

Information Modeling in Mechanical Design: With Application to Cam Mechanism Design


by

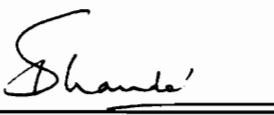
Steven B. Shooter

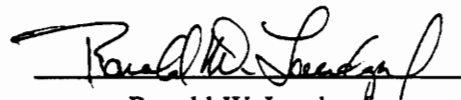
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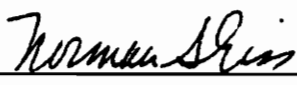
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Steven B. Shooter

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Department of Mechanical Engineering

(ABSTRACT)

Good engineering practice requires designers to incorporate knowledge, processes and skills to produce a superior product. Each stage of the product realization process requires that the designer utilize available resources to make sound engineering decisions in a timely manner. Much of the research on engineering design has focused on formulating general models for the design process. However, it has been shown that these models are rarely used by engineers in practice.

This dissertation advances the concept that useful design models must include methodologies that are particular to a given field or type of design. The inclusion of these knowledge-domain-dependent methodologies provides a complete framework for the greatest utility to the designer.

This dissertation describes a general approach to engineering design and proposes a model for developing design assistance tools useful to the practicing designer. The methodology and the model are applied to the domain of cam mechanism design. The model describes the conceptual design process that begins with formulating objectives and establishing specifications and concludes with the actual synthesis of the cam profile. The design model is then incorporated into a comprehensive modular computer tool that is integrated with a PC-based CAD package.

This dissertation contributes to both the field of engineering design and cam mechanism design. It provides a design model that incorporates a detailed methodology with information and analytical tools for design. By focusing on the knowledge domain of cam mechanism design it contributes to this field as well. Most prior research focused on techniques for synthesizing the cam profile and provided little assistance for the earlier stages of design. No previous tools have been developed that provide the scope of assistance presented in this dissertation.

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Of course, I cannot forget to thank my wife, Catherine. Her support has never relented throughout the many trials and tribulations. She has picked me up when I have stumbled and carried the light when the end of the tunnel was not in sight. The attainment of this degree is as much a testament to her support as to my own efforts.

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Chapter 1

Introduction

National public attention has recently been directed toward global competitiveness of U.S. companies. One response has been a marked increase in research in design methodology across the country. This dissertation will describe the author's contribution to the fields of design methodology and kinematics through the development of a knowledge-based model for designing cam mechanisms. This model is integrated with a PC-based CAD package and includes modules and tools to aid the designer throughout the process of designing a cam mechanism, from the problem confrontation to synthesizing the cam profile. There are currently no tools available with such a scope. This chapter will provide some general background on design methodology and the motivation for selecting the knowledge domain of cam-mechanism design.

1.1 A Brief Introduction to Design Theory and Methodology

There are nearly as many kinds of design theories as there are authors writing on the topic. Perhaps one of the most notable early design representations is Sandor's Seven Stages of Design (Sandor, 1964) that is shown in Figure 1.1. Sandor described the design process using a Y-shaped structure where the upper left branch represents the evolution of the design task and the upper right branch represents the development of the available and applicable engineering background. The junction of the Y represents the merging to generate the design concepts. The leg of the Y is the guideline towards completion of the design, based on the selected concept. Sandor notes that this is not a purely linear process and often involves iteration.

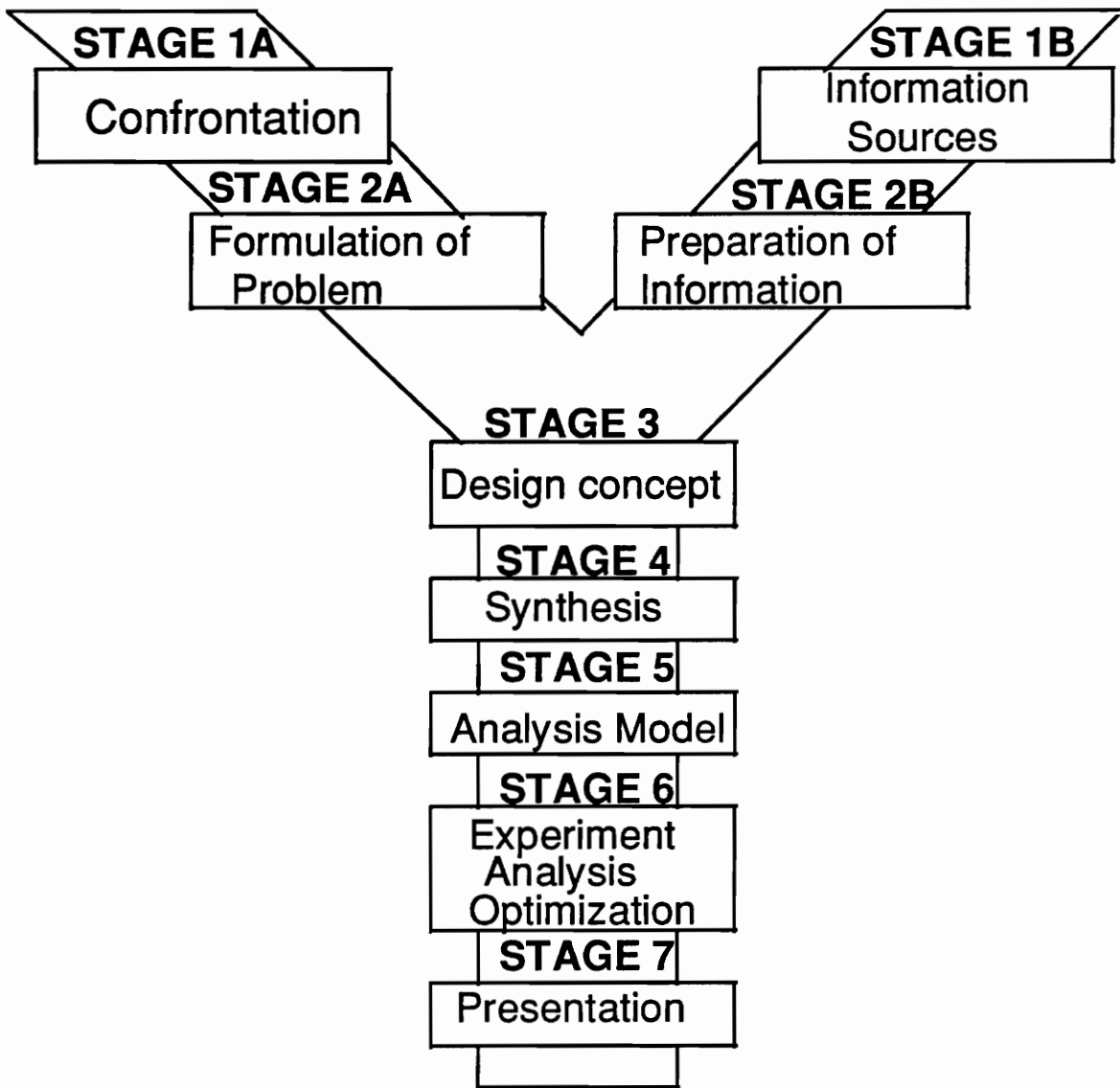


Figure 1.1: Sandor's 7 Stages of Engineering Design (1964)

Referring to the flowchart, the confrontation in Stage 1A is the actual encounter of the engineer with a need to take action. Because this initial confrontation usually lacks sufficient information and is indefinite, the engineer must clarify the problem that is to be solved by ascertaining the real need and defining it in concrete terms in Stage 2A. On the right branch of the Y, Stage 1B represents the sources of information available to the engineer, including other people as well as the engineer's own experience base. The applicable areas of information are organized in Stage 2B, and the gaps must be filled with sound assumptions. In Stage 3 all conceivable designs are developed and represented in schematic skeletal form. Here, creativity is an asset for generating a large list of design alternatives from which is selected the best candidate. In Stages 4, 5 and 6 the concept is given more substance so that an analyzable model is created for experiment, analysis and optimization. The fine points of the design are added for the presentation in Stage 7.

Sandor's description of the design process is good for gaining an overview of the general stages in the design process. However, he does not provide any detail on how to carry out the numerous and complicated processes within each of the stages. In addition, he does not include influences from such "outside" sources as marketing, production or maintenance. More current models include the participation of all of those involved in the product realization process (PRP). Such considerations are often referred to as concurrent engineering.

Finger and Dixon performed a survey of the research in design theory and methodology (1989a, 1989b). They characterize engineering design research using the following six categories which they point out as not mutually exclusive:

1. Prescriptive Models - Researchers formulate methodologies on how they believe the design process should be carried out. One of the better-known models is the highly-structured approach by Pahl and Beitz (1977). They describe a rigid methodology for proceeding throughout the design process. The authors concede that their process must be followed very closely to result in an optimal design.
2. Descriptive Models - Researchers perform protocol studies of designers engaged in the process of design in order to gain insight for developing new methodologies. For example, Ullman and Dieterich (1986) studied novice and expert designers designing products. One of the interesting conclusions of their work is that both novice and experienced designers tend to pursue a single concept that they will "patch and repair" rather than explore new alternatives. This result demonstrates

that designers tend to not conform to the prescriptive models.

3. Computer-based Models of Design Processes - Researchers develop means for the computer to design or assist in designing. A large focus of this work has been in the area of artificial intelligence and the development of expert systems. For example, Kota et. al (1988) developed an expert system called Dwell-Expert that explores configurations of linkages that can approximate a dwell or hold in position. These efforts tend to be closely dependent on particular domains.
4. Languages, Representations and Environments for Design - Researchers formulate means of communicating design parameters among design tasks. Perhaps the most noteworthy commercial development in this area has come from Parametric Technologies design interface Pro-Engineer. Pro-Engineer allows the designer to specify dimensions as variables rather than actual values for parts drawings. This parametric approach allows easy update of drawings when a dimension is changed. When a parameter is changed on one drawing, the extensive software package updates all of the other drawings that are affected. This development has enabled a tremendous time savings in the design process.
5. Analysis to Support Design Decisions- Researchers develop new algorithms and optimization techniques as well as CAD support such as finite element analysis. Many new tools have been developed in this area. One noteworthy product is Working Model by Knowledge Revolution. This software package allows the user to simulate kinematic and dynamic effects. It provides a user-friendly interface for quick development of the models. It also integrates smoothly with commercial CAD packages.
6. Design for Manufacturing and the Life-Cycle - Researchers develop means of incorporating complete lifetime issues of a product into each stage of development. Included in this area are the many facets of concurrent engineering where people from marketing, engineering and production interact closely throughout new product development.

These six areas of research in design theory and methodology provide a good overview of the field. Its important to note that most research in design methodology overlaps two or more of these six categories. More detail in specific work in areas relevant to this dissertation will be presented in the literature review.

1.2 Motivation and Significance of Research in Conceptual Design

An examination of the tasks of engineering design reveals that designers who are adept at incorporating background knowledge with processes for using it along with engineering skills will be more proficient in creating useful designs in a timely manner. A review of engineering education over the past three decades reveals that the curriculum has focused on presenting the fundamental principles of engineering science and processes for performing engineering analysis (Dixon, 1991a, 1991b). The result has been that engineers are more capable at engineering analysis, but are left to formulate their own methodologies and processes for engineering design. Engineering textbooks generally reflect this same focus by presenting models for engineering analysis.

The formulation of advanced models for engineering analysis has been critical to improving the quality of products produced in the United States. However, global competitiveness makes it imperative to develop models for the other stages in the product realization process. An examination of Sandor's Seven Stages of Design reveals that the majority of the research in engineering over the past several decades has contributed mostly to stages 5 and 6. Very little aid is available for the earlier stages of problem formulation or conceptual design. However, it has been shown that the decisions that will affect 70% of the life-cycle cost are made during these stages (NRC, 1991).

Figure 1.2 illustrates the commitment to life-cycle cost versus the background knowledge. This figure conceptually illustrates that designers tend to learn about the domain of the design as they go through the design process. However, a large percentage of the decisions affecting the life-cycle cost are made early in the design process. As the designers learn more in later stages, they may discover that early decisions are invalid. They must then decide whether to iterate back to the point of the invalid decision and repeat the process, attempt to "band-aid" the current design, or ignore it. Any of the decisions lead to more design time and cost or, possibly, to an inferior product. It is clear that improving the designer's background knowledge and providing assistance in the early stages of design will help to reduce cost and lead to better designs.

Like the effort to establish analytical models, a similar effort must be made to develop design models across the fields and knowledge domains of engineering. Practicing engineers cannot be expected to return to school to learn the processes and skills necessary to improve their design abilities. We must embody these principles, processes, and skills

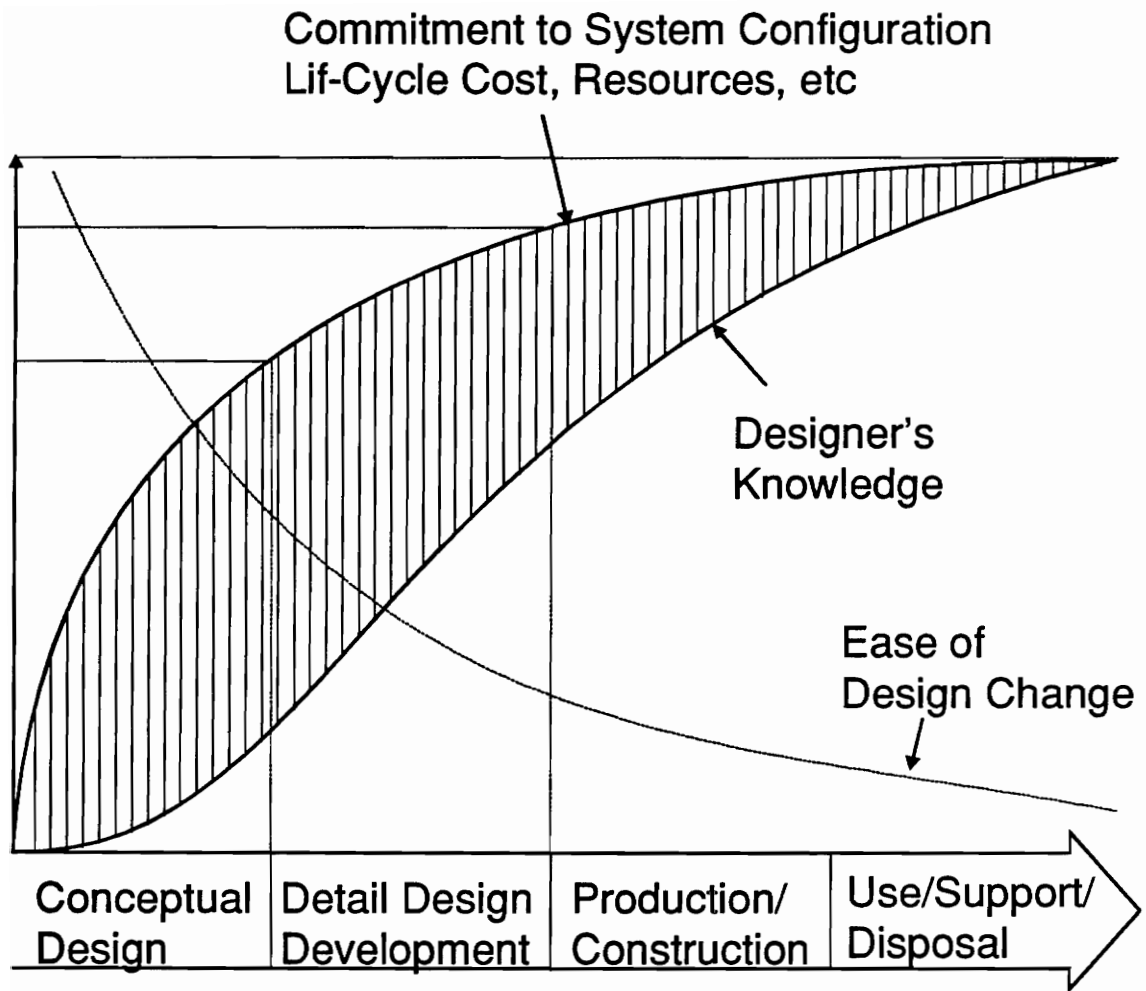


Figure 1.2: Cost Commitment and Background Knowledge

in a tool that is useful to the designer. This can best be done by integrating them with familiar tools already in use, such as CAD packages. By developing tools for computer platforms, there is the greatest potential for reaching a wide audience.

New tools that increase the designer productivity or performance will inevitably induce positive changes in design practice. CAD/CAM technology has had a profound effect on the design environment in industry. Powerful analytical tools have been developed to aid in design evaluation and improvement. In short, the technological development seems to have provided excellent drafting tools as well as some powerful analysis tools to the designer. However, as Figure 1.3 illustrates, there is a void where an integrated system for design synthesis is needed, particularly with a focus on conceptual design. Several companies have emerged with new computer systems to integrate and streamline the design process using techniques of concurrent engineering (Puttre, 1992). These systems are being developed around the core of existing CAD technologies. However, these systems are more focused on the downstream activities of design. A system will have the greatest utility if it covers the entire design process. The system architecture must provide seamless integration with available CAD software.

1.3 Significance of Research in Conceptual Cam Mechanism Design

Cam mechanisms are prevalent in many types of machinery ranging from automobiles to manufacturing equipment. A cam mechanism is used to drive an output device through a prescribed motion. Because the shape of the cam directly affects the motion of the output, great care must be given to determining the shape. Analytical techniques for formulating the cam shape for a desired motion have been developed and several computer tools are available. However, these systems assume the designer has selected the type of cam-and-follower arrangement and knows the desired motion program. The cam-and-follower arrangement and motion program greatly affect the utility and performance of the cam mechanism, yet no tools are available to aid the designer during these critical early stages of the design process.

A review of the available literature on cam mechanisms results in a plethora of material. Entire texts have been published purely on cam mechanisms, and several of these are cited in the literature review. Most of these texts focus on techniques for synthesizing the cam profile and analyzing the dynamic performance. Cam profile optimization

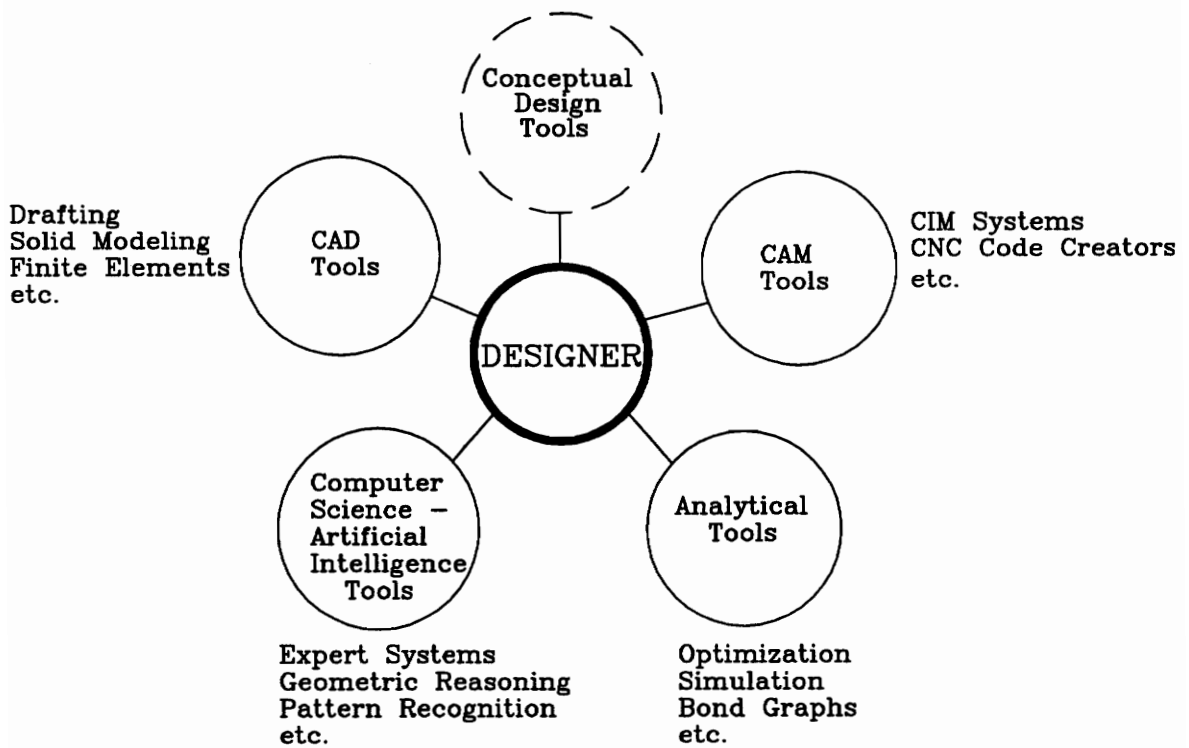


Figure 1.3: Available Engineering Design Aids

techniques are also addressed in some detail. The literature presents common cam-and-follower arrangements and a variety of curves used to formulate the motion program. A process for selecting the cam-and-follower arrangement and a process for formulating the motion program are clearly lacking, however. During the decision-making processes, the designer requires information on the possible effects of these decisions on mechanism performance. Also lacking in the literature is information or a method for establishing the specifications for the design. This important stage of the design process is often neglected. For designers to make valid decisions, it is important that the objectives be clearly defined and each objective must be characterized as necessary or negotiable. Of course, the naive cam-mechanism designer has little or no background to draw on in determining what is important. This makes an aid vital because models for these processes must be formulated and communicated.

It is important to note that the design model described in this dissertation could be applied to any knowledge domain. Several other domains were considered for development. Among these were linkage design and robot design. The domain of cam mechanism design was selected for several reasons. It is a field with well-established techniques for synthesis. As shown in the literature review, many textbooks describe methods for synthesizing the cam profile. These techniques provide a foundation for expanding a design model and methodology. Also, cam mechanism design requires the consideration of spacial relations among components. Integrating the system with computer drafting tools demonstrates the benefit of adding “intelligence” for assisting the designer with these spacial relationships. An additional consideration was that the number of components for cam mechanisms is well-bounded. This helped to ensure that the development was tractable. The background of the author of this dissertation was also a factor. He had been teaching the junior-level course on kinematics and dynamics of machinery. He was interested in exploring the implications to cam mechanism design beyond the established approaches for cam profile synthesis.

1.4 Scope and Organization of the Dissertation

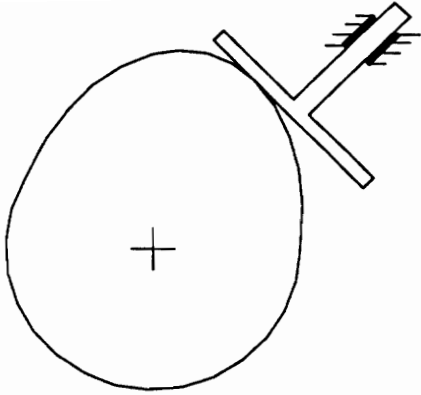
This dissertation presents an overview of design models and methodologies. Some of the better-known methodologies are critiqued and developed into a broader perspective on design. A general model for developing PC-based tools to assist design is then presented. The model and methodologies are then applied to the conceptual design of cam

mechanisms.

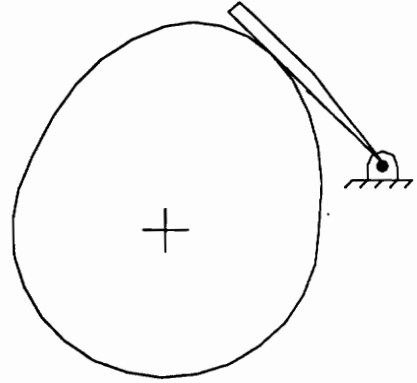
The long-term goal of this research is to integrate design tools and methodologies throughout the product realization process. The immediate development focuses on the design of cam mechanisms. The resulting system will guide the designer from the confrontation through detailed design, manufacturing and maintenance planning. The focus of this work has been on the early stages of the design process, typically termed the conceptual design phase. This includes establishing specifications, formulating a motion program, selecting the cam-and-follower arrangement, and synthesizing the cam profile.

The dissertation focuses on the design of disk cams with the common types of followers shown in Figure 1.4. Followers are typically described by the shape of the follower and the follower motion. The two most-common follower shapes are flat-faced and roller followers. The motion can be either translating or oscillating. In the case of a translating roller follower, we can also describe the line of motion of the follower as either radial or offset from the radial line. Describing an offset for a translating flat-faced follower has no kinematic significance because it does not affect the resulting cam profile.

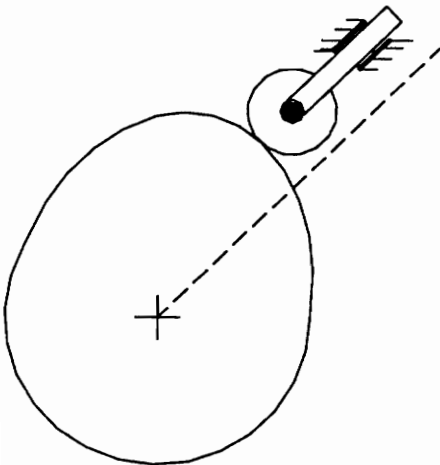
The organization of this dissertation follows the strategy for the research. The effort for this dissertation required an intensive review of research in design theory and methodology. It also required that knowledge on conceptual cam design be generated and compiled and integrated with a model for the cam design process. A modular PC-based tool, AutoCam, was developed and integrated with the Autocad CAD package. The remainder of the dissertation describes the results of this effort. Chapter 2 provides an extensive literature search of conceptual design, conceptual mechanism design, cam-mechanism literature, and available mechanism design tools. Chapter 3 critiques many of the design methodologies available and formulates a general methodology for design. Chapter 4 discusses the translation of methodology to usable design tools and presents a model for a computer tool for design assistance. Chapters 5 and 6 apply the methodology and the model to conceptual cam design. Chapter 5 illustrates the information modeling and chapter 6 describes the resulting AutoCam system. The dissertation then closes with conclusions and considerations for future work.



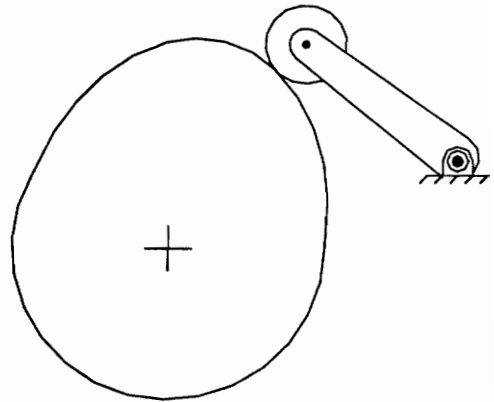
Translating Flat-faced Follower



Oscillating Flat-faced Follower



Translating Roller Follower



Oscillating Roller Follower

Figure 1.4: Cam-and-Follower Arrangements

Chapter 2

Review of Pertinent Literature

The material presented within this dissertation relies on a background in design theory and methodology, kinematics, and cam design. Presented here is a brief overview of design theory, design process models, and conceptual design. This is followed by a recognition of efforts in conceptual mechanism design and cam design. Finally, relevant efforts in mechanism design software and, specifically, cam design software are presented. More detailed discussion of particularly relevant work will be presented as appropriate throughout the remainder of the dissertation.

2.1 Design Theory Overview

The past decade has seen an intensified interest in the field of design theory and methodology. As mentioned in the introduction, Finger and Dixon (1989a, 1989b) presented a review of research related to mechanical engineering design. These works provide an excellent overview of the field. Interest has also been increased by an influential document published by the National Research Council: **Improving Engineering Design - Design for Competitive Advantage** (1991). It outlines a national research agenda to guide research priorities and emphasis. The research described in this dissertation has sought to encompass these goals, which can be stated as follows:

1. Developing scientific foundations for design models and methods.
2. Creating and improving design support tools.
3. Relating design to the business enterprise
4. Relating design research to design education.

Ullman (1991) describes the status of design research in the United States. He provides an overview of design research and suggests directions for the future based on the NRC report mentioned above. He points out that the majority of the focus tends to be on computer based tool development.

2.2 Design Process Models

There are several books that propose methods for carrying through the design process. Among these are Pahl and Beitz (1984), Suh (1990), French (1988), Pugh (1991) and Cross (1993). Pahl and Beitz present a systematic approach to design. They suggest developing concepts by formulating a morphological chart to abstract the essential desired functions and formulate a structure to fulfill the problem need. Suh presents an axiomatic approach to design which rests on the assumption that there exists a set of principles that determines good design practice. While Suh acknowledges the role of information in design, he does not propose a method for delivering or applying it. French is most interested in the early stages of design and the generation of new and novel ideas. He describes several methods for stimulating ideas that he terms maieutics. He proposes that maieutics involve two mechanisms: making the strange familiar, and making the familiar strange. He states that “it is of the utmost advantage to make familiar the subject matter of the problem because we can handle the commonplace with a certainty and insight which is not possible with the esoteric.” Pugh also focused on the early stages of the design process, specifically, the formulation of the specifications. This stage is critical to the design process but is often overlooked or given only modest attention. Cross formulates a methodology for carrying through the entire design process. He presents techniques that are a combination of other theories and methodologies.

The books cited above describe methods for carrying through the design process. However, Finger and Dixon (1989a) suggest that these design processes, as given, are not followed precisely by designers in practice. They state that “no research that we are aware of attempts to verify that better designs would result if the prescribed process were followed.” It is the author’s contention that these methodologies provide a guideline for proceeding through the design process, but that some methodologies are better suited for use in a particular knowledge domain. Therefore, there is a need to establish domain-dependent methodologies.

Some researchers formulate prescriptive models, that is, they describe methods for

how they believe design ought to be done. Others try to formulate descriptive models that describe how design is actually carried out. Stauffer and Ullman (1988) summarize and discuss six investigations of human designers in the design process. The six studies were Marples (1961), Ramstrom and Rhenman (1965), Mitroff (1967), Lewis(1981), Waldron and Waldron (1987) and Ullman, Stauffer and Dietterich (1987). They compiled a long list of conclusions from this work. Their review suggests that the design process is so complicated that studies that seek to observe the general process of design will result in a large collection of heuristics, some of which are contradictory. In order to draw valid conclusions, studies should focus on specific areas with clear distinction of what to look for. Other notable efforts on descriptive models include Bucciarelli (1988), Kuffner and Ullman (1991), and Radcliffe and Lee (1989).

2.3 Brief Overview of Conceptual Design Research

Conceptual design is the least understood of the design stages and has the fewest people researching the area. The prescriptive models discussed above include a section on the early stages of design. There are additionally several papers of particular interest to the general overview of conceptual design. Will (1991) points out that almost no tools exist to help designers in the concept generation stage, although the later stages of design have sophisticated modeling and analysis tools. Will states that a useful tool for conceptual design would include information of alternatives and knowledge of performance and cost. Kota and Ward (1990) present two different viewpoints on conceptual design. Kota presents a functional design methodology and argues that distinctions between functions, constraints and structures are essential to well-organized design processes. Ward addresses both functions and constraints together to iteratively determine a solution.

2.4 Research in Conceptual Mechanism Design

Most of the work in conceptual mechanism design has focused on type synthesis; that is, formulating the possible kinematic arrangements of links and joints. These arrangements, or chains, are depicted using graph theory. Nodes are used to represent links and edges represent joints. Freudenstein has been instrumental in this work. Mayourian and Freudenstein (1984) describe an atlas of kinematic structures with up to six links. These graphs provide a useful method for cataloging kinematic structures for exploration in a

given application. Olson, Erdman and Riley (1985) formulate systematic procedure for type synthesis of mechanisms using graph theory that is suitable for computer implementation. They also provide an extensive literature review on the topic.

More recently, the focus of research in conceptual mechanism design has been on artificial intelligence and expert systems approaches. Hoeltzel, Chieng and Zissimides (1987) developed an interactive expert system, MECXPRT, to assist nonexpert design engineers in creating mechanisms for specific motion-conversion and/or power transmission requirements. Yang et al. (1991) developed an expert system, DOMES, that uses design criteria to perform a complete search of the possible candidate designs that are represented using graph theory. Kota, et al. (1988) developed a network based expert system, Dwell-Expert, to aid in designing dwell linkages. Kota (1990) developed a matrix representation for a set of design building blocks based on a function hierarchy consisting mainly of motion characteristics.

It is clear from the review of efforts in conceptual mechanism design that the focus has been primarily in the area of linkages. No work has been found pertaining to the conceptual design of cam mechanisms.

2.5 Mechanism Design Software

Mechanism design is one of the few areas that lends itself to direct mathematical techniques for synthesizing the mechanism. These mathematical techniques, in turn, lend themselves to the development of computer tools. Numerous computer tools are available to assist in the synthesis and analysis of mechanisms. One of the earliest packages was KINSYN (Rubel and Kaufman, 1977; Kaufman, 1978) which was developed in the late 1960's. Some other software packages include RECSYN (Waldron and Song, 1981), SYNTRA (Barker and Tso, 1988), and MECSYN (Sivertsen and Myklebust, 1980). Perhaps the most popular synthesis software is the LINCAGES package developed by Erdman and his colleagues (Erdman and Gustafson, 1977). LINCAGES provides for the synthesis of four-bar and six-bar linkages. It includes analysis information for optimization and allows for elimination of solutions based on branch, order and Grashoff defects. Erdman continues to upgrade and maintain this software for commercial use.

With the increase in computing power, software has been improved by the inclusion of more graphics and animation. Lear-Links (Lear Com, 1993) allows for animation as well as three and four precision point synthesis. Analytix (Saltire Software, 1993a)

is a sketch-based mechanism design and analysis tool that combines integrated static, kinematic, dynamic and tolerance analysis that operates in the Windows environment. Kinematix provides for the optimization of linkage designs chosen from an atlas of design configurations. It also provides linkage animation capability.

Efforts have been made to integrate kinematic software with popular CAD software. Salem and Manoochehri (1990) developed a design system that is integrated with the Autocad environment. The software, written in Autolisp, performs kinematic and dynamic analysis of planar mechanisms. Algor (1990) developed Dynapak and Kinepak to add kinematics and rigid-body dynamics to its package. DE/MEC (Desktop Engineering International, 1991) allows the user to associate CAD geometry to the mechanism for analysis and optimization. Working Model allows the user to import a mechanism from any CAD package. After the user specifies the types of joints and enters physical characteristics, the system will analyze the mechanism and animate its motion.

2.6 Related Work in Cam Design

Many textbooks on kinematics and dynamics of machinery address the topic of cam synthesis. Texts such as Mabie and Reinholtz (1987), Barton (1993), Wilson and Sadler (1993), and Sandor and Erdman (1984), to name a few, focus on an overview of cam synthesis with graphical techniques and methods for deriving the governing equations to analytically synthesize the cam profiles. These texts also present the common follower types and some of the common curves used to formulate a motion program. These texts do not present a process for selecting the follower type or reasons for choosing one type over another. The information on formulating the motion program is typically limited to techniques for ensuring that there is no infinite jerk at the junction between the curve types. Norton's text (1992) presents cam design in more detail with more insight to follower types and many more possible curves for formulating a motion program.

There are numerous texts that focus on cam mechanisms. These include Tesar and Mathew (1976), Chakraborty and Dhande (1977), Chen (1992) and Rothbart (1956). In addition to the graphical and analytical synthesis techniques, follower types and motion program formulation, these texts include detailed analysis of modeled cam systems. Jensen (1987), Molian (1967), and Norton (1992) provide insight to the process of cam-mechanism design with a thorough discussion of such considerations as pressure angles and radius of curvature. They also include manufacturing considerations. While each

text provides insight to reasons for selecting follower types and motion curves, no single source provides a complete picture of the entire cam-mechanism realization process from the problem confrontation to manufacturing.

Recent papers on cam design have focused on new techniques for deriving the governing equations for synthesizing the cam profile such as Eventoff (1992), Lederer (1993), Gonzalez-Palacios and Angeles (1992a, 1992b), Blechscidt and Lee (1991), Schoenher (1993), Zhang and Wang (1993). Others including Zhao, Liang and Ma (1992), Peng, Zhou and Dong (1992) have focused on optimization techniques for operating parameters and dynamic performance.

Two relevant papers have been published by the author of this work. The first presents an approach to teaching analytical cam design using conjugate geometry (Shooter, West and Reinholtz, 1994). The second presents an analytical method for designing cam-modulated linkages that was applied to the design of an inker mechanism at Pitney-Bowes, Inc. (Shooter, Tidwell and Reinholtz, 1994).

2.7 Cam Design Software

Most of the available software for cam-mechanism design focuses on the synthesis of the cam profile and dynamic analysis. Some of these packages include ANICAM (Ghandi, 1985) and CAMPRF (Cleghorn and Podhorodeski, 1988). Some textbooks include kinematics software that can be used for cam design. Norton (1992) has software written in BASIC that can synthesize the cam profile for basic cam-and-follower arrangements and motion programs. His software uses envelope theory to synthesize the cam profile. Jensen's "Cam Design and Manufacture" software (1987) performs both synthesis and analysis of disk cams with translating and oscillating roller followers. Mabie and Reinholtz's "Kinematic Toolkit" (1987) includes BASIC programs of examples for translating and oscillating followers.

The most recent cam synthesis package was developed by Payne (1994) at Virginia Tech. His software is integrated with the PC-based CAD package Cadkey. The user must specify the motion program and the cam-and-follower arrangement. The program then synthesizes the cam profile from analytical equations derived by using conjugate geometry.

A notable software development for cam design was presented by Lin, Chang, and Wang (1988) and Lin and Wang (1988). Their software is the most extensive in covering

the cam-mechanism realization process. In addition to cam profile synthesis and dynamic analysis, the software aids the designer in selecting some detailed components such as the follower guide and the spring. The modular approach also aids the designer in formulating a manufacturing plan. The most significant contribution of the work was in the area of process planning and manufacturing, where an expert system was developed to aid the designer. The system was limited to the cases of disk cams with reciprocating-radial-roller followers, reciprocating-offset-roller followers, and reciprocating-flat-face followers. Oscillating follower motion was not included. In addition, the system does not aid the designer in the early stages of the cams design process such as design specification or classification.

2.8 Conclusions

Review of the literature provides insight to the fields of design methodology and cam-mechanism design. It is clear that the vast majority of research focuses on the analysis and optimization stages of design. Very little work has been done in the earlier stages of design such as specification formulation and conceptual design. In a field seemingly as well developed as cam design, there is a similar lack of support for the early stages. The bulk of the literature focuses on analytical techniques for synthesizing the cam profile and performing dynamic analysis. Some recent work does consider manufacturing, but no work exists on the basic conceptual design of cam mechanisms.

The remainder of the dissertation describes the author's contribution to the area of design methodology and the development of a model for the early stages of cam mechanism design. This model uses as a basis concepts from several of the fundamental design theory models. Therefore, several of these models are discussed in more detail along with comments and additions from the author of this dissertation. The concepts are then considered for the development of a model for conceptual design of cam mechanisms. The cam-mechanism design model is then embodied in a software package that is integrated with Autocad, a PC-based CAD package.

Chapter 3

Design Theories and Methodologies

Design is a social activity.

As a social activity, design is influenced by culture. Countries have a culture. Geographic regions have a culture. Companies have a culture. Departments have a culture. Offices have a culture.

The design process should be considered in conjunction with the social interactions and the cultural influences. Many prescriptive models have been developed that describe how the design process ought to be carried out. These models vary in structure, form and rigor. The German professional engineers' body, Verein Deutscher Ingenieure (VDI), produced a guideline known as VDI 2221, "Systematic Approach to the Design of Technical Systems and Products". This structured and systematic approach is contrasted by the efforts of Tuomaala (1995) and French (1998) who describe a more free-flowing, creative approach to design.

Many engineering design researchers have performed protocol studies in an effort to understand the design process. They have discovered that the design process is too complicated to study all at once, and different studies have often produced contradictory results. They suggest that it would be better to study particular aspects of the design process to formulate meaningful results. One interesting result from the many protocol studies indicates that none of the prescriptive models are actually followed by designers in practice (Finger and Dixon, 1989a). Does this mean that the formulation of design methodologies is a hopeless endeavor? Not at all. One must recognize that design is a social activity. Influencing the design activity requires influencing the culture. Different cultures will accept some methodologies easier than others. It is foremost important that the cultures be educated on the various methodologies, and then work out for themselves the best suited one. Any methodology, however, is better than following no particular

approach.

This chapter describes facets of the better known design methodologies. These design methodologies influenced the formulation of the methodology for cam mechanism design to be presented later in this dissertation.

3.1 Establishing and Clarifying Objectives

One aspect of the design process on which all of the prescriptive models agree is the need to establish and clarify the objectives of the design. This critical stage is often treated lightly or overlooked entirely. Often the problem is not stated clearly and the designers are left to ascertain the real need. The designers may be tempted to proceed without clarifying the objectives and develop a prototype design. After criticism of this design is obtained, the designers believe that they have a better idea of what is actually wanted. They then proceed to alter the design or start over. At best, through numerous iterations an acceptable solution evolves. At worst, an inferior design is accepted because of time and economic constraints.

Why does this approach at first appear attractive? Often, new designs require background knowledge for making sound decisions. This knowledge is not apparent in the early phases of the design process. Designers will try to draw on any previous knowledge and will try to manipulate the problem to fit in a realm in which they are more comfortable. Any other knowledge they will plan to learn as they go. There is a problem with this approach. As more information is gathered, designers are forced to re-examine past decisions that may have been based on invalid information. They are then forced to iterate the design for a complete fix, compensate for the flaw, or accept the flaw. It seems clear, then, that a great aid to the designer would be easy access to background information needed for the design. This domain specific information is best obtained when establishing and clarifying the objectives. Information on the issues for decision making is also valuable.

3.1.1 Prescriptive Models for Establishing and Clarifying Objectives

While all of the prescriptive models agree that clarifying objectives is a critical stage of the design process, most of them do not offer much in the way of aid in performing this process. Asimow (1961) doesn't describe how to establish objectives in detail, but

suggests that they come down from management. He describes the need for a feasibility study. “The first step in the feasibility study is to demonstrate whether the original need, which was presumed to be valid, does indeed have current existence, or strong evidence of latent existence.” He does not offer any additional guidance in this process.

Pahl and Beitz (1977) see this stage as answering the following questions:

- What is the problem really about?
- What implicit wishes and expectations are involved?
- Do the specified constraints actually exist?
- What paths are open for development?

They stress that “fixed solution ideas or concrete indications implicit in the task formulation often have an adverse effect on the final outcome.” In other words, one should avoid statements such as ‘design a new type of bicycle’, but rather ‘develop a means of land locomotion requiring only human power’.

Suh is well known for his axiomatic approach to design. He sees the design process as starting with the establishment of functional requirements (FR’s) that will later be transformed into an artifact that satisfies them. He also recognizes that the design is limited by constraints. He describes the recognition of requirements and constraints as “clearly one of the most critical stages in the design process.” But he does not elaborate on a process for establishing FR’s or constraints.

3.1.2 Suggested Model for Establishing and Clarifying Objectives

The best description of the stage of clarifying objectives is given by Cross (1994). He describes an approach called the *objectives tree method*. The model described here is based on his suggestions with additions and adaptations provided by the author of this dissertation.

It is helpful at all stages of the design process to have a clear idea of the objectives, even though the objectives might change as the design proceeds. The starting point for a design is often an ill-defined problem or a vague requirement. It is necessary, then, to expand this brief statement into a list of objective statements. This can be accomplished by asking the simple questions of ‘Why?’, ‘How?’ and ‘What?’. “Why do we want to

achieve this objective? How can we achieve it? and What implicit objectives underlie the stated ones?” (Cross, 1994).

One question clearly lacking in this list is ‘Who?’. Yet the answer to this question is critical to the design development. As stated before, design is a social activity. It is helpful to delineate all of the players involved in the activity and what their roles are. A question to ask is ‘Who has influence on the design objectives and design specifications?’ The answer to this question could be the customer, the marketing department, production, or the design department head, to name a few. Another important question to ask is ‘Who has ultimate authority for determining an acceptable design solution?’ The best answer to this question would be the designers, who are required to meet the specification list. But, most likely, designs are reviewed and scrutinized by a panel. It is important to identify the people who have authority over the design in the early stages of the design. Each should be involved in the establishment of the objectives or, at least, aware of the objectives after they are established. This will greatly reduce the possibility of someone later claiming that the resulting design was ‘not what they meant’, and ultimately, reduce the number of design iterations.

As the list of objectives develops, it will become clear that some are more important than others. Sub-objectives for meeting higher-level objectives will also emerge. The objectives should then be organized in groups and arranged in some order of importance. It can be helpful to place each objective on a notecard for easy access and organization. A *virtual notecard* on the computer can also be helpful. Included on the notecard should be the date the objective was established, as well as any revisions. An example of sub-objectives is given by Cross (1994). The lower-level objectives that appear deeper in the outline are clearly a means of achieving the higher level ones.

1. Machine must be safe.
 - (a) Low risk of injury to operator.
 - (b) Low risk of operator mistakes.
 - (c) Low risk of damage to workpiece or tool.
 - i. Automatic cut-out on overload.

Organizing the objectives in this fashion helps to clarify the objectives and the relationships between them. When organizing the objectives, it may be found that some sub-objectives contribute to more than one higher-level objective. For example, ‘Low

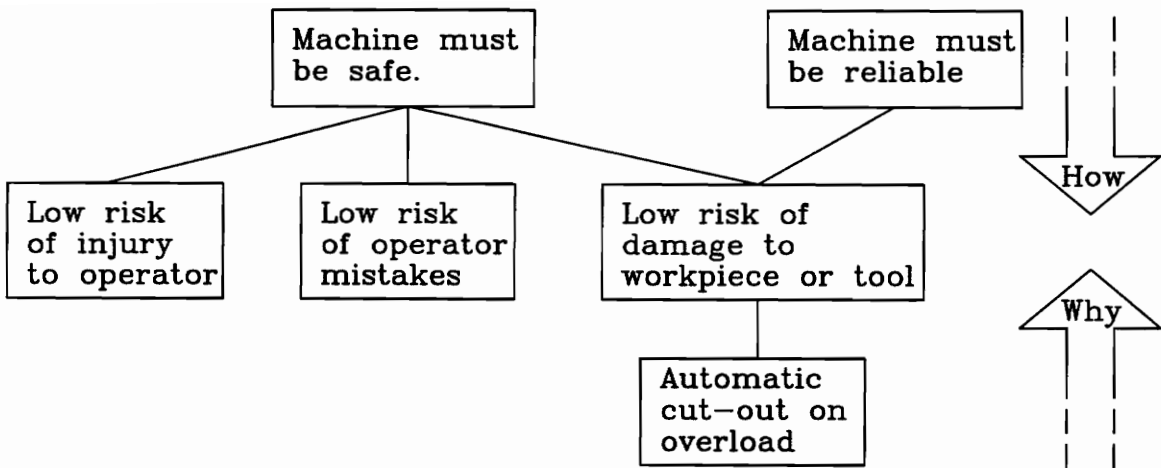


Figure 3.1: Hierarchical Relationships of Objectives - Based on a figure in Cross (1994)

risk of damage to workpiece or tool’ can also be a sub-objective to ‘Machine must be reliable’. For this reason it may be best to organize an objectives tree where lines indicate the connectivity between the objectives and sub-objectives. As Cross (1994) points out, “Each connecting link that is drawn is a means of achieving the higher-level objective to which it is linked. Working down the tree indicates how a higher-level objective might be achieved, and working up the tree a link indicates why a lower-level objective is included.” Figure 3.1 may help to clarify this point.

In establishing and clarifying the objectives, it is important to note that it is not the end product of the objective tree that is important. Rather, the process of working through the method is of most value. It forces the designers to ask questions and articulate the concepts that one might be tempted to accept as implied. The objectives are also not necessarily fixed. They are dynamic and free for revision throughout the process. Good records of revisions helps provide perspective throughout the design process.

3.1.3 Evaluation of Resources

A valuable task to work on in conjunction with formulating the objectives is an evaluation of resources. This is another consideration that none of the previous design models consider. The available and required resources can greatly influence the design. The list does not need to be extensive and should be considered dynamic. A principle resource is typically money. However, in many organizations all sources of money are not treated

as equal. It can be helpful to consider how much money can be spent on what types of things. Anyone who has ever worked with a government budget can appreciate this importance. One should also include personnel and their possible time commitments. This project is likely to be one of several for which people will be responsible. Manufacturing and production facilities are a concern. Must the resulting product use existing facilities, adapted facilities, or will a new production system be developed. Prototyping and shop facilities should also be included. Having this information will greatly facilitate needs that will arise later in the design process.

3.2 Formulating the Specifications

The objectives establish the goals for the design. They are often stated in loose terms and set the tone and direction for the design. The specifications, however, set precise limitations for the design. The specifications limit the range of acceptable solutions. When at all possible, the specifications should be stated in quantifiable and measurable terms. The specifications will be used later for evaluating acceptable solutions. Great care should be given to setting the specifications. The temptation might be to make them too tight in hopes of obtaining the ideal solution. However, overly ambitious specifications can eliminate many otherwise acceptable solutions. In contrast, loose specifications can mislead the designers into performing a less rigorous search and accepting an inferior solution. The specification list should be an honest appraisal of the requirements for the design.

The need to formulate and communicate accurate specifications is illustrated by the following example. A corporate sponsor requested that the Mechanisms and Robotics Group at Virginia Tech explore alternatives for a new service robot. The Virginia Tech group was one among several groups who would independently develop concepts for later evaluation. The other groups were formed from the company's engineering personnel. The company provided a detailed list of specifications. Among the specifications was the requirement that the robot fit in a particular size box for shipment. Before the design review meeting, the Virginia Tech group revised and refined their strongest concept so that it would meet the size specifications. At the design review meeting one of the groups proposed a concept that obviously did not meet the size specification. When this was pointed out in the discussions, the leader of that design group responded that the box was going to be shipped in an 18 foot long truck. So why not use the 18 feet? After group

discussions, the project leader decided that this was a valid argument and accepted the design for further development and evaluation.

The point of this story is that the Virginia Tech group accepted the specifications as hard-fast requirements. The other groups recognized that the specifications were negotiable. This example further illustrates point that design is a social activity and is influenced by culture. The Virginia Tech group, which was not part of the company's internal culture, was unaware of the negotiation factor in meeting design specifications. The problem is that the unnecessarily restrictive specification reduced the design space of acceptable alternatives. It unnecessarily invalidated design decisions based on space requirement and could have led to an inferior design.

Concurrent engineering practices result in more groups participating in the design process which makes the establishment of valid specifications even more important. All of those involved in the process should contribute to the establishment of the specifications and their acceptance. As the development proceeds, new information may suggest a change in the specifications. The decision to alter the specifications is best left to the project leader who should then provide a revised list to all of those involved.

Many of the prescriptive design models acknowledge the importance of formulating a specification list. However, few of them offer a methodology for establishing it. The best approach located was presented by Pahl and Beitz(1977). The method presented here is based on their approach with adaptations provided by the author of this dissertation.

3.2.1 Suggested Model for Formulating the Specifications

The first step in formulating the specifications is to create a list of performance characteristics. Special attention should be given to stating the performance attributes in a manner that is independent of any particular solution. The objectives tree is helpful in formulating this list. The statements should be recognized as either quantitative or qualitative. Quantitative specifications involve values such as maximum weight, minimum space, or limited power. The qualitative specifications don't involve numbers but lend themselves to evaluation, for example, waterproof or corrosion proof. Listing these specifications is often a difficult task. One must be knowledgeable in the domain of the design to establish this list. Pahl and Beitz suggest items to be considered when forming the specifications list. These are shown in Table 3.1.

All quantitative specifications should be assigned acceptable values. It is best to

Table 3.1: Checklist for Formulating Specifications, Pahl and Beitz (1977)

Main Headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension.
Kinematics	Type of motion, direction of motion, velocity, acceleration.
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance.
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials, physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations, etc).
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct protection systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clearness of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality Control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport, (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulfurous atmosphere, tropical conditions).
Maintenance	Servicing intervals, inspection, exchange and repair, painting, cleaning.
Costs	Maximum permissible manufacturing costs, cost of tools, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date.

give an acceptable range rather than a specific value. This can be extremely difficult early in the design phase. Notations clarifying the specification can be helpful later in the project development. For example, noting that values were selected on minimal information and stating their basis. “Special indications of important influences, intentions or procedures may also be included in the specification” (Pahl and Beitz, 1977). The specification should convey as much information as possible without overwhelming the designer.

The specifications should then be classified as demands or wishes. “Demands are requirements that must be met under all circumstances, in other words, requirements without whose fulfillment the solution is unacceptable. Wishes are requirements that should be taken into consideration whenever possible, perhaps with the stipulation that they only warrant limited increases in cost” (Pahl and Beitz, 1977). The wishes should be classified as being of major, medium or minor importance. Determining this importance is not an easy task. A method for establishing importance that has gained recent recognition is called *Quality Function Deployment*, QFD, or referred to as the *House of Quality* (Hauser and Clausing, 1988). This will be presented in more detail later.

Figure 3.2 is a recommendation of a specification layout by Pahl and Beitz (1977). Of course, the layout should conform to demands set by individual companies or cultures. The important information to be contained in the specification sheet is: the specification statement with quantified or qualified limitations, the date the statement was established, the date of any subsequent changes, clarification as to demand or wish and how strong of a wish, and any additional notations. It may also be helpful to list who was responsible for the specification or any changes.

3.2.2 Quality Function Deployment and The House of Quality

The group that has the greatest influence on the financial success of a design is the customer. Recognizing the ‘voice of the customer’ can greatly influence the specifications for a design. Recognizing this fact has brought marketing closer to the engineering enterprise. However, those in marketing who speak with the ‘voice of the customer’ tend to describe desirable attributes for the design. Engineers are more concerned with performance characteristics. For example, the customer may describe a desirable attribute of a car as responsiveness. How does responsiveness convert to engineering performance characteristics? Responsiveness is influenced by torque to the driveshaft, car weight and wheel base, to name a few. In establishing priorities for specifications, the language of

User		Specification for Project, product	Identification Classification Page
Change	D W	Requirements	Responsible
Date of Change	Specify whether item is D or W	Objective or property with qualitative and quantitative data If necessary, split into sub-systems (functions or assemblies) or base on checklist headings	Design Group Responsible
		Replaces	issue on

Figure 3.2: Layout of a Specification, Pahl and Beitz (1977)

the customer and marketing must be translated to the language of the engineer.

The concept of Quality Function Deployment was developed by the Japanese and introduced broadly in the U.S. by Hauser and Clausing (1988). It is basically a means for recognizing the customer as king and translating the customers wants into functional performance characteristics. The method starts with activities generally associated with marketing: determining the requirements of the customer in terms of attributes. This is accomplished through several means such as questionnaires, product tests, and competition analyses. The difficult part of this process involves determining the association between what the customers indicate they want and what they are willing to pay for. The next step is to list the customer requirements in order of importance. This should involve the input of the customer in any number of weighted objectives methods. If competing products are already available on the market, the customer may describe the attributes relative to the competition. In this case, a thorough examination of the competitor's product is essential.

After obtaining the required attributes in the 'voice of the customer', they must be translated to engineering performance characteristics. The QFD method suggests forming a matrix. The required attributes are listed vertically down the left side of the matrix. If some form of weighted objectives method has been used, the weight of importance

should be listed beside the attribute. The relevant performance characteristics are listed horizontally along the top of the matrix. A grid is then formed where each box represents the connectivity between the required attribute and the performance characteristic.

In each of the boxes of the grid is placed the relationship between the attribute and the characteristic. The relationships aren't often easily expressed with 'yes' or 'no' answers. Often, an attribute will be influenced by some characteristics more than others. This relative influence should be acknowledged in the accompanying grid point. It may be best to express this relationship verbally as 'strong', 'moderate', 'weak', or 'not applicable'. The same relationship may be expressed with accompanying values. Perhaps this is best expressed on a ten point scale where ten indicates a very strong relationship and zero indicates no relationship. There is a danger in assigning values, however. Values tend to influence the observer as 'hard' information. The advantage of using the number system is that the relationship value may be multiplied by the relative importance value to obtain an idea of the relative strength in the design specification. Care should be taken to recognize the results as trends. For example, a value of 50 is more influential than a value of ten, but not measurably five times more influential. The method is meant to provide insight which does not take away the power of reason.

It can be beneficial to include the relationship between performance characteristics in the diagram. The relationship was seen in the objectives tree where lower-level objectives were the means for attaining one or more higher-level ones. This relationship can be represented on the diagram by creating a triangular grid above the performance characteristics. Each grid position represents the relationship between the characteristics. This addition places a roof on the diagram which led to the the phrase 'the house of quality'. It is often found beneficial to include relevant information in the diagram such as units for the characteristics or target values and ranges. These are typically placed on the bottom of the diagram. In essence, forming the basement of the house.

Figure 3.3 presents an example diagram obtained from Ramaswamy and Ulrich (1992). The diagram illustrates the basic attributes for a cordless drill and the corresponding characteristics. The designers include positive and negative values with the characteristics to indicate a preference for increasing or decreasing the value of the characteristic. The complexities of the engineering characteristics themselves are demonstrated in Figure 3.4. This network diagram shows the influence of physical properties on the engineering characteristics. It is the determination of these physical properties that leads the designer to the final solution.

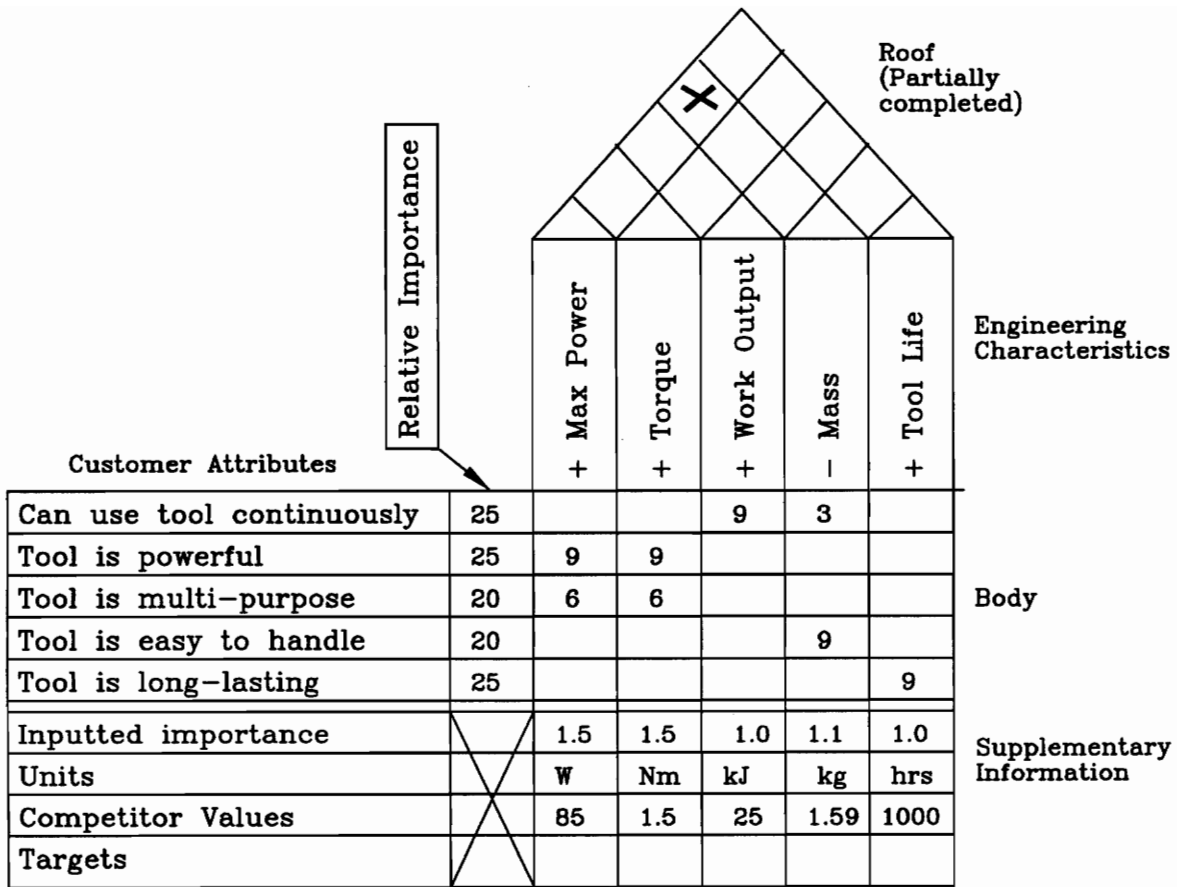


Figure 3.3: House of Quality for Cordless Drill Design, Ramaswamy and Ulrich (1992)

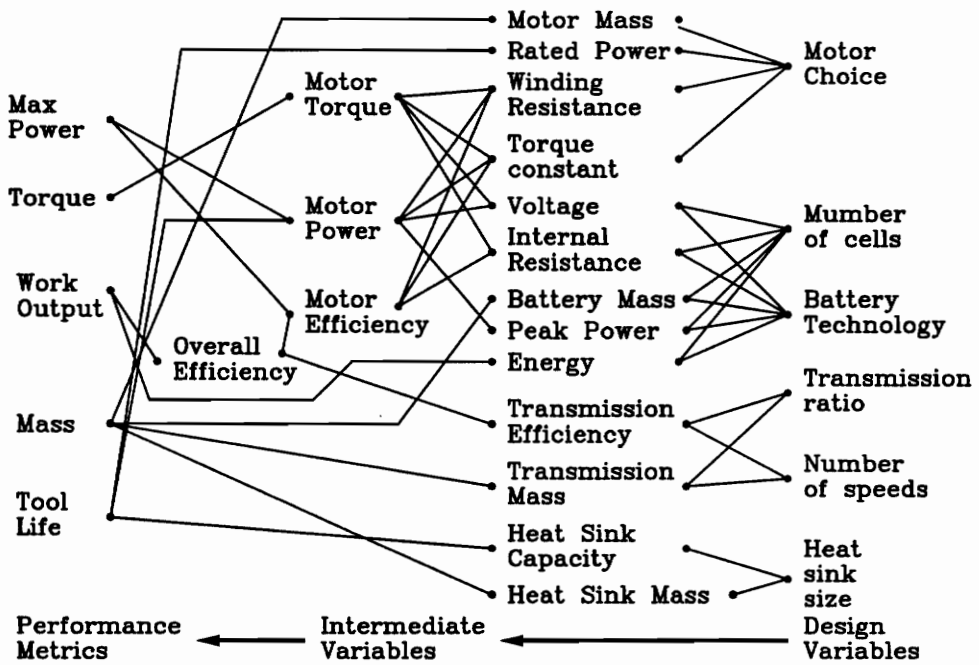


Figure 3.4: Network of Characteristic Influences, Ramaswamy and Ulrich (1992)

It is possible to expand the House of Quality even further. For example, one can include estimated costs for implementing the customer's desired attributes. Armed with this information, the designers can perform a cost-benefit analysis to determine areas for focusing the design.

3.2.3 Establishing a Project Timeline

Table 3.1 presented items to be considered when forming the specifications list. Included on that list was, of course, cost. Cost is always a limiting factor in any design. Another important limiting factor is time. Pahl and Beitz list time as a consideration for inclusion in the specifications. With the advent of concurrent engineering principles and the inclusion of larger teams in the design process, much more time management planning should be considered. None of the models included any insight into the formulation of a project timeline. Project timelines are an integral part of process engineering and logistics engineering. Yet very little aid in formulating a timeline was found in texts on these subjects.

The purpose of the project timeline is to coordinate the efforts of all of those involved in the design project. The timeline establishes 'who' will have done 'what' by 'when'. Of course, this is difficult to establish early in the development because unseen barriers are bound to arise. However, a goal has much less hope of being attained if it is not established.

The first step in establishing the timeline is to acknowledge the major commitments. A big one is the product release date. This is the date when a certain number of the artifact being designed must be delivered. There are other significant milestones along the product realization process. Companies will often establish a design freeze date. On this date the design is accepted as complete for the first production. This is the target date that most concerns the designers. The designers may also wish to establish dates by which other major hurdles must be met. For example, a machine may be designed by several groups, each of which is developing one or more of the many components. While the early phases of design may be performed on each component concurrently, some decisions for other designs may be dependent on the results of one or more components. This establishes primary and dependent components. At one or more points in time the primary component designs may be frozen to allow the dependent components to be developed. Depending on the overall timeline, a certain number of iterations may be allowed.

It is likely beneficial to set dates for the completion of each phase of the design process. Set the date for the establishing of objectives and formulating the specification lists. Conceptual design, detailed design, analysis and optimization, manufacturing and production planning should also have completion dates established. Because resources must be allocated, it is good to consider when the phases will begin as well as when they must end.

The timeline can include deeper levels of detail if desired. The project leader may want to establish when there will be design review meetings and who will attend. It's important to remember that establishing the timeline is a guideline that can be as rigid or as flexible as desired. One should expect some delays. The process of planning will provide tremendous insight that is at least as valuable as the formulated timeline.

3.3 Conceptual Design

The conceptual design phase is characterized by the generation of alternative solutions to the problem statement and the objectives. In this phase, engineering science, practical knowledge, production methods and commercial aspects come together. It is the phase that places the greatest demands on the designers and where the most important decisions are made. The decisions made in the conceptual design phase have the greatest affect on life-cycle cost and the overall success of the product. Yet, the conceptual design phase has the fewest number of tools or aids for the designers.

3.3.1 Models for Conceptual Design

There are many opinions on the optimal method for approaching conceptual design. These range from the structured, disciplined approach presented by Pahl and Beitz (1977) to the intuitive approach espoused by Tuomaala (1995). Each has its benefits and insights.

Pahl and Beitz

A highly structured approach to conceptual design is presented by Pahl and Beitz (1977). They describe a step-by-step procedure for ensuring that all alternatives are explored. The first step involves abstraction. The specifications list contains a lot of details that will be helpful later in the design process when the alternatives are evaluated and the best solution is selected. But this detail can be cumbersome for the conceptual design phase.

Abstraction involves reducing the detailed quantitative specifications to the fundamental qualitative functions desired. The Pahl and Beitz model does not include formulating objectives early in the design. With an objectives list and objectives tree, a lot of this is done. However, only a few of the most important high-level objectives should be considered in conceptual design – those objectives that best represent the essence of the problem.

The second step requires the establishment of function structures. Pahl and Beitz state that “it is possible to indicate an overall function that, based on the flow of energy, material or signals can, with the use of a block diagram, express the relationship between inputs and outputs independently of the solution.” They provide a lot of details for formulating the functions and subfunctions that they insist must be followed with great regimen. Each subfunction must then be mapped to a solution principle that is a design feature for accomplishing the subfunction. They mention several techniques for doing this mapping, including well-known intuitive methods such as brainstorming. However, they do not put much credence in intuitive techniques, which they believe have the following disadvantages: the right idea does not come at the right time because it cannot be forced; current conventions and personal prejudices may inhibit original developments; and, new technologies or procedures may fail to reach the designer’s consciousness because of inadequate information. Instead, they advocate a search for physical effects to transform the subfunction.

Figure 3.5 illustrates three subfunctions, each mapped to a solution principle. Their method requires an exhaustive search for all possible solution principles to each subfunction. Solution principles are then combined in various combinations to fulfill the overall function. This can be an overwhelming number of combinations, some of which are nonsensical. The suitable combinations are then selected by elimination and preference and then firmed up into concept variants. Enough details are added so that the alternatives can be evaluated and the best ones selected for further development in the design process.

A lot of details in the process have been omitted here. But it can be clearly seen the enormity of the task the designers face if they are to follow exactly Pahl and Beitz method. Pahl and Beitz insist that the method be followed diligently so that optimal alternatives are not overlooked.

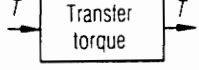
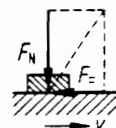
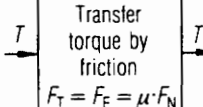
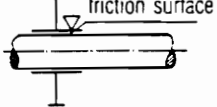
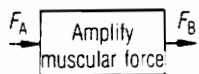
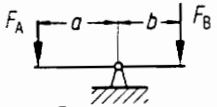
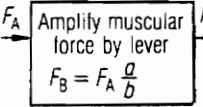

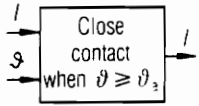

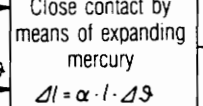
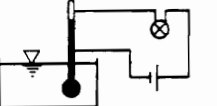
Sub-function	Physical effect (independent of solution)	Physical principle (Subfunction and physical effect)	Solution principle (Physical principle and form design features)
	Friction  $F_f = \mu \cdot F_N$	 $F_T = F_f = \mu \cdot F_N$	
	Lever  $F_A \cdot a = F_B \cdot b$	 $F_B = F_A \frac{a}{b}$	
	Expansion  $\Delta l = \alpha \cdot l \cdot \Delta \vartheta$	 $\Delta l = \alpha \cdot l \cdot \Delta \vartheta$	

Figure 3.5: Sub-functions Transformed to Solution Principles, Pahl and Beitz (1977)

Suh's Axiomatic Design

Suh does not outline a process for design, but rather espouses the existence of axioms that should be considered throughout the design process. "Axioms are fundamental truths that are observed to be valid and for which there are no counter examples or exceptions (Suh, 1990). Suh suggests that the satisfaction of the following two axioms that govern good design will lead to an optimal design.

Axiom 1: The Independence Axiom

Maintain the independence of functional requirements.

Axiom 2: The Information Axiom

Minimize information content of the design.

If a design concept satisfies the axioms, it should be developed further. If not, a new concept must be developed. Suh describes the design process as a mapping of functional requirements (FRs) to design parameters (DPs).

Axiom 1 states that the design process involves the transformation of FRs in the functional domain to DPs in the physical domain. "The mapping must be such that a perturbation in a particular DP must affect only its referent FR" (Suh, 1990). The

reasoning behind this is that each design parameter can be tweaked and optimized to best satisfy the functional requirement without affecting any other functional requirement. This is not to say that each functional requirement must be met by its own physical part of the design. It is possible to satisfy more than one functional requirement on the same physical part with separate design parameters. An example of this is the simple “bottle-can opener” that meets both functional requirements of removing a bottle cap and puncturing an opening in a can.

Axiom 2 states that the best design meets *Axiom 1* and is the least in complexity. In other words, an optimal design satisfying three functional requirements would exhibit three design parameters. This, of course, is very difficult if not impossible for all but the simplest design problems. However, this goal will lead to the most elegant solutions. Suh was concerned with design for manufacturing. *Axiom 2* gets its motivation from the desire to simplify the manufacturing process. Each design parameter signified another consideration in the manufacturing process. The information needed to describe the design that meets the functional requirements must be implemented in manufacturing. Minimizing the governing information streamlines the manufacturing process.

Suh describes in great detail supportive corollaries and theorems based on the two fundamental axioms. These corollaries and theorems provide guidance for the designers throughout the design process. Through his formulation of the axiomatic approach to design, Suh has sought to make the design enterprise more accepted as a science. Suh claims that since counter examples to the axioms have yet to be found, they must be taken as valid. The consideration of these axioms is helpful when generating alternatives and refining the concepts.

Tuomaala’s Intuitive Engineering Design

Tuomaala (1995) is critical of the systematic approaches to design such as that proposed by Pahl and Beitz (1977). Instead, he proposes an approach that utilizes and stimulates the subconscious mind. His approach has a firm foundation in psychology and research on creativity as well as an understanding of the engineering enterprise. The method is based on the idea that the subconscious mind continues to work on a problem even if the conscious mind is unaware of it. In fact, the subconscious mind is far more efficient at problem solving and can handle many more operations than the conscious mind. When the subconscious mind formulates a solution, it is transferred to the conscious in what

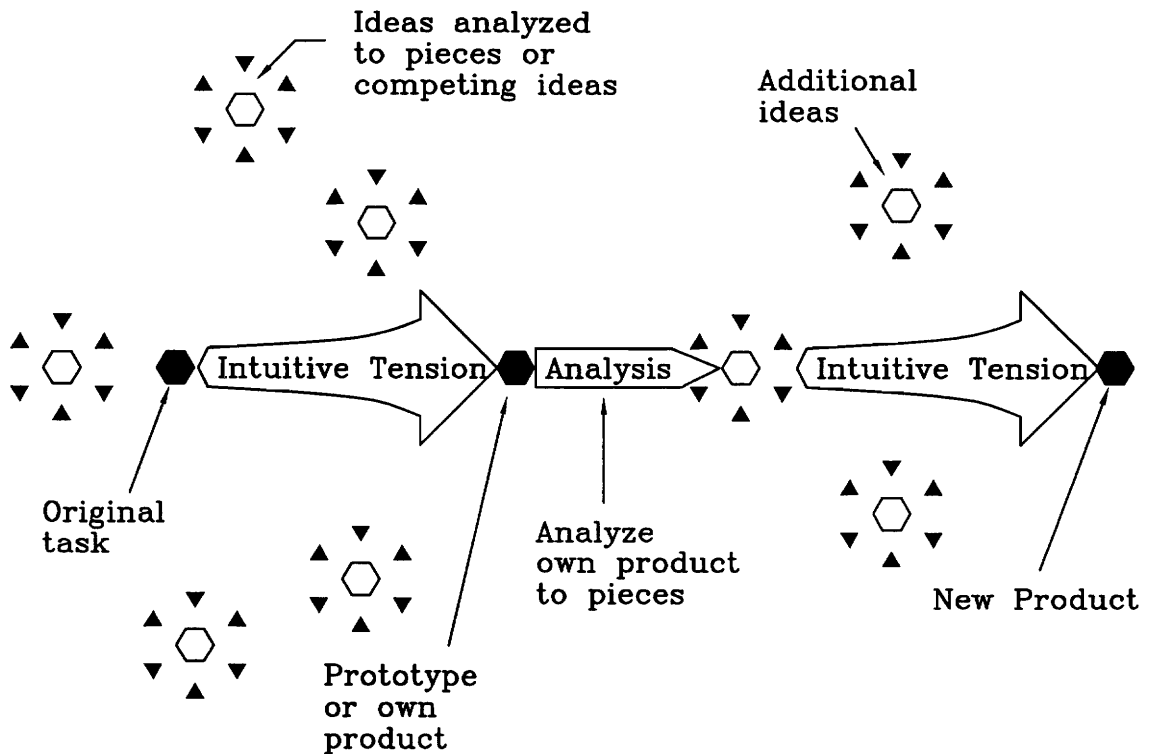


Figure 3.6: Tuomaala's Intuitive Design Method

Tuomaala describes as the Eureka Principle.

Critical to the intuitive design process is the presence of tension. The tension stimulates the subconscious and prompts it to give priority to the solution of the design problem. Therefore, he states that it is important to have a firm deadline established for each phase that the designers know cannot be altered. Often the Eureka effect occurs just before the deadline when the tension is greatest.

The intuitive method is illustrated in Figure 3.6. The black hexagons represent the complete design idea, while the empty hexagons illustrate the "breaking up" of the idea into pieces represented by the triangles. Tuomaala acknowledges the importance of establishing a thorough specification list. In fact, he suggests taking it one step further to the point where every item on the list is scrutinized and questioned for validity and accuracy. This focused scrutiny helps to establish the tension in addition to gaining a thorough understanding for the demands of the design. He also suggests a thorough analysis of any existing or competing design ideas. The concept's structure should be

decomposed into the smallest analyzable parts and closely scrutinized. The structure is composed of parts that have their own functions, materials, strengths, weights, colors, manufacturing methods, etc. The idea is to “steal the expertise and the point of view of the designers who have constructed them” and learn from it (Tuomaala, 1995). He goes on to state that “in this way we gradually come to a situation where the structure is no more a reference or competing entity but a collection of functions, purposes, successes and failures.”

The tension from this decomposition process will suggest one or more possible solutions. These solutions should then be “analyzed to pieces” in the same manner as the previous designs. Through iterations of this creation and decomposition of ideas, the optimum solution will arise for further detailed development.

3.4 Creative Methods

There are several methods that help to stimulate creative thinking. Their purpose is to increase the flow of ideas and remove mental blocks that can inhibit creativity.

Probably the best known creative method is brainstorming. It is a technique for generating a large number of alternatives, many of which will be easily discarded later. It is a group activity that is best undertaken with only a few people of varying backgrounds. It is based on the idea that everyone has something to offer from some background knowledge but may be inhibited to present it. For this reason, all criticism must be delayed until all concept generation has been exhausted. This is an extremely important, and often overlooked, point. Criticism may not only inhibit people from putting forth ideas that may be perceived as silly, but changes the entire dynamics of the session.

One person must take the role of group leader. His role is to maintain the pace of the session and determine when it should end. The process starts by each person taking a few minutes to generate as many ideas as possible that satisfy the problem statement. Each person will then take a turn to present his idea. The other members of the group do not criticise, but rather, try to build on the idea. After allowing some discussion, the group leader will call on the next person to present an idea. This continues until all ideas have been presented and no new ideas are forthcoming. The group leader may wish to stop the process early if boredom is perceived in the group. The entire process should not last more than an hour. Having fun is also a requirement.

Another group creative activity is called synectics. Synectics requires the same

ground rules as brainstorming. However, the individuals are encouraged to use various types of analogies to generate new ideas collectively. *Direct analogies* draw connections from the natural and biological world. For example, a mobile robot can be thought of as moving like a person, a deer, a spider, or a caterpillar. Many designs resemble known biological systems. *Personal analogies or anthropomorphism* involve the group members imagining themselves in the role of the artifact being designed. What does it feel like in that environment? How do I get the job done? *Symbolic analogies* are more poetic and draw on simile and metaphor. The friendliness of a computer or the hand and claw of a hammer are examples. *Fantasy analogies* let the team members create a fantasy world where things work differently from our reality. Concepts generated to operate in this fantasy world can then be altered to meet real requirements.

Another method developed by DeBono (1970) involves the participants alternately wearing different hats. Each hat allows the wearer to act only in a prescribed way. For example, one hat can represent the crazy professor who formulates wild ideas. Another hat may be that of a precocious child who always wants to know why. Or the hat of the manager whose overriding concern is what its going to cost him. The method creates a playful atmosphere where the participants each get a turn playing the different roles.

Other methods have been developed, but they each use variations of the ones presented here. The goal of each of these methods is to generate as many concepts as possible in a short time frame. The concepts will be evaluated and developed in more detail in a later phase of the design process.

3.5 Evaluation

Evaluation takes place throughout the design process. However, it is best to delay evaluation until after concepts have been generated. An evaluation of the concepts should take place after conceptual design and at different levels of detailed design. The procedure is generally the same. However, the details of the process must vary to suit the amount of information that is known about the design. The prescriptive models vary on the detail that should be attributed to the evaluation. As stated earlier, Suh suggests that evaluation occurs constantly by considering the two axioms that govern all design.

Pahl and Beitz (1977) present the most systematic approach to evaluating the concepts. They first suggest formulating a list of objectives that should be as independent of one another as possible. If the method suggested in this dissertation is followed, then the

objectives list is already formulated. However, the objectives list should be reviewed in light of new information that inevitably arose during the design process. Pahl and Beitz then suggest that the objectives be assessed for their relative contribution to the overall value of the solution so that unimportant criteria can be eliminated. The remaining criteria should be given weighting factors that indicate their relative importance. The number of evaluation criteria should be kept small at first to avoid overwhelming the designers. New criteria can be added as needed for more detailed decision making.

Pahl and Beitz suggest formulating an objectives tree similar to the one suggested earlier in the dissertation. The objectives tree is useful for assigning weights to the objectives and sub-objectives. Figure 3.7 illustrates the procedure for assigning weights to objectives. The system is based on the premise that the sum of all factors of the sub-objectives at the lowest level must equal to one. The procedure begins with the main objective having a value of one. The sub-objectives are then assigned a fraction of one that represents its importance in contributing to the main objective. The next level sub-objectives can only receive a total of this fraction. This is continued to the bottom level of sub-objectives. In Figure 3.7 the objectives are numbered with increasing subscripts for each level of sub-objectives. The subweight is that fraction of 1.0 given to the sub-objective at that level. The resultant weight is obtained by multiplying the subweight with the resultant weight of the objective above.

With weighting values established, it is then necessary to establish quantifiable evaluation parameters. For example, overall weight should be established with varying parameters. This does not have to be a linear scale. If light weight is desired, the weights can be broken into ranges and assigned evaluation values. For example, over 100 kg = 0; 80 to 100 = 1; 70 to 80 = 2; 73 to 80 = 3; 66 to 73 = 4; and 65 and under = 5. This example illustrates a five point scale. More refinement may be applied with a ten point scale if desired, but the scale must be applied consistently for all criteria.

Each of the design alternatives are evaluated based on these criteria. The scores are then tallied and multiplied by the weighting values. The results are tabulated and summed to give a total value for each design alternative. This evaluation value is used to determine the best design alternative or alternatives for further development and evaluation.

This method has several merits and drawbacks. The foremost drawback is that quantifying the criteria can give a false sense of preciseness that may not be present. In the earliest stages of design such as the conceptual design phase, it may be difficult to pinpoint the values needed to evaluate the alternatives. The concepts may not be developed enough

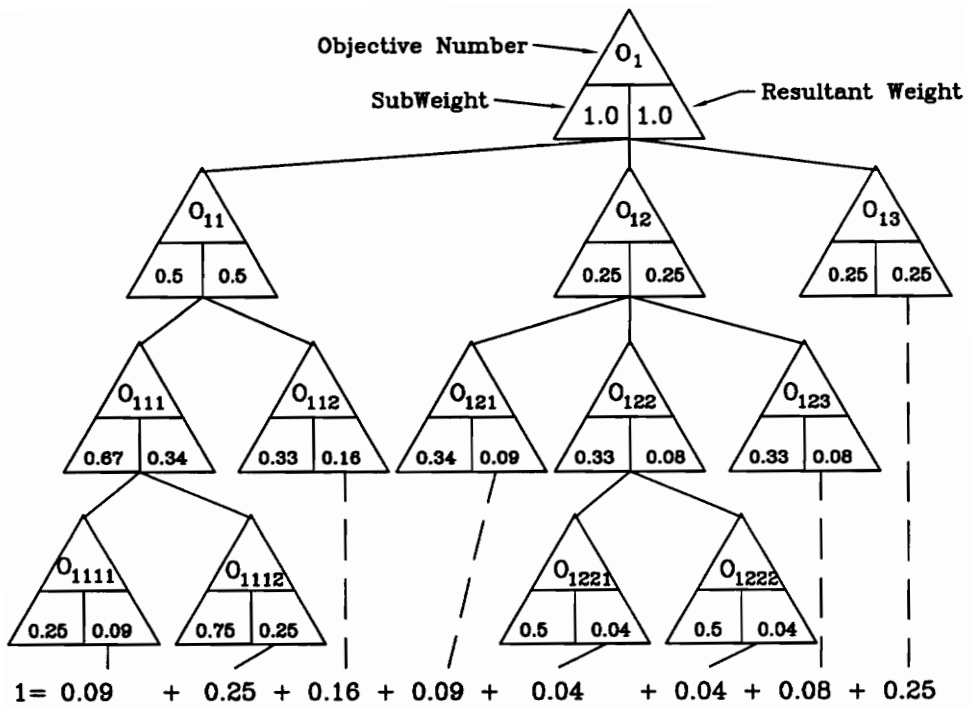


Figure 3.7: Objectives Tree with Weighting Values

Table 3.2: Relative Weights of Objectives, Cross (1994)

Objectives	A	B	C	D	E	Row Totals
A	X	0	0	0	1	1
B	1	X	1	1	1	4
C	1	0	X	1	1	3
D	1	0	0	X	1	2
E	0	0	0	0	X	0

to assign valid parameters. Parameters will then be applied by constructive guesswork or intuition. This further invalidates the precision of the resulting evaluation. This method, therefore, produces the best results for evaluation of design alternatives later in the design process after more details have been added. This is not to say that performing this type of evaluation has no benefit in conceptual design. Undergoing the process will inevitably provide insight and information that will be useful in the decision-making process.

Cross (1994) agrees with the method provided by Pahl and Beitz but suggests that a simpler method may also be useful. In this method, alternative objectives are simply compared to each other to establish a rank order of importance. This process can be tabulated as shown in Table 3.2. Here the five objectives named A through E are compared to one another across the rows. If the objective on the left is more important than that appearing in the column then a one is placed in the grid; otherwise, a zero is placed in the grid. The values in the rows are then totaled to give a rank order for the objectives. If the objectives are deemed equally important, a value of 1/2 can be entered, but this should be avoided if possible. With the ranking established, relative weights can be assigned and the evaluation procedure performed as mentioned before.

French takes a much more basic approach, at least for evaluation after conceptual design. He believes “that rather than eliminating cautiously and finally, it is quicker and better to eliminate in a rather cavalier fashion in the first place and later review the rejects in the improved insight developed in the interim” (French, 1971). He calls this process *repechage*. He suggests that it is best to simply set aside the weakness of each option and decide whether there is any plea to be made on its behalf. Determine if there are any advantages of the design alternative or any circumstances in which it would be viable. Then a decision is made on the alternative or alternatives to pursue for more detailed development and analysis. If the further development shows a flaw, another alternative

can be selected for development or some appealing aspect can be incorporated into the present one.

French suggests this basic evaluation out of the acknowledgement that during conceptual design, information is minimal. Yet, a decision must be made to make the further design process tractable. He believes that it is best to openly select an alternative in a 'cavalier fashion' than to disguise some personal predisposition in false evaluation values. Keeping the process open allows opportunity for others involved to share in the decision making.

3.5.1 Suggested Method of Evaluation

The evaluation method proposed by Pahl and Beitz (1977) and espoused by Cross (1994) is most useful in the later stages of the design process when details have been sufficiently developed to provide meaning to the resulting values. In conceptual design the details are not available, yet, the field of alternatives must be reduced for the remaining processes to be tractable. The suggestion by French has its merits, especially if used in conjunction with Suh's axioms. However, there is something to be gained by following a rational procedure. It is suggested that the number of alternatives can best be thinned by establishing two levels of criteria: screening criteria and evaluative criteria.

The screening criteria are those that the design **must** satisfy. These criteria are not weighted and not up for debate. The screening criteria should ideally be written in a fashion that will allow a simple pass/fail answer. If necessary, a shade of gray can be added by including a category on possible failure if the alternative appears borderline. Those alternatives that fail any of the screening criteria are eliminated. Those receiving a possible failure rating may be found to pass with only slight modification. These concepts may be developed to the point where they can be distinctively screened or saved for later consideration. Care should be given in establishing the screening criteria. Only criteria that must be absolutely met should be included. These criteria often involve environmental restrictions, space requirements, or restrictions imposed by code-writing organizations such as ASME or ASHRAE.

A surprising number of alternatives will often be eliminated by the screening criteria. The remaining alternatives are then evaluated by a limited number of evaluative criteria. The evaluative criteria are established by weighted objectives in a manner proposed by Pahl and Beitz (1977) or Cross (1994). The suggestion here is to keep the decision

parameters as coarse as possible. For conceptual design a scale of 0 to 5 is recommended or even 0 to 3. The idea is to avoid any false indications of more precise decisions making. The resulting values should be used as a guideline for selecting the best alternatives for further development. This number of alternatives, of course, is restricted by the resources available.

A design alternative with a low score might not necessarily need to be completely ruled out. Often a designer likes one alternative for reasons other than those shown in the evaluation. The detailed evaluation can be used to locate particular areas of weakness that may be improved with a little thought and development. Tuomaala's intuitive method can be useful here to analyze the design alternative to pieces and formulate a superior alternative.

Evaluation of the alternatives should be performed regularly throughout the further stages of development. Ideally, different designers will be assigned to develop one alternative. Regularly scheduled design reviews should be held to assess the progress of the development of competing alternatives. As more details are developed, the evaluation will become clearer. The evaluation results at these design reviews can be used to determine if further consideration of an alternative is warranted. This leads to an optimal allocation of resources in the development. A limit of resources may force fewer alternatives to be developed. This may require more iteration in coming to a final solution. An advantage, however, is that information need be shared among fewer people.

3.6 Detailed Design, Analysis and Optimization

All products are made of subsystems and components whose form is determined during conceptual design but whose detail depends on various factors such as manufacturing, detailed component selection, etc. The detailed design phase is the most labor intensive. Here, subsystems and components are selected, analyzed, optimized and drawn in detail for production. The individual subsystems and components must also interface with other components and integrate with other subsystems. For this reason this phase also involves a lot of iteration.

This phase requires the expertise of several fields of engineering. Materials need to be selected, mechanical systems designed, electrical systems coordinated and manufacturing concerns incorporated, to name just a few. The skills and background knowledge required is obviously dependent on the type of product being developed. A discussion of

all of these considerations can take up several volumes. However, there are some general considerations that are valid for any detailed design.

Cross (1994) suggests a cost-value approach. He suggests a checklist of cost reduction guidelines to be followed.

Eliminate: Can any function, and therefore its components, be eliminated altogether?
Are any components redundant?

Reduce: Can the number of components be reduced? Can several components be reduced into one?

Simplify: Is there a simpler alternative? Is there an easier assembly sequence? Is there a simpler shape?

Modify: Is there a satisfactory cheaper material? Can the method of manufacture be improved?

Standardize: Can parts be standard rather than special? Can dimensions be standardized or modularized? Can components be duplicated?

Adding value to the product considers what the customer finds valuable. This can be learned from such techniques as Quality Function Deployment (QFD) mentioned earlier. Cross suggests a list of attributes which commonly contribute to the quality or value of a product.

Utility: Performance on aspects such as capacity, power, speed, accuracy or versatility.

Reliability: Freedom from breakdown or malfunction; performance under varying environmental conditions.

Safety: Secure, hazard-free operation.

Maintenance: Simple, infrequent or no maintenance requirements.

Lifetime: Except for disposable products, a long lifetime which offers good value for the initial purchase price.

Pollution: Little or no unpleasant or unwanted byproducts, including noise and heat.

Aesthetics: Appearance of a product - color, form, style, etc.

Pugh (1990) suggests that it is valuable to establish a component design specification (CDS) that describes the requirements for each component of the design. Formulating the CDS requires an evaluation of the original design specification so that the components include those considerations as well as any new ones. Formulating a CDS should follow the same procedure as the design specification and should include all participants for its acceptance.

Pugh points out that in component design the emphasis will always be on local performance, local environment, and local constraints. He adds some general points that must always be borne in mind during detailed design.

1. Never carry out detail design without reference to the chosen concept or vice versa.
2. The interaction between the various areas of the design must be considered together with the constraints imposed on those areas.
3. The very act of defining a component within a system places constraints on the system, from the component definition itself.
4. The simplest and cheapest component design may not always be the most economic in a total sense.
5. The simplest and cheapest component design is achievable only in the context of the CDS.
6. Generally, a reduction of component variety leads to shorter lead times and minimum cost.
7. Think of the way the components are to be manufactured. If you have a manufacturing plant, should you design to utilize it?
8. Think of subassembly breakdowns.
9. Is there a simpler way?
10. How do other industries do it?
11. Can it be abolished?
12. Can any part or function be abolished or reduced?

13. Can any or all of the parts or functions be taken over by other components?
14. Can parts or functions be split, possibly giving more but simpler pieces?
15. Can parts or functions be amalgamated?
16. Can it be bought economically?
17. Can it be made of standard parts?
18. Would it help to make it standard?
19. Can a new or different principle be used?
20. Should it be made larger, or smaller?

Much can be said about considerations of design for manufacturing (DFM) or design for assembly (DFA). Entire books are dedicated to just these topics. One main consideration is that a reduction of the total number of parts will inevitably reduce the total cost of the product. Not only does it reduce the cost by the price of the part, but it reduces inventory requirements and assembly time. Another consideration is that parts should be specified with the minimum amount of complexity. This will reduce manufacturing time and production difficulties. Also, standard parts should be used whenever possible. It is almost always cheaper to buy parts than it is to make them in house.

Chapter 4

Decision Support Modeling in Design

4.1 Introduction

The previous chapter presented general models of the design process. These models provide a guideline, or methodology, for the approach to a design problem. A practicing designer may argue that these methodologies are not directly applicable to real-world design problems. The methods give good ideas, but their generality makes them difficult to apply to an actual design.

Design can be seen as a problem-solving process where the designer must explore possible alternatives and make decisions. The decisions are supported by information in the form of facts, procedures, mathematical formulations and calculations. Every designer approaches the decision-making process in a unique way. Some may begin by establishing objectives. Others tend to start with a solution and then work backwards toward justifying it. Perhaps it is most common to combine strategies for the top-down and bottom-up approaches throughout the development of the design.

The practicing designers tend to be unconcerned with methodologies and theories for approaching design. They tend to be more interested in support and assistance with the design details. Those tools which have been successful have assisted designers with common tasks such as drafting, word-processing, and analysis tasks like finite element or kinematic analysis. This chapter explores models for assisting designers in the decision making process that can be incorporated with the general design theories and methodologies.

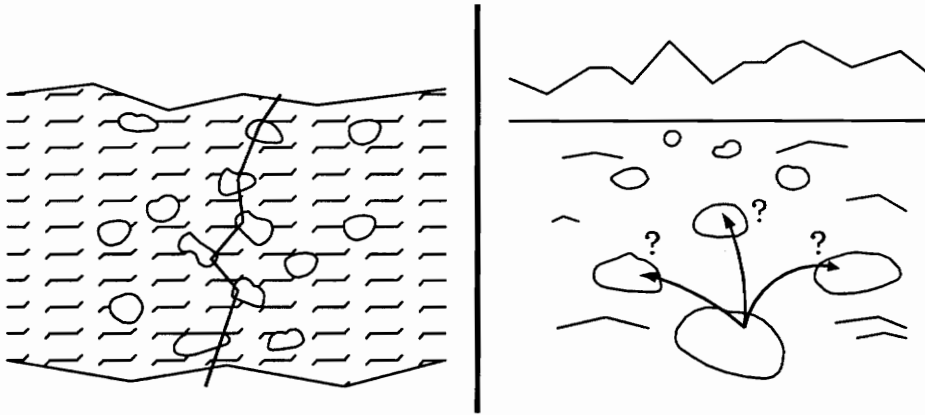


Figure 4.1: Planning vs. Navigating a River

4.2 Planning and Navigating in Design

While designers may differ on how they choose to begin a design problem, they all must find a way to proceed. They seek to convert an ill-structured problem to a better-structured problem by reducing it to suitably organized subtasks. Each of these subtasks result in information that will, in the ideal case, support a designer's decisions that lead to an optimal design. Some may choose to plan a path through these subtasks toward the design goal. Such designers can be referred to as planners. Others are more comfortable starting the process and navigating the path as it arises. These designers are referred to as navigators.

This process is analogous to a problem where a person needs to cross a river as shown in Figure 4.1. Crossing the river requires stepping on rocks and wading through the water. Planners would seek a vantage point where the entire crossing could be observed. The planners would then map a path for the crossing. The path would be influenced by the background and strengths of the individual. One who was more adept at jumping and had more balance may establish a path that minimizes the need for wading and requires more daring jumps. Another more comfortable in water may plan to do more wading and avoid daring jumps. A navigator would tend to start crossing the water and handle obstacles as they are presented. This process would also be influenced by the background and strengths of the individual.

Neither of these approaches is more right or wrong than the other, and they each have advantages and disadvantages. A planner plots a path from a broad vantage point. While the starting point and goal can be seen, the details of the terrain may not be clear. When these details are encountered, they can affect the plan in unforeseeable ways. The planner must then retrace steps back to the vantage point to plot a new path or navigate with the hope of rejoining the path later. The navigator runs the risk of reaching points where further progress is unnavigable. It then becomes necessary to backtrack and explore new paths.

Clearly, both the planner and navigator would benefit from a guide. The planner would be helped by a guide who can find a good vantage point for viewing the river and then assist in formulating a plan that considers possible shortcomings in the crossing. A navigator would benefit from a guide who can foresee paths that are more likely to lead to a dead end. The guide's usefulness would depend on his background. A guide adept at crossing rivers but whom has never seen this river could provide some support. A guide who lives near the river and has crossed at this spot many times would be more helpful for the problem at hand. If a complete trip requires many river crossings, a guide possessing general knowledge on river crossing and experience with some of the crossings may be better than the previous two.

General design methodologies tend to support the design planner from a broad vantage point but lack the details to handle the specifics of a particular problem. Existing tools such as drafting packages and word processors are useful, but they lack the connectivity for efficiently handling a particular problem. An effective support tool would support the general planning and assist the decision making of particular navigations.

4.3 Simulation, Optimization and AI in Design

Decision support tools in design can tend to be classified in two categories, namely, simulation and optimization. Simulation is useful for predicting the performance of a given potential design. Optimization identifies designs that have the potential designs to meet a given performance goal.

Simulation support is only useful for analysis tasks and does not help with synthesis. Optimization, however, can be a powerful tool. Once a problem is mathematically formulated in terms of criteria, constraints and decision variables, optimization provides a powerful search strategy. However, optimization has failed to influence the field of design

greatly (Coyne et al, 1989). This can be largely attributed to the need for well-packaged mathematical formulations. The design enterprise does not lend itself well to mathematical formulations, but rather requires the manipulation and handling of information. The manipulation of non-mathematical information is associated with the field of artificial intelligence.

Researchers in artificial intelligence (AI) have started to recognize design as an application for their theories (Coyne et al, 1989). Efforts in AI have a similar approach as optimization. Optimization uses a search strategy to find a minima or maxima to an objective function in a space bounded by constraints. In optimization the current value of the decision variables in the objective function represents the current state of the system. Algorithms are employed to explore other possible states, and a move is made in a direction that improves the state of the objective function. If a search shows that no other state can produce an improved objective function, an optimum state is declared.

Techniques in artificial intelligence perform similar operations with information. Facts are organized by grammars that lead to classes, groups and objects. Searching through this space of descriptions of objects leads to alternatives that best match a description provided by the user. This set of alternative(s) is then declared an optimum. The problem with AI techniques is that the search is largely dictated by the syntax of the information provided to the system. The present state of development in AI techniques makes it beneficial only to rudimentary configuration design where alternatives can be precisely described.

4.4 An Alternative Model for Decision Support in Design

Design is a complicated human activity that can employ a wide range of methodologies. Different people approach the design enterprise in many different ways. A single approach is unclear, and it is questionable whether a model will ever be able to satisfy all designers. However, this does not mean that models and tools for the design process can not be helpful to the designer. A practical designer is most interested in utilizing tools that can assist in performing the needed tasks.

The arguments in the preceding sections suggest that a tool that can guide the designer through the design process will be of benefit. The guide should not seek to dictate the approach, but allow the designer to choose a path for design. It should include some of the methodologies found useful in design theory, but it should also give

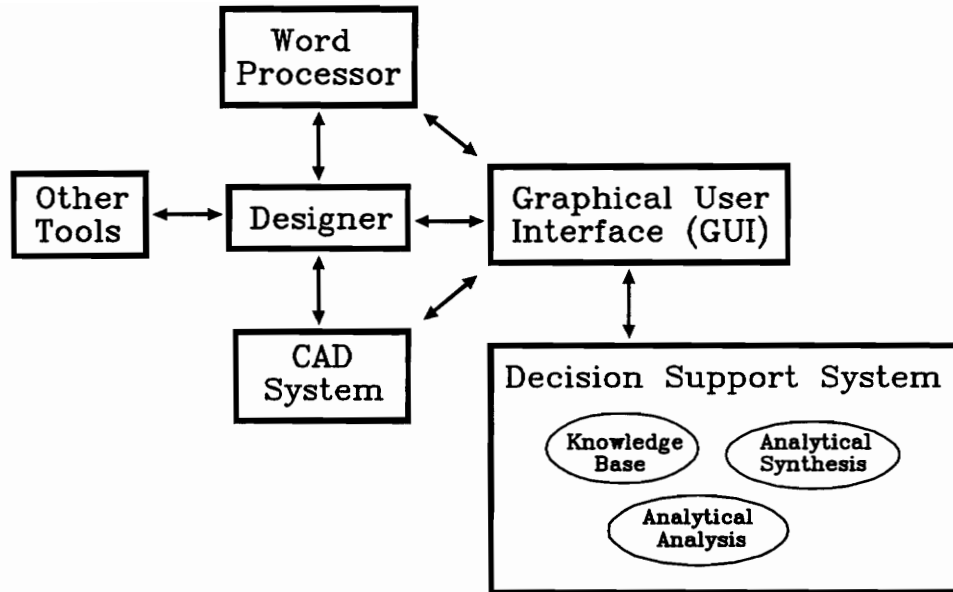


Figure 4.2: Proposed Design System Model

the designer freedom to decide when and if they will be accessed. It should not seek to replace the designer's decision making, but rather enhance it by providing pertinent information and assistance in performing analytical tasks.

Figure 4.2 illustrates a proposed model for a system to assist designers. The system provides the designer with access to a CAD system, word processor and other tools. The designer also has access to a decision support system that is integrated with the other tools. The decision support system contains a knowledge base of useful information and procedures, and synthesis and analysis formulations. The decision support system is broken into modules that follow the general methodologies presented in the last chapter. The designer may follow the methodology or use any module independently. Access to information is context sensitive. If the designer wants assistance, information relevant to the present task will be accessed directly. The designer can then explore related topics or go on with the design.

The support tools and the knowledge base must consider the stage of development of the design. During detailed design the designer can be best helped by providing easy access to specific analysis tools and information on available components. For example,

when considering how to assemble a part, general information on types of fastening techniques would be beneficial. The designer could then consider screws, rivets, welding, or epoxy, among others. Specific analysis tools for determining stresses and fatigue would be helpful. On-line catalogs of vendors would also be a benefit.

Many tools can be of assistance when designing for manufacturing. This can include information on alternative manufacturing techniques and process planning, along with detailed assistance for tasks such as determining speeds and feeds for cutting parts. An example of an area of particular assistance would be in establishing tolerances. Desired tolerances greatly affect the manufacturing processes. Information on processes and expected tolerances would be of great assistance to the designer.

The later stages of design require assistance with detailed decision making. The conceptual design stage, in contrast, requires more general information. During this stage, the exploration is broader. Details would likely only confuse matters. Special consideration must be given to the type of information provided and the manner in which it is organized. Because this stage involves a great deal of exploration, general tools for organizing information are helpful. Of particular help would be tools to assist the designer in clarifying the design objectives and formulating specifications. Integrating the information with drawing packages is especially helpful for conceptual design. The drawings help to clarify and communicate spatial relationships that are a common consideration during conceptual design.

Other stages of design require similar consideration. Organizing the tools and information with consideration for stages in design gives the designer the greatest freedom in approach and access.

4.5 Decision Support and Knowledge-Domain Dependence

General methodologies provide a guideline for the approach to a design problem. However, there are certain considerations and procedures particular to the field governing the majority of decisions that are more appropriate. The governing field for the design is often referred to as the knowledge domain. For a tool to be useful to a practical designer, it must include domain-dependent information and procedures. Rather than overwhelming the designer with information all at once, the tool should provide information and assistance useful for the current state of the design process.

Ideally, a designer would have access to knowledge and procedures for any knowl-

edge domain needed. The size of such a system would be enormous and beyond the capabilities of current technology. For practical purposes, it is necessary to focus on particular knowledge domains for development. The same model can be applied to any knowledge domain, however.

There are many software packages that assist in particular aspects of a knowledge domain. The literature review cites several examples for linkage synthesis and analysis and cam synthesis. In isolation, the software packages have limited utility. Integrating domain-specific support tools that cover the entire design process into a user-friendly environment will increase usability and productivity.

4.6 Conclusions

The design enterprise is as complicated as the human mind. We cannot fathom