on the basic rack produces a corresponding point on the cutter profile. On rare occasions some of these points may be irrelevant in respect to the final profile. Consider that the profile of the cutter in reality is a surface of a solid object and therefore some points produced by one part of the basic rack profile can be later removed by an other part of the basic rack. For the analytical profile it results in the curve that is crossed over itself. The parts that are crossed over should be removed as no material exists "in space" beyond the surface of the cutter. To remove those non-existent portions of the profile an implementation of the Shamos-Hoey algorithm [52] in Python language was created, that finds the intersection points of the curve with itself and removes closed regions of the profile. The algorithm uses a sweep line approach to track intersection between segments of the polyline. When the intersection is found, the intersection point is computed and the portion of the polyline that forms an enclosed region is removed from the profile.

6.7   Summary

A weak point of the purely theoretical research is its unproven ability to help in real world tasks. With the software that uses the developed analytical model, its

applicability to the real world requirements could be easily verified. In addition, the ability to test the model with real world examples gives confidence that the analytical model is correct.

Web-based CAD software architecture was used because it provides several important advantages over traditional one. All compatibility problems between different versions of client CAD software, operating system and other installed applications are resolved because of the ability of the client portion of the system to run inside a regular web browser. In addition, browser-based interface allows remote access and access from portable devices, which would in turn allow initial data input by customers. Because no external CAD program is needed, the Total Cost of Ownership (TCO) of the system is reduced as well.
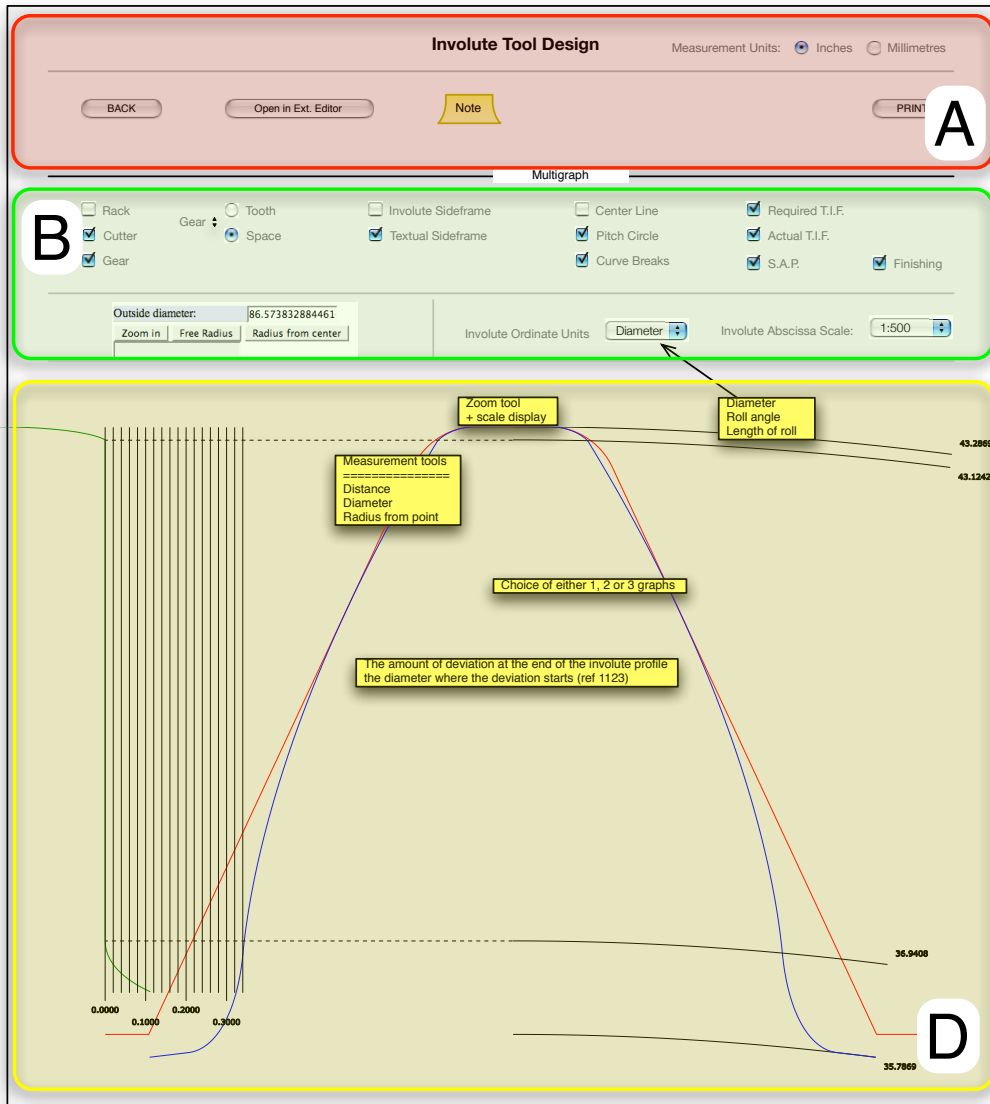
Figure 6.4: CAD software interface prototype: multigraph page
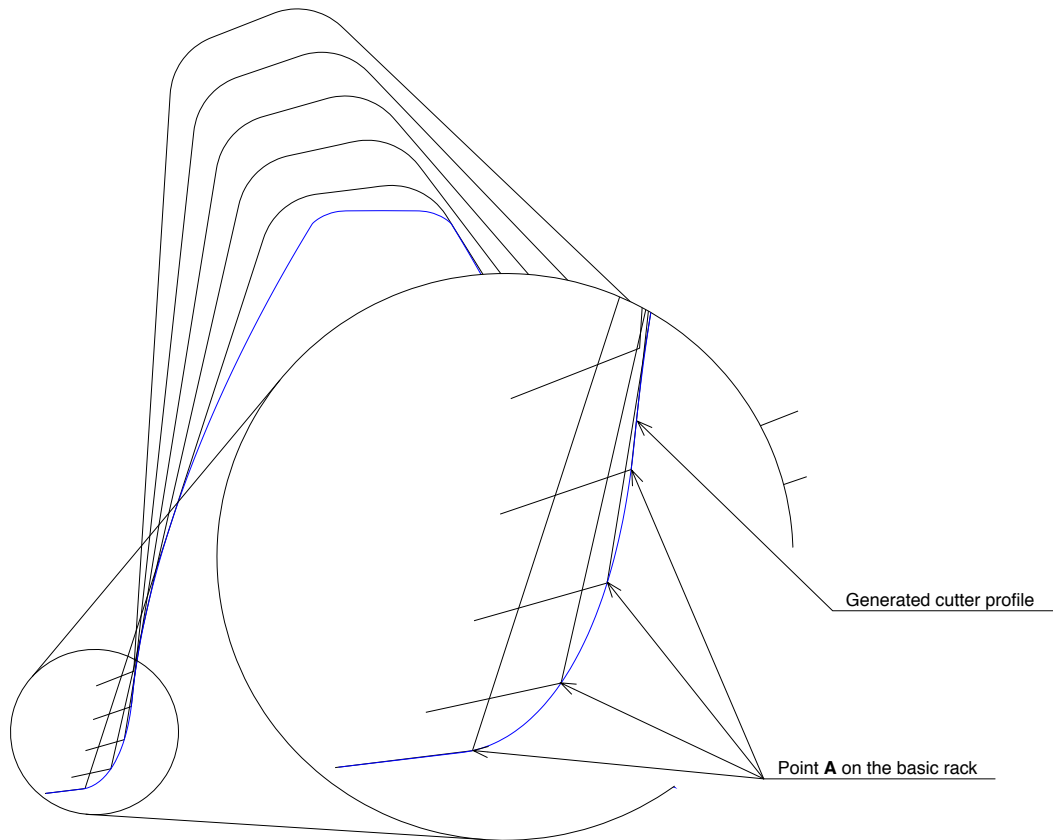
Figure 6.5: Cutter generation with a basic rack

Chapter 7

Real life case studies

7.1 Case study selection rationale

The case study approach applies in-depth thorough examination to a limited set of events called *cases,* rather than using rigid examination algorithms on large sampling sets. Therefore, the problem of choosing the cases that are most beneficial for the research becomes a primary importance. Using a sampling method that relies on the amount of information contained within the case rather than any form of random sampling should produce better result as an average case may be poor on information.

Considering the selected cases as a set, it should satisfy a couple of conditions to be relevant. First, the set should provide a sufficient coverage of the problem area. Referring to the design process description provided in Chapter 4 and the list of the profile modifications in Chapter 2, the following necessary coverage conditions may be defined:

- each design process case should be covered with at least one case study;

- the key profile modifications should be covered.

To keep the number of cases small and reduce the amount of work required for case studies, one more condition should be added for the case set: diversity. The cases should be as different from each other as possible, which in terms of the present research means that if one case covers chamfering modification on design master gear then others should include some other modifications and (or) internal gearing examples.

In light of the mentioned details, three cases were selected. First case is the simplest one with the cutter being directly specified through its parameters. The second case shows the use of the internal design master gear that is used to define a cutter. Finally, the third case encompasses the redesign situation, whereby the design master gear is redefined at a different pressure angle in order to obtain a better geometry of the cutter.

7.2   Cutter only case

The cutter only case is the basic design case whereby the cutter is directly specified by its parameters. The particular gear shaper cutter is designed as 'custom', i.e., not having standard proportions. That allows for a greater control over cutter geometry parameters (standard cutters are restricted to have many of the profile modifications).

The general parameters that define the cutter profile are listed in Table 7.1. This is a small cutter with lots of teeth so the undercut is not likely. It has a round fillet with a radius of 0.5 mm. When cutting a gear the cutter would have 0.5 mm clearance from the bottom of cutter tooth space to the crest of the gear tooth.

The cutter has protuberance profile modification. This means that the cutter produces an artificial undercut on the gear to avoid the sharp step that appears on the gear tooth after finishing. Referring to Table 7.2 the protuberance is offset from

Standard:	Custom
mod:	2.5
No of teeth:	40
Addendum:	3.125mm
Dedendum:	2.5mm
Circular thickness:	3.5mm
Fillet type:	Round
Height of fillet:	0.5mm
Oversize:	1mm
Clearance:	0.5mm
Top rake:	6°
Front rake:	5°
Root rad on rack:	0mm
Life:	15mm

Table 7.1: Cutter profile parameters: General

the main profile by 0.08 mm with a ramp angle of 10°. Note that the protuberance ramp angle is on the extreme side and is chosen only as it provides a better illustration of the protuberance. In reality the protuberance ramp angle values are usually smaller, as this avoids sharp profile changes on the tool.

Another modification applied to the cutter profile is tip rise. It is applied to improve the meshing conditions of the gears cut by this cutter. The choice of the tip rise modification is interesting because both the tip rise and the previously mentioned protuberance modification alter the tip of the cutter tooth. Provided the software works right it should cope with these modifications occurring simultaneously. Referring to Table 7.3, one can see that the tip of the cutter tooth is raised by 0.03 mm, meaning that the protuberance portion of the profile will have a total

Protuberance:	0.08mm
Prot land height:	1mm
Prot ramp angle:	10°

Table 7.2: Cutter profile parameters: Protuberance

Tip rise:	0.03mm
Tip rise type:	Curved
Addendum to start:	0.7mm

Table 7.3: Cutter profile parameters: Tip rise

offset of 0.11 mm. The 'curved' tip rise type means that the tip rise is generated by a portion of the basic rack having a radius on it. Finally, the addendum to start specifies at what height from the pitch line does the tip rise start.

By following the equations obtained in Chapter 5 the profile of the basic rack that is shown in Figure 7.1 can be produced. The tip of the basic rack has radial rise that is followed by the protuberance ramp that is inclined at 10°to the main profile. The protuberance land (the offset portion of the protuberance) joins the radial fillet that has an adjusted position.

Having the basic rack profile calculated, it is possible to obtain the conjugate profile of the cutter. Figure 7.2 illustrates the cutter profile drawn alongside the involute deviation graph at a proper scale. The involute deviation graph shows the tangential deviation from the theoretical ideal involute profile of the cutter tooth. IN this example the cutter tooth has true involute profile only on approximately half of its total height (where the involute deviation graph shows zero deviation). The involute profile is immediately followed by a curved root rise, as is clearly visible from the involute deviation graph. The root rise is continued by the linear protuberance ramp, until the required offset of 0.11 mm is reached. Then follows the protuberance (a top vertical portion of the involute graph) and finally the profile curve enters the
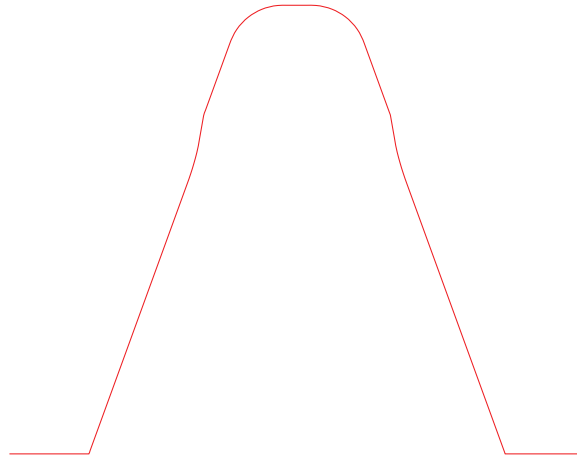
Figure 7.1: Case study 1: Basic rack profile

fillet part. Figure 7.2 shows the cutter profile at its nominal outside diameter, however, the gear shaper cutters are usually manufactured slightly oversized from the nominal dimensions to get a longer tool life. The profile of the cutter tooth changes accordingly to the generating conditions. Referring to Figure 7.3, it may be noted that the cutter tooth profile changes considerably even for the cutters with relatively big number of teeth. The changes are more prominent if the cutter has small number of teeth. For the reader's convenience it is worth to point out that the profile marked **A** shows the cutter when it is new, i.e., oversized. In our case the diametral oversize is 1 mm, as stated in Table 7.1, that results in the radial oversize of 0.5 mm. The profile **B** corresponds to the cutter at its nominal outside diameter, it is the same profile as shown in Figure 7.2. The profile marked **C** show the cutter at the end of its life. Note how the fillet and the tip rise forms have changed.

There is now gear profile drawing as no gear data has been defined. Although it is easy to add a gear to the existing design to see what curve does the cutter cut in the gear blank, the author reserves description of the gear profiles generated by the cutter to a later stage.
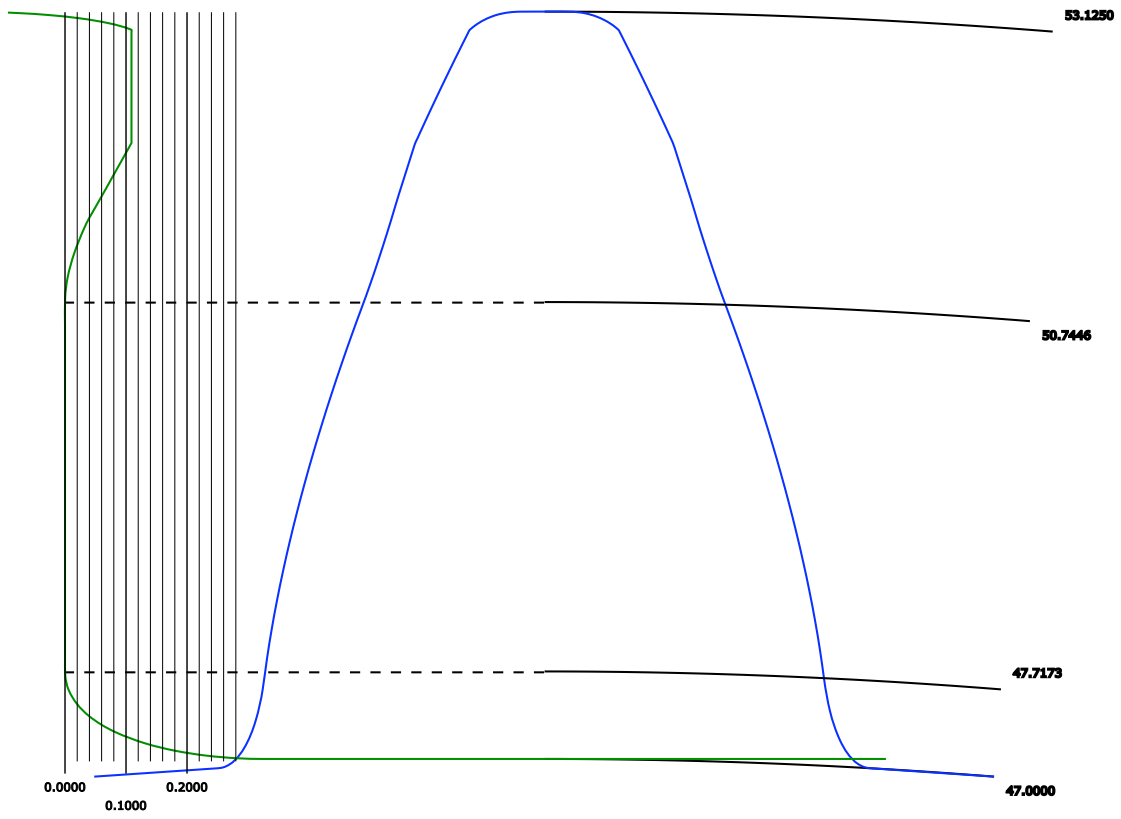
Figure 7.2: Case study 1: Cutter profile
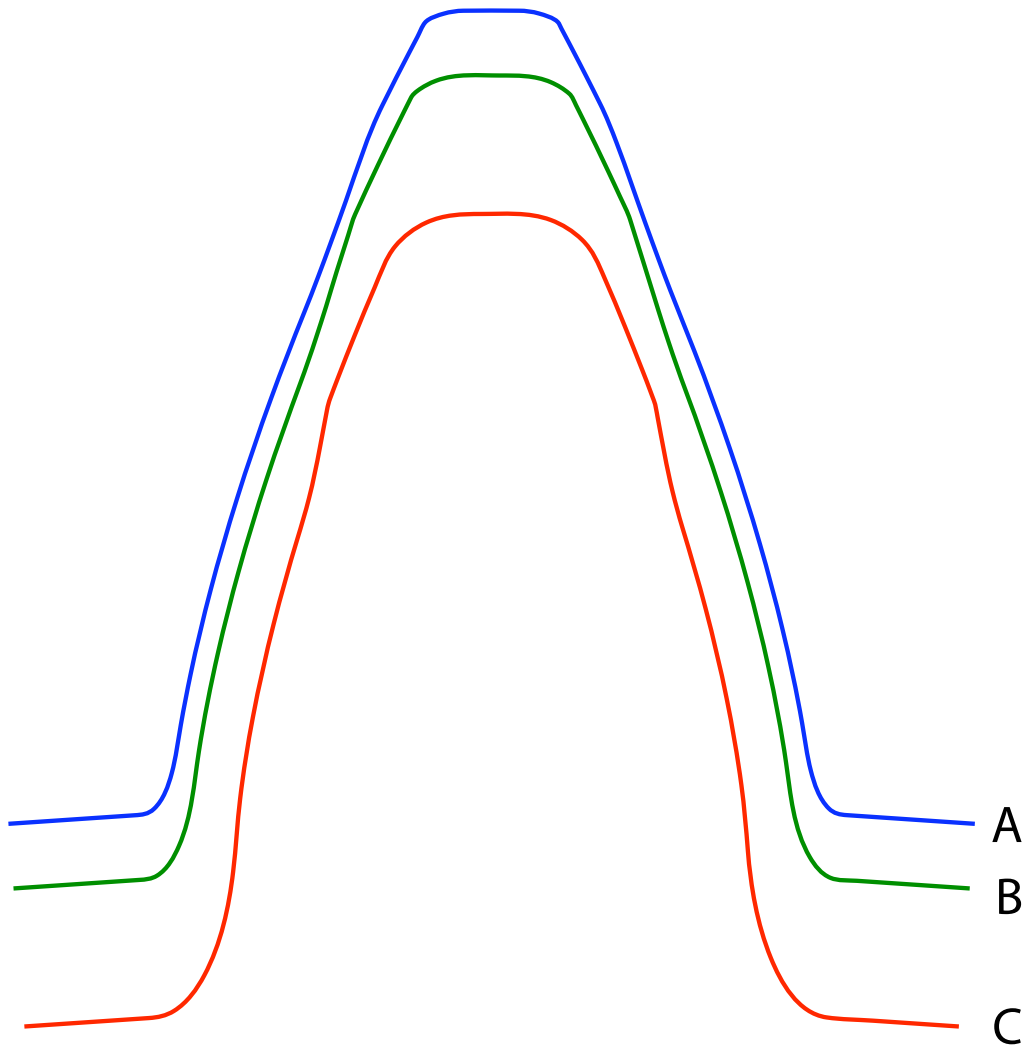
Figure 7.3: Case study 1: Cutter profile at different wear levels

Gear type:	Internal
mod:	2
Pressure angle:	20°
Teeth count:	70
Major dia max:	145.1mm
Major dia min:	145mm
Major dia min:	136mm
Circular thickness:	3.141mm

Table 7.4: Design master gear parameters

7.3   Internal gear and cutter case

Internal gear and cutter case addresses the second gear shaper cutter design process workflow, whereby the parameters of the dimensions of the cutter are defined by means of the design master gear geometry. The input parameters of the design master gear are presented in Table 7.4.

The cutter parameter list is appropriately reduced, because the cutter geometry is defined by the design master gear. Referring to Table 7.5, the parameters for the standard, diametral pitch, addendum, dedendum and circular thickness are not included, and only the parameters that define cutter-specific features like number of teeth in the cutter and the top rake are left.

Having both the design master gear and the cutter parameters in place, it is possible to obtain the profile of the cutter's basic rack as shown in Figure 7.4. The profile of the basic rack has round fillet with no profile modification defined.

Knowledge about the basic rack geometry allows to produce the conjugate cutter profile as described in Section 5.2. The obtained profile of the cutter is presented in Figure 7.5. The same profile could be generated by rolling the basic rack around

No of teeth:	40
Fillet type:	Round
Height of fillet:	0.5mm
Oversize:	1mm
Clearance:	0.5mm
Top rake:	6°
Front rake:	5°
Root rad on rack:	0mm
Life:	15mm

Table 7.5: Cutter profile parameters
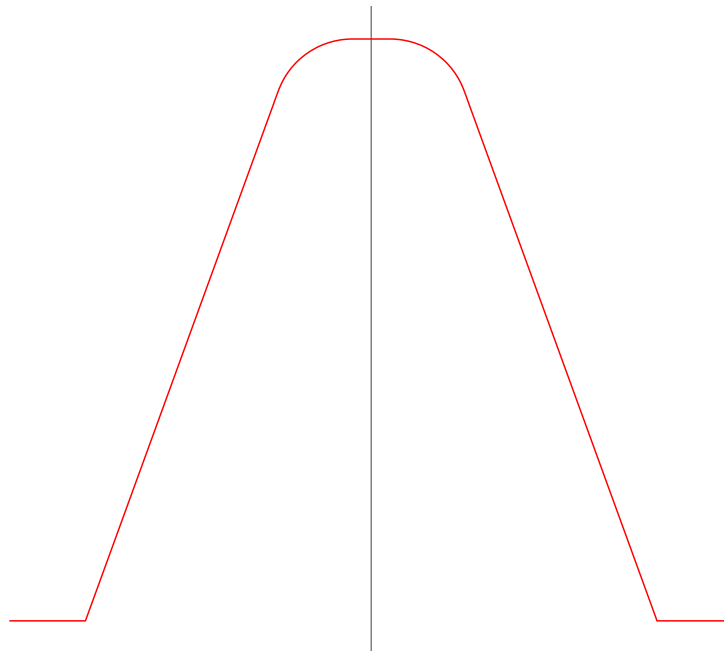
Figure 7.4: Case study 2: The profile of the basic rack of the cutter
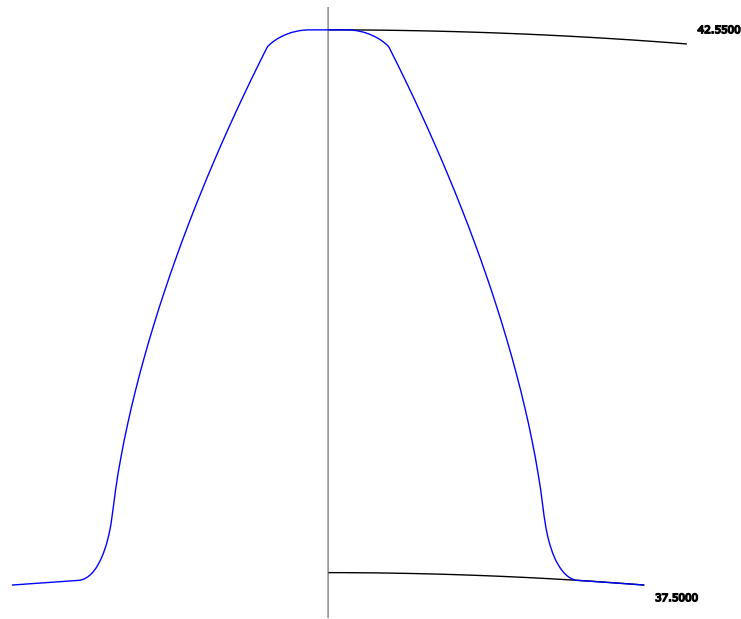
Figure 7.5: Case study 2: The profile of the cutter

the pitch circle of the cutter using a device similar to the one presented in Figure 1.4. Figure 7.6 illustrates the basic rack drawn multiple times in proper relation to produce the cutter profile.

If the coordinates of the cutter profile are known, the gear profile could be obtained by following Section 5.3. Figure 7.7 illustrates the gear profile obtained from the cutter at nominal outside diameter. Note, that the gear has inside diameter of 145.1 mm, which is at the upper boundary of the allowed inside diameter range. As the cutter outside diameter changes, it produces gears with a slightly different profile and different root diameter. Consider Figure 7.8 that shows the gear tooth produced by a new cutter drawn on top of the nominal one. While being identical to the nominal profile in its involute portion, the profile cut by new cutter is different in the fillet and face parts of the tooth. What is even more important, the variations in the cutter outside diameter change the root diameter of the gear.
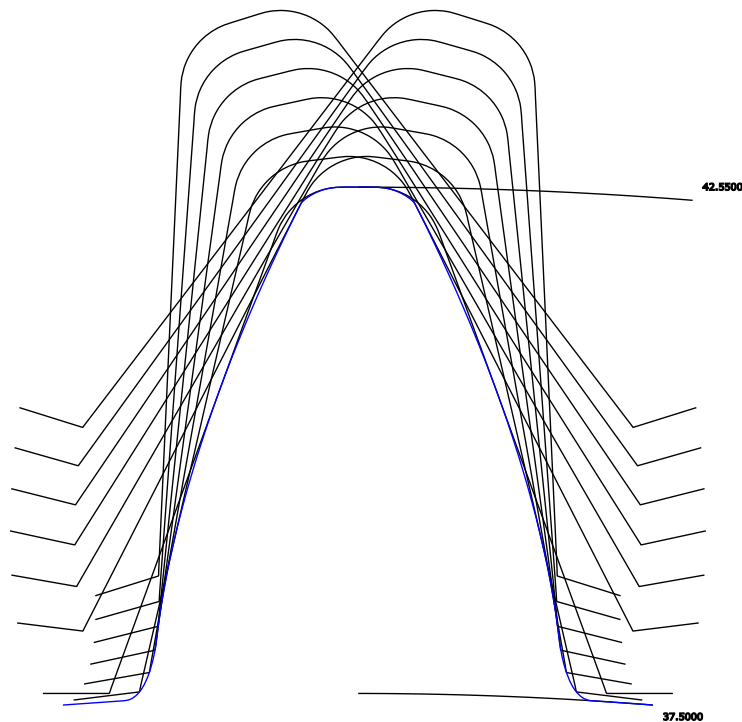
Figure 7.6: Case study 2: Generation of the cutter profile by rolling the basic rack around its pitch circle

7.4 External cutter and gear case with redesign

Previous case studies considered the case of the cutter geometry being directly defined as well as when it is being defined by the design master gear dimensions. The question remained unanswered is how to proceed if the cutter profile defined by the design master gear is unsuitable for manufacturing. From Chapter 4 it follows, that the solution is to use the same gear profile at a different pitch diameter to define the cutter. This is the third design workflow identified in the gear shaper cutter design process.

As in the previous case, the gear shaper cutter geometry is defined by the design master gear, so the gear parameters should be input first. Those are listed in

72.5500

67.5000
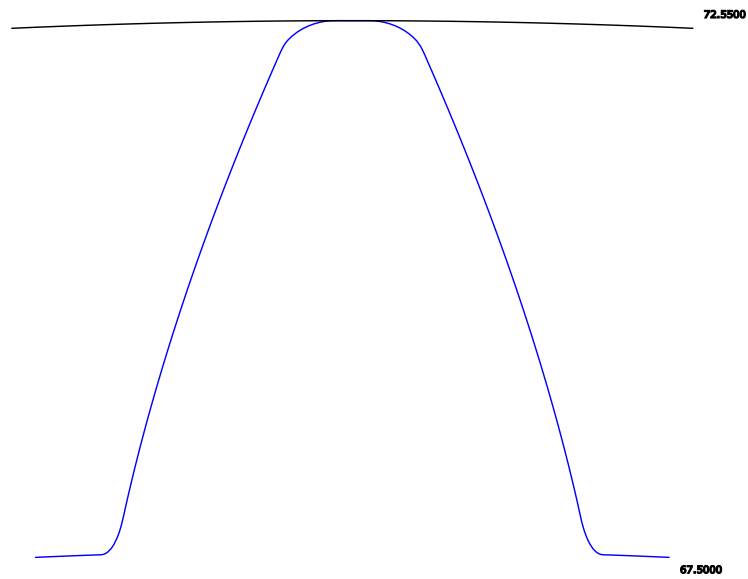
Figure 7.7: Case study 2: Gear profile cut by the cutter at nominal outside diameter

72.5500

Nominal

New

67.5000
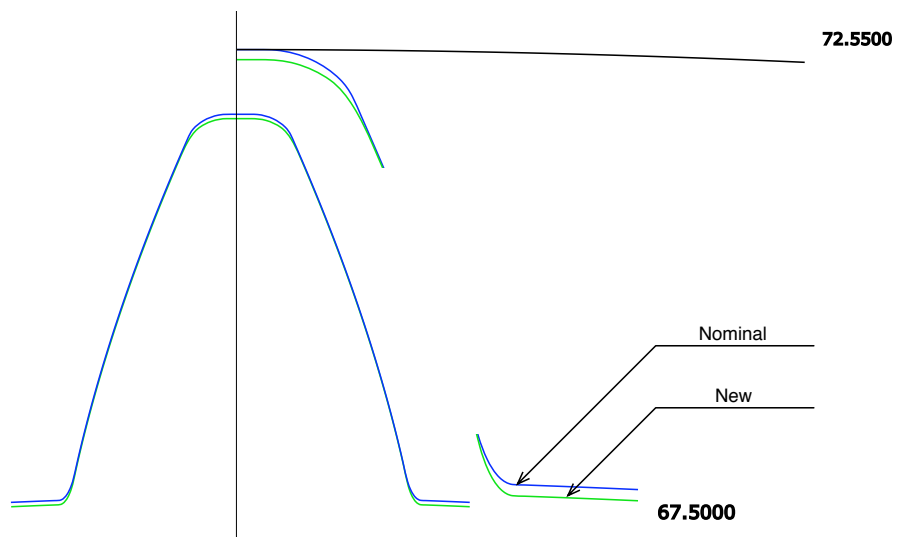
Figure 7.8: Case study 2: Gear profile cut by the cutter at maximal outside diameter

Gear type:	External
mod:	3
Pressure angle:	14.5°
Teeth count:	12
Major dia max:	46mm
Minor dia max:	32mm
Minor dia min:	31.9mm
Circular thickness:	5.6176mm

Table 7.6: Design master gear parameters

Table 7.6. Note that the design master gear is defined at the pressure angle $\psi = 14.5°$.

In the next step, the cutter-specific parameters as shown in Table 7.7 should be input. No profile modifications would be defined initially to avoid confusion.

If one is going to use directly the gear data as defined in Table 7.6, it would result in a cutter shape that is not suitable for manufacturing. The drawing of cutter tooth at different stages of its life is shown in Figure 7.9. As can be seen the cutter tooth is significantly undercut and its shape varies considerably as the cutter becomes old. One way to improve the cutter tooth shape is to use radial root rise modification, which aims to improve the undercut tooth flanks by making them straight radii. As any non-involute curve this modification varies across the life of the cutter. Therefore, the radial root rise modification should be calculated at a definite cutter outside diameter. Figure 7.10 shows the cutter tooth profile with radial root rise modification at nominal outside diameter applied.

Another way to improve the cutter tooth profile is to redefine the design master gear at a different pitch diameter. The redesign operation does not change the gear profile, instead, it changes the conditions of the generating process, and that

No of teeth:	25
Fillet type:	Round
Radius of fillet:	0.4mm
Oversize:	1.25mm
Clearance:	0.5mm
Top rake:	5°
Front rake:	5°
Root rad on rack:	0mm
Life:	12mm

Table 7.7: Cutter profile parameters
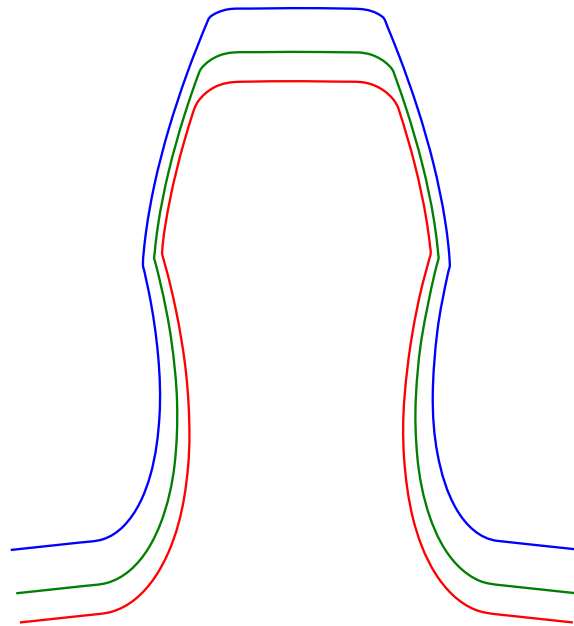
Figure 7.9: Case study 3: Cutter shape obtained from non-redesigned master gear
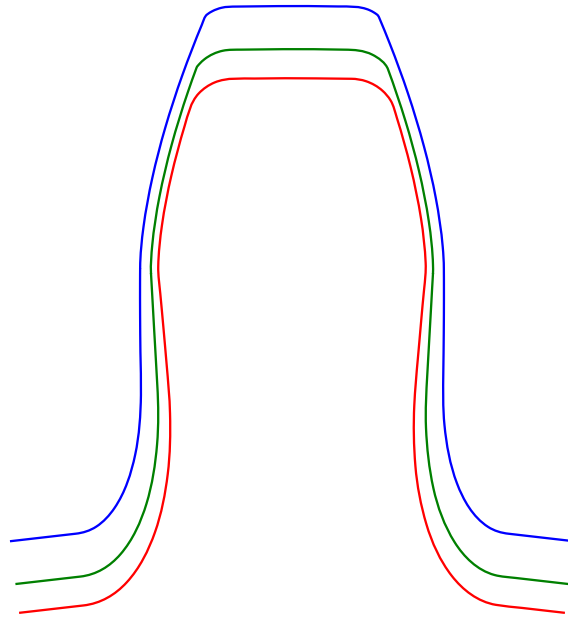
Figure 7.10: Case study 3: Cutter shape obtained from non-redesigned master gear with radial root rise modification

results in a different profile of the cutter. For example, the gear could be redefined at the pressure angle $\psi = 25°$. This results in a completely different profile of the cutter, which is presented in Figure 7.11. This cutter profile is significantly better for manufacturing. The teeth are much stronger and their shape does not change so much over the life span of the tool as with the non-redesigned cutter.

It is interesting to know what is the difference between the gear profiles cut by the redesigned and non-redesigned cutters. Seeing that the redesigned cutter shape is completely different from the non-redesigned one it is natural to expect that the gear profiles cut by those cutters are also very different from the other.

Consider Figure 7.12 that contains a drawing of the gear profile cut by the redesigned cutter superimposed onto the gear profile obtained from the non-redesigned cutter. At the first glance the profiles only have a little difference in the fillet por-
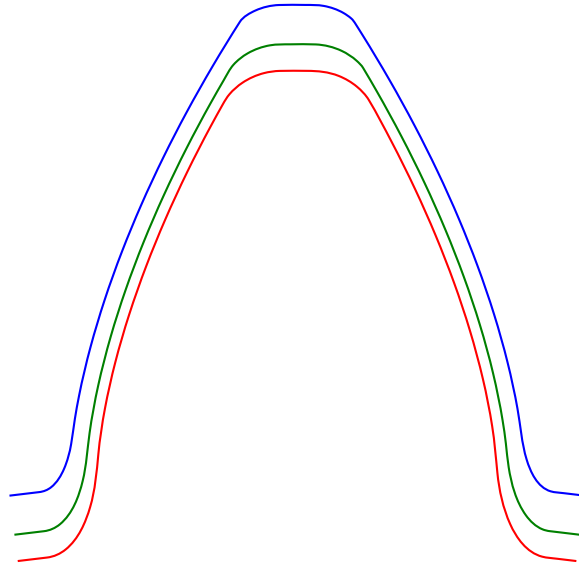
Figure 7.11: Case study 3: Cutter shape obtained from gear redesigned at $\psi = 25°$

tion. In fact, the redesigned cutter cuts true involute all the way up to the outside diameter of the gear, while the non-redesigned cutter stops producing an involute from approximately half of the gear tooth height upwards. The deviation is almost impossible to discern by the naked eye but is clearly visible on the involute deviation graph. Overall, the redesigned cutter cuts a gear with less undercut and more true involute profile on it.

The gear root diameter changes as the re-sharpening operations are carried out on the cutter. The changes in the gear root and chamfer (if the gear has a chamfer profile modification) diameters define the boundaries for the outside diameter of the cutter, and consequently the tool life. Therefore it is necessary to know the variations in the root and chamfer diameters of the gear as the cutter ages. Suppose the gear has a chamfering modification with the parameters defined in Table 7.8. The variations in the gear root and chamfer diameters are illustrated in Figure 7.13.
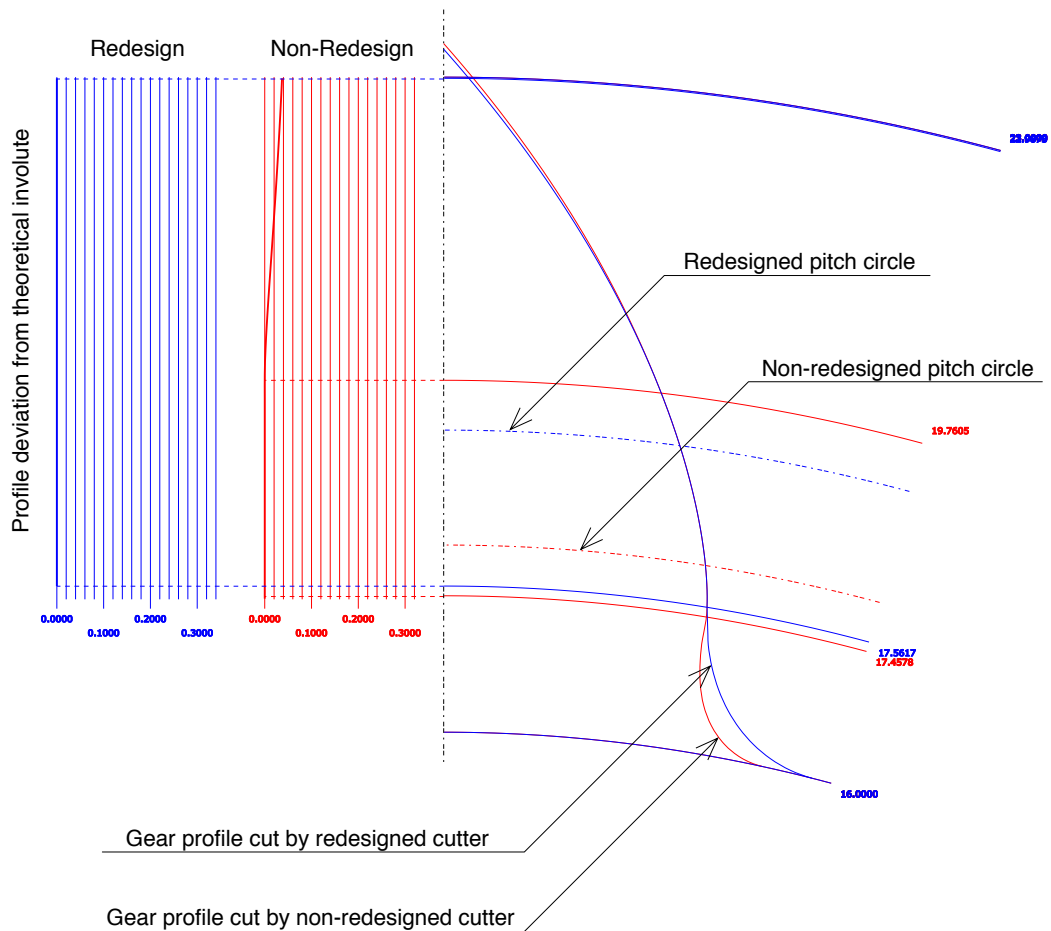
Figure 7.12: Case study 3: Gear profiles cut by non-redesigned and redesigned cutters

The dashed line refers to the gear root diameter while the solid one corresponds to the chamfer diameter of the gear.

Appendix E contains an example of the final drawing for this design. Only the form of the basic rack of the cutter is required to manufacture the cutter. In addition, the information about the tool body, i.e., the part whereby the tool is fastened to the machine is needed.

Chamfer dia max:	44mm
Chamfer dia min:	43mm
Chamfer angle:	50°

Table 7.8: Gear chamfer parameters
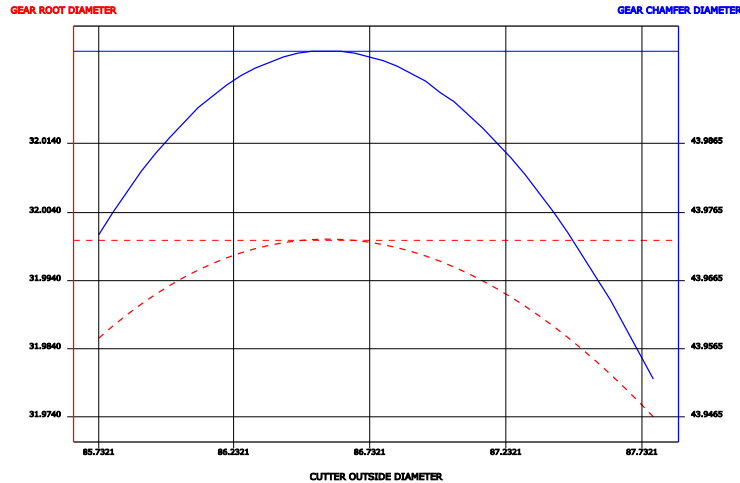
Figure 7.13: Case study 3: Root and chamfer diameter graphs of the gear

7.5   Validation

The profiles of gear shaper cutters from the three case studies were subjected to a two-stage validation process. First, the profiles were compared to the profiles obtained by other means. The profiles from old and new systems were exported to DXF format and compared using AutoCAD software package. Second, the involute graphs from the system were compared to the involute inspection results of real components. It was found that no differences exists between the output of the old system versus the new one except for the undercut area in the 3rd case study without redesign (see Figure 7.9). The difference was attributed to the inability of the old system to deal with extreme undercut cases. And indeed, comparison to

the involute inspection data from real components manufactured using design data found the results from the new system correct.

7.6   Summary

This chapter is devoted to case studies made using the developed CAD software. Three case studies were performed, each of the covers one of the workflows of the gear shaper cutter design process.

A number of profile modifications were presented with the changes in the cutter and where appropriate the gear profile pointed out and accompanied with comments. Special attention was paid to the problem of changes in the profile of the cutter as it is being re-sharpened.

The time required to complete the case studies using the new system was on average 1.6 times lower than using the previous system. It was observed that the system produced results with precision within manufacturing tolerances.

Chapter 8

Discussion and conclusions

This chapter was created to provide the reader with a short summary of all the good and bad that the author thinks about his own work.

8.1 Discussion

With so many papers available on the topic of gear design it came to surprise that the area of gear cutting tools and in particular the design of gear shaper cutters were largely untapped. The quality of the existing gear cutting tools may therefore be attributed to the extensive experience of those who are responsible for the tool design and manufacturing. This thesis is an attempt to make the demanding task of designing a good gear shaper cutter easier.

8.1.1 Contributions

The author sees the gear shaper cutter design process description presented in this work as an important contribution to knowledge. Knowledge about the process provides the foundation for future research, in particular the analytical model presented in Chapter 5 and the CAD software presented in Chapter 6.

The analytical model uses full form generation technique for the purpose of obtaining the conjugate profile. This technique improves the process of the gear shaper cutter design by allowing to add arbitrary profile modifications to the basic rack and produce the conjugate cutter and gear profiles without extending the analytical model for each modification. Consequently, it allows non-involute gear shaper cutters to be designed and verified using the same set of equations. Unfortunately, the full form generation technique produces conjugate profiles that may be crossed over themselves and therefore of a limited use to the gear designer. A successful application of the Shamos-Hoey algorithm [52] allows to produce profiles without crossed sections while still using the full form generation.

The gear shaper cutter design software provides a validation test bed for the analytical and process models of gear shaper cutter design. On a side note, the software is a rare example of a fully web-based cross-platform CAD software, that requires no auxiliary programs on the client computer. Being web-based it is not a proof of concept, but a feature-full system able to solve real life design tasks.

8.1.2   Limitations of the present work

The biggest limitation of this thesis is that the findings presented herein are not applicable to the other gear types except cylindrical gears. The present work deals exclusively with cylindrical gears.Also several profile modifications were not considered, like the elliptical fillet.

The other area that needs attention is the identification of the tasks that are currently being solved manually by the gear shaper cutter designer and trying to automate them. The process of finding the compromise between the parameters of the gear shaper cutter is a multi-objective optimisation problem and it should be possible to solve using multi-objective optimisation techniques. This thesis does not try to solve optimisation problems of the design process.

One more limitation is that the developed CAD software does not have link with the CAM system used to operate the CNC machines.

8.2 Future work

It is the author's sincere hope to provide a guideline for those wanting to further explore the field of the gear cutting tools. A guideline that consists not only of answers, but more so of questions that have yet to be answered. The following is the list of 'yet to be...' written by the author in the course of the present research.

One direction for the future work would be to define the gear shaper cutter design problem as a multi-objective optimisation problem and try to solve it. In theory, it should provide a completely automated way to obtain the profile of the cutter suitable for a CAM system from the input data.

The other area of the research is to define new cutter profile modifications based on the experimental data. Each modification should be accompanied with a guide on how to apply it on the basic rack.

Important issue left outside of the scope of the current research are the trimming problems in the internal gear - cutter pairs. In internal gears the cutter and the gear profile could interfere during backoff and infeed motions of the tool. The gear shaper cutter design software should be able to detect such situations and advice the user on the actions that should be taken to prevent interference. Consequently, there analytical model should be extended with equations of internal gear profile interference with a cutter.

8.3   Conclusions

This thesis is considered by the author as a successful attempt to study and document the gear shaper cutter design process. It provides a base for future research in describing the scope and the nature of the design process and providing the tools to aid the gear designer and researcher in constructing the conjugate profiles of the basic rack, cutter and gear.

The tools allow to visualise any given profile modification and see what the cutter with this modification cuts in the gear blank.

The thesis contributes to the knowledge with the description and the process model of the gear shaper cutter design process. Another contributions is the full form generation technique used in conjunction with the algorithm presented in [52] to obtain a correct conjugate profile.

The software developed in the course of this project is a rare example of a CAD system with web-based interface. The system provides scalable drawings and interacts with the user in real time through the browser.

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Appendix A

Interview questions

Interview questions:

Could you describe your typical workflow?

What are the special cases that should be considered?

How is the cutter geometry specified?

How is the gear geometry specified?

What modifications are used for the cutter profile?

How are these modifications specified?

How the results of the design process look like?

How the results should be measured?

Who will be the user of the system?

What functions must the system perform?

What requirements does the function X impose on the system?

What does this requirements mean to you as a cutter designer?

Could this requirement to be reformulated to be more specific?

Will some of the users be dedicated/casual users?

Should access control be implemented?

Are there any standards on inputs/data processing/outputs?

Are there any identified/expected constraints?

Are there any other questions that I should ask you?

Appendix B

Gear shaper cutter design process inputs

INPUTS – CUTTER DETAILS ONLY

COMMON AND SPUR	HELICAL VARIATIONS / ADDITIONS
DP/MOD/CP	NDP/CDP,N MOD/C MOD,NCP/CCP
PA	NPA/CPA
BIAS PA / INVOLUTE DEVIATION AT TIP	BIAS NPA/CPA
	HELIX ANGLE
ADDENDUM	
DEDENDUM	
CIRC TOOTH THICKNESS	NORM / TRANS CIRC TH
HEIGHT OF FILLET / RADIUS OF FILLET / ELIPTICAL FILLET HT & WIDTH	HEIGHT OF FILLET / TRANSVERSE RAD OF FILLET / ELIPTICAL HT & WIDTH TRANS & NORM
OVERSIZE	
CLEARANCE	
TOP RAKE	NORMAL TO RAKE / TRANSVERSE TOP RAKE
FRONT RAKE	
	SHARPENING ANGLE
	HAND
ROOT RAD ON RACK	TRANSVERSE ROOT RAD ON RACK
LIFE (for graphics)	
Optional if chamfering	
CHAMFER DEDENDUM	
CHAMFER PA	TRANS CHAM PA / NORMAL CHAM PA
Optional if protuberance	
PROTUBERANCE	NORMAL PROT / TRANS PROT
PROT LAND HEIGHT	
PROT RAMP HEIGHT / PROT RAMP ANGLE	
Selectable options for root rise – selection box title ROOT RISE / RELIEF LINEAR / CURVED	
If linear or curved tip rise / relief then inputs required of:-	
TIP RISE	TRANS / NORMAL TIP RISE
ADDENDUM TO TIP RISE START	
Selectable options for tip rise – selection box title TIP RISE / RELIEF LINEAR / CURVED / RADIAL / BS 436	
If linear or curved root rise / relief then inputs required of:-	
ROOT RISE	TRANS/NORMAL ROOT RISE
DEDENDUM TO ROOT RISE START	
If radial root rise input of:-	
OVERSIZE AT RADIAL PLANE	
If false topped	
FALSE TOP RAKE	
TIP CHAMFER / TIP RADIUS	
If for taper cutting	
TAPER ANGLE	

WHERE THERE ARE TWO OR MORE INPUTS IN ONE BOX THEY ARE OPTIONAL QUESTIONS TO GET TO THE SAME ANSWER EG PROT RAMP HEIGHT / PROT RAMP ANGLE. ONLY ONE OF THE OPTIONS IS REQUIRED TO BE ANSWERED

INPUTS – STANDARD CUTTER

COMMON AND SPUR	HELICAL VARIATIONS / ADDITIONS
DP/MOD/CP	NDP/CDP,N MOD/C MOD,NCP/CCP (6 options!)
PA	NPA/CPA
NO OF TEETH	
	HELIX ANGLE
OVERSIZE	
CLEARANCE	
TOP RAKE	NORMAL TO RAKE / TRANSVERSE TOP RAKE
FRONT RAKE	
	SHARPENING ANGLE
	HAND
ROOT RAD ON RACK	TRANSVERSE ROOT RAD ON RACK
LIFE (for graphics)	

Selectable options for root rise – selection box title ROOT RISE

NONE	
B.S. 436	
RADIAL	

If radial is selected in the root rise option then an input is required of:-

OVERSIZE AT RADIAL PLANE	

For standards there are no other options – any other modification to profile makes a tool non standard and the custom option should be used.

THE FRONT RAKE FOR STANDARD CUTTERS IS 5 deg WITH ONE EXCEPTION FOR STANDARD DOUBLE HELICAL CUTTERS WHICH HAVE 0 deg

NOTE AS YET I HAVE ONLY DEFINED THE SPUR STANDARDS - A MUCH REDUCED LIST IS NEEDED FOER HELICALS.

SOME OF THE SPUR STANDARDS IN THE LIST ARE A SET PA. SO DO NOT REQIURE THE PA INPUT. THE STANDARDS DOCUMENT/LIST HAS THE PA IN THE NAME OF THE STANDARD IF THIS IS SO EXCEPT DIN 5480 AND BS.3550 WHICH ARE ALWAYS 30 PA.

INPUTS – GEAR & CUTTER DETAILS

COMMON AND SPUR	HELICAL VARIATIONS / ADDITIONS
GEAR DETAILS	
INTERNAL OR EXTERNAL	
DP/MOD/CP	NDP/CDP,N MOD/C MOD,NCP/CCP
PA	NPA/CPA
BIAS PA / INVOLUTE DEVIATION AT TIP	BIAS NPA/CPA
	HELIX ANGLE
NO OF TEETH	
MAJOR DIA MAX	
MAJOR DIA MIN (option for external)	
MINOR DIA MAX (option for internal)	
MINOR DIA MIN	
REQUIRED S.A.P. (option)	
REQUIRED T.I.F. (option)	
SHAPED CIRC TOOTH THICKNESS/DIMENSION OVER/UNDER BALLS/SPAN DIMENSION	NORM / TRANS CIRC TH
Optional if pre-finishing	
FINISHED CIRC TOOTH THICKNESS/DIMENSION OVER/UNDER BALLS/SPAN DIMENSION	NORM / TRANS CIRC TH
Optional if chamfering	
CHAMFER DIA MAX	
CHAMFER DIA MIN	
CHAMFER ANGLE	TRANS CHAM ANG / NORMAL CHAM ANG
Selectable options for tip relief – selection box title TIP RELIEF / RISE LINEAR / CURVED	
TIP RELIEF	TRANS / NORMAL TIP RELIEF
DIA /ROLL ANG /ROLL LENGTH /ADDENDUM AT RELIEF START	
Selectable options for root relief – selection box title ROOT RELIEF / RISE LINEAR / CURVED	
ROOT RISE	TRANS/NORMAL ROOT RISE
DIA /ROLL ANG /ROLL LENGTH /DEDENDUM AT RISE START	
If taper gear	
TAPER ANGLE/SIDE RAKE ON PART	

COMMON AND SPUR	HELICAL VARIATIONS / ADDITIONS
CUTTER DETAILS	
NO OF TEETH	
HEIGHT OF FILLET / RADIUS OF FILLET / ELIPTICAL FILLET HT & WIDTH	HEIGHT OF FILLET / TRANSVERSE RAD OF FILLET / ELIPTICAL HT & WIDTH TRANS & NORM
OVERSIZE	
CLEARANCE	
TOP RAKE	NORMAL TO RAKE / TRANSVERSE TOP RAKE
FRONT RAKE	
	SHARPENING ANGLE
	HAND (options of right/left or both)
ROOT RAD ON RACK	TRANSVERSE ROOT RAD ON RACK
LIFE (for graphics)	
Optional if protuberance	
PROTUBERANCE	NORMAL PROT / TRANS PROT
PROT LAND HEIGHT	
PROT RAMP HEIGHT / PROT RAMP ANGLE	
Selectable option of radial root rise on cutter - only if no tip relief is selected in gear section (this is used to suppress undercut on the tool only. Tool is not required to produce modification on part even if it does have to.)	
OVERSIZE AT RADIAL RISE	
If false topped	
TIP CHAMFER / TIP RADIUS	

DESIGN DETAILS	
TYPE OF DESIGN	
If redesign	
REDESIGN PA / REDESIGN PCD	REDESIGN NPA/CPA
If th/add redesign	
CUTTER THICKNESS / ADDENDUM	
If not auto root dia optimisation	
DESIGN ROOT DIAMETER	
If not auto chamfer dia optimisation	
DESIGN CHAMFER DIAMETER	

Appendix C

Software interface prototype

Involute Tool Design

Measurement Units: ○ Inches   ○ Millimetres

File   Utilities   CNC   Output   Options   Users   Current User   ● Log out

Cutter   Gear   Mfg.   Body   Output Design   Editing: **105/48/1**   Design Type: Spur

⚠ Design master gear present!

A

B

Standard: [BS.436 ⇕]

DP: ⇕ [   ]

Pressure Angle: [   ]

appears only for custom tools

Bias PA: ⇕ [   ]

Number of Teeth: [   ]

Top Rake: [   ]

Clearance: [   ]

Oversize: [   ]

Rack Root Radius: [   ]

Life for Graphs: [   ]

Helix Angle: [   ]

Appear only for helical tools

Sharpening Angle: [   ]

Hand: [Right ⇕]

Addendum: [   ]

Dedendum: [   ]

Circular Tooth TH: [   ]

Height of Fillet: ⇕ [   ]

Front Rake: [   ]

appear only for custom tools

[Chamfering ▾]

Ch. Dedendum: [   ]

Ch. PA: [   ]

[Protuberance ▾]

Protuberance: [   ]

Pr. Land Height: [   ]

Pr. Ramp Height: ⇕ [   ]

[Tip Rise] ▾   ▲

Magnitude: [   ]

Addendum to Start: [   ]

Tip Rise: [Radial ⇕]

[Root Rise:]   ▾

Magnitude: [   ]

Dedendum to Start: [   ]

Root Rise: [Radial ⇕]

Ovrsz at Rad. Rise: [   ]

[False Top] ▾

False Top Rake: [   ]

Tip Chamfer: ⇕ [   ]

[Taper Cutting ▾]

Taper Angle: [   ]

Cutter Details

Click for Details

Click for Details

C

Finished O.D.: [0]
Theo O.D.: [0]
Pitch circle dia: [0]
Base circle dia: [0]
Addendum: [0]
Dedendum: [0]
Finished span over teeth: [0]
Finished circ tooth th: [0]
Theo span over teeth: [0]
Theo circ tooth th: [0]
Side relief angle at pcd: [0]
Side relief angle at bcd: [0]
Cutter point th: [0]
Rack land th: [0]
Ht of max fillet: [0]
Ht of min fillet: [0]
Rad of fillet: [0]
Ht of fillet: [0]

more
Correction factor: [0]
Corrected PA: [0]
Former PA: [0]
PA at fin OD: [0]
Theo chordal ht: [0]
Theo chordal th: [0]
Fin chordal ht: [0]
Fin chordal th: [0]
Former Tip Th: [0]

D

GEAR ROOT DIAMETER

31.9906

31.9806

31.9706

31.9606

85.2092   85.7092   86.2092   86.7092

CUTTER OUTSIDE DIAMETER

Click for Det

Involute Tool Design

Measurement Units: ⦿ Inches ◯ Millimetres

[BACK]   [Open in Ext. Editor]   [Note]   [PRINT]

A

☐ Rack   ◯ Tooth   ☐ Involute Sideframe   ☐ Center Line   ☑ Required T.I.F.
Gear ⇕
☑ Cutter   ⦿ Space   ☑ Textual Sideframe   ☑ Pitch Circle   ☑ Actual T.I.F.
☑ Gear   ☑ Curve Breaks   ☑ S.A.P.   ☑ Finishing

B

Outside diameter: 86.573832884461
[Zoom in] [Free Radius] [Radius from center]

Involute Ordinate Units [Diameter ⇕]   Involute Abscissa Scale: [1:500 ⇕]

Zoom tool
+ scale display

Diameter
Roll angle
Length of roll

Measurement tools
================
Distance
Diameter
Radius from point

Choice of either 1, 2 or 3 graphs

The amount of deviation at the end of the involute profile
the diameter where the deviation starts (ref 1123)

43.2869

43.1242

36.9408

0.0000
0.1000   0.2000
0.3000

35.7869

D

Involute Tool Design

Measurement Units: ○ Inches ○ Millimetres

File   Utilities   CNC   Output   Options   Users   *Current User*   ● Log out

Cutter   **Gear**   Mfg.   Body   **Output Design**   Editing: **105/48/1**   Design Type: | Spur

A

Gear Design: | Gear1 ⬦ | [ADD] [RENAME] [DELETE] ☑ Design Master Gear

---

B

○ External   ○ Internal

DP: ⬦ [   ]

Appear only for master
Pressure Angle: [   ]
design gear

Bias PA: ⬦ [   ]

Number of Teeth: [   ]

Major Dia Max: [   ]

Minor Dia Min: [   ]

Major/Minor Dia
Min/Max: [   ]

Major/Minor Dia Min/Max   *Internal*

Diameter: [   ]

Sh. Circ. Tooth Th.: ⬦ [   ]

———— Options ▾

Required T.I.F. (dia): ⬦ [   ]

Required S.A.P
(dia): ⬦ [   ]

———— Pre-finishing ▾

Fin. Circ. Tooth Th.: ⬦ [   ]

———— Chamfering ▾

Ch. Dia. Max: [   ]

Ch. Dia. Min: [   ]

Ch. Angle [   ]

———— Tip Relief ▾   ▴

Magnitude: [   ]

Diameter: ⬦ [   ]

———— Root Relief ▾

Magnitude: [   ]

Diameter: ⬦ [   ]

———— Taper Cutting ▾

Taper Angle: ⬦ [   ]

Gear Details

23.0000

17.8130

16.0000

GEAR ROOT DIAMETER

31.9906

31.9806

31.9706

31.9606

85.2092   85.7092   86.2092   86.7092   87.2092   87.7092

CUTTER OUTSIDE DIAMETER

D

Involute Tool Design

Measurement Units: ● Inches   ○ Millimetres

| File | Utilities | CNC | Output | | Options | Users | | *Current User* | ● Log out |

Editing: **105/48/1**   Design Type: [Spur ▼]

| Cutter | Gear | **Mfg.** | Body | Output Design |

Cutter: [Cutter1 ▼]   (ADD)   (RENAME)   (DELETE)   ● Gearshaper / Hob / Rack   ○ Milling

Cutter Details

Base Pitch Cutter: [0.2951]   Ideal Clearance: [0.025]   Actual Clearance: [0.025]

Reference	Base Pitch	Clearance for Th	...
Text Field	Text Field	Text Field	Text Field
103/10	Identical	0.0321	Text Field
Text Field	Text Field	Text Field	Hob/shaper/rack; form modifications
Text Field	Text Field	Text Field	Text Field
Text Field	Text Field	Text Field	Text Field
Text Field	Text Field	Text Field	Text Field
Text Field	Text Field	Text Field	Text Field

Depth: [0.5]

☑ Draw with finished profile

Appendix D

Software requirements specification

Software Requirements Specification

for

CAD "Dathan"

Version 1.2

Prepared by Eugene Butan

11-Dec-06

Table of Contents

Revision History

Name	Date	Reason For Changes	Version
Initial	22-Nov-06		1.0
RC-1	01-Dec-06	Additional user classes, CNC iface, nonfunctional requirements	1.1
Release-1	11-Dec-06	Small fixes	1.2

1. Introduction

1.1 Purpose

This document defines Software Requirements Specification for CAD "Dathan", version 1.0. The focus of the document is on involute spur and helical gear cutter design modules.

1.2 Intended Audience and Reading Suggestions

This document is intended for all project members.

1.3 Project Scope

The aim of the project is to develop software to automate gear cutter design process. The software should be able to handle more than 90% usage patterns, reducing time required to design a cutter compared to the current system. Additional goals include greater design precision and better integration with modern CAD packages. The software will enable the company to deal with multiple low-volume orders efficiently and quickly.

1.4 References

*[IFPROTO]   CAD "Dathan" Interface Prototype   file://CEP CADCAM Interface Prototype_v1.pdf*
[DTCCPA]   DATHAN CADCAM PROJECT   file://DATHAN CADCAM PROJECT.doc

2. Overall Description

2.1 Product Perspective

The product is intended as a replacement for existing HP-based CAD system. The software will be a major part of integrated gear cutter design system, dealing with spur and helical gear cutter designs.

Consider the following diagram:
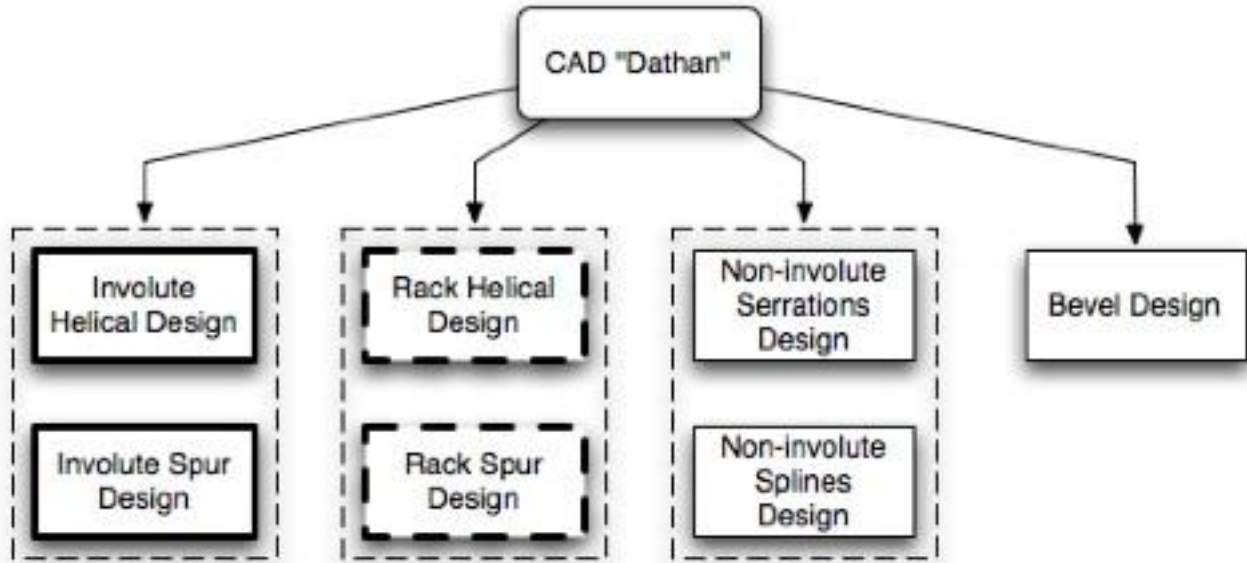
 *Solid elements in **bold** "——" indicate mandatory components, dashed elements in **bold** "---"
indicate optional components.*

2.2 Product Features

The software should provide the following major features:
- *Design of involute spur gear cutter*
- *Design of involute helical gear cutter*
- *Switchable imprerial or metric output*
- *Formula input into fields*
- *Export to DXF format*

2.3 User Classes and Characteristics

Two different classes of user to be supported:
- *Primary Users with full access to all facilities;*
- *Secondary Users (Customers) to access only information relevant to their account with no
  modification to tool design information. These users must be able to add additional gear
  information to check what an existing tool will cut – printable output but not saved data.*

2.4 Operating Environment

*The system will operate on a dedicated server running Ubuntu GNU/Linux operating system. The
server will utilize IA32 or AMD64 architecture. A user should have modern web browser application
installed on his workstation.*

2.5 Design and Implementation Constraints

A single P4 3Ghz 512 MB RAM server should be sufficient for serving 5 users. The interface should feature real-time response to user actions.
The software should be implemented using the Python language and TurboGears framework. PostgreSQL will be used as a database backend. Secure communications between server and client will rely on SSL encryption.
Currently the maintenance of the delivered software is the responsibility of the customer.

2.6 User Documentation

The delivered software should feature interactive context-sensitive help system. Built-in help is supplemented with user manual in PDF format.
Full development documentation should be provided as well.

2.7 Assumptions and Dependencies

A PDF reader program such as Adobe Acrobat Reader should be installed on a user's computer in order to view and print output files.
The system uses external DXF editor to support custom modifications of design files.

3. System Features

3.1 Involute Helical Design

3.1.1 Description and Priority

A set of tools integrated under a single interface that allows to specify, calculate and simulate involute helical gear shaper cutter. This feature is of high priority.

3.1.2 Stimulus/Response Sequences

A user is starting a new design or loading an existing one with the type "Helical"

3.1.3 Functional Requirements

Refer to the [DTCCPA] for a list of software capabilities associated with this feature.

IHD-1:
IHD-2:
IHD-3:

3.2 Involute Spur Design

3.1.1 Description and Priority

A set of tools integrated under a single interface that allows to specify, calculate and simulate involute spur gear shaper cutter. This feature is of high priority.

3.1.2 Stimulus/Response Sequences

A user is starting a new design or loading an existing one with the type "Spur"

3.1.3   Functional Requirements

Refer to the [DTCCPA] for a list of software capabilities associated with this feature.

ISD-1:
ISD-2:
ISD-3:

3.3 Formula input into fields

3.1.1   Description and Priority

The system should allow input of simple mathematical formulas into all input fields. It should be able to recognize imperial and metric units in formulas. This feature is of high priority.

3.1.2   Stimulus/Response Sequences

User inputs a formula in the input field. The system calculates the formula and takes result as the input value.

3.1.3   Functional Requirements

Refer to the [DTCCPA] for a list of software capabilities associated with this feature.

FOR-1:
FOR-2:
FOR-3:

3.4 DXF export

3.1.1   Description and Priority

Ability to export design files in DXF format. This feature is of high priority.

3.1.2   Stimulus/Response Sequences

User presses "Edit in External Editor" button. System displays dialog box prompting to save DXF file.

3.1.3   Functional Requirements

Refer to the [DTCCPA] for a list of software capabilities associated with this feature.

DXF-1: Compatibility with SolidWorks; Unigraphics; CATIA; Autocad.
DXF-2:
DXF-3:

3.5 Rack Helical Design

3.1.1   Description and Priority

A set of tools integrated under a single interface that allows to specify, calculate and simulate helical rack cutter. This feature is of low priority.

3.1.2   Stimulus/Response Sequences

A user is starting a new design or loading an existing one with the type "Helical Rack"

3.1.3   Functional Requirements

Refer to the [DTCCPA] for a list of software capabilities associated with this feature.

RHD-1:
RHD-2:
RHD-3:

3.6 Rack Spur Design

3.1.1   Description and Priority

A set of tools integrated under a single interface that allows to specify, calculate and simulate spur rack cutter. This feature is of low priority.

3.1.2   Stimulus/Response Sequences

A user is starting a new design or loading an existing one with the type "Spur Rack"

3.1.3   Functional Requirements

Refer to the [DTCCPA] for a list of software capabilities associated with this feature.

RSD-1:
RSD-2:
RSD-3:

4. External Interface Requirements

4.1 User Interfaces

The system should use CSS based GUI and rely on standard HTML interface components wherever possible. See [IFPROTO] for details on the user interface.

4.2 Hardware Interfaces

The system relies on abilities of users' computers to print DXF and PDF documents. No additional modifications to the system to accommodate for new output devices should be necessary.

4.3 Software Interfaces

A possibility of connection with existing order management system JobShop should be explored. Hooks for interfacing with CNC routines must be present. (Data format and communication protocol to be defined)

4.4 Communications Interfaces

The server will communicate with clients using HTTP protocol with optional SSL encryption. The system should not exhibit any noticeable communication latency on a standard 100 Base-T Ethernet network.

5. Other Nonfunctional Requirements

5.1 Performance Requirements

- A delivered system – to specification - in line with the original Project Charter completion dates.
- Costs in line with original budget.

5.2 Safety Requirements

- System must error trap / foolproof / highlight any out of range inputs.
- System must error trap / foolproof / highlight any out of range outputs. (Ranges to be agreed)

5.3 Security Requirements

- Unauthorized remote access to any systems must be prevented.
- The system must be able to guarantee no loss of data in the event of hardware failures.
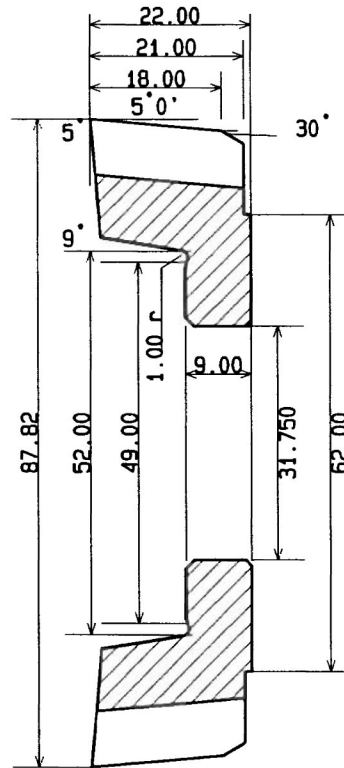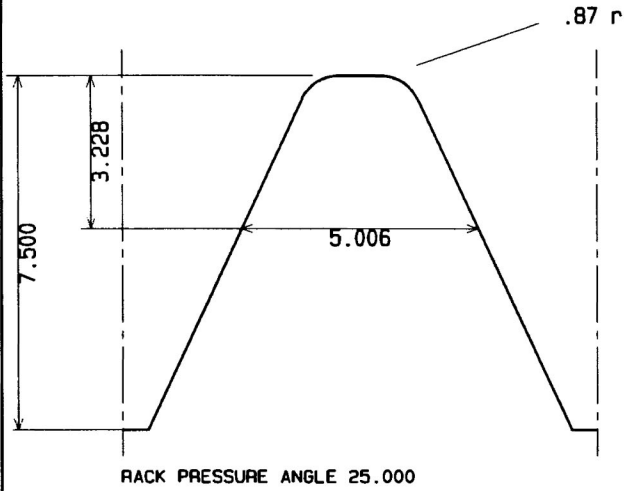- System security must conform to best practices

5.4 Software Quality Attributes

- 24 hour maximum downtime during typical operation
- Less than 6 critical errors within last 6 weeks
- The system must have documentation sufficient to allow future modifications and issue resolution to take place at Dathan.

Appendix E

Final drawing

**BASIC RACK
OF CUTTER TOOTH
IN CUTTING PLANE**

.87 r

3.228

7.500

5.006

RACK PRESSURE ANGLE 25.000

22.00
21.00
18.00
5°0'
5°
30°
9°
1.00 r
9.00
87.82
52.00
49.00
31.750
62.00
31.750

TOOL DESIGN DETAILS

PRESSURE ANGLE	25.0000	MODULE	0.0000
No OF TEETH	25	PITCH DIAMETER	80.117
BASE CIRCLE DIAMETER	72.511	CIRC TOOTH TH AT NOM DIAMETER	5.006
MINIMUM DEPTH	7.333	CUTTING DEPTH	7.000
CIRCULAR PITCH	10.0679	SIDE RELIEF ANGLE	2.3542
PROTUBERANCE	0.000	TIP RADIUS	
NOMINAL OUTSIDE DIAMETER	86.574	SPAN OVER 5 T AT NOM DIAMETER	43.212

EXTERNAL PART DETAILS

MAJOR DIAMETER	46.000	MINOR DIA MAX / MIN	32.000 / 31.900
MODULE	3.0000	No OF TEETH	12
CIRC TOOTH TH	5.6176	PRESSURE ANGLE	14.5000

DESCRIPTION OF TOOL   GRADE

DISC TYPE SPUR GEAR SHAPER CUTTER
3 MOD   14.5

COMPT No.		REF. 0/0/
CUSTOMER TOOL No.		
CUSTOMER		

ROCKWELL C		MAT'L	
DRAWN	RAM/ 0	DATE	29 APR 2008

ALL DIMENSIONS IN MILLIMETRES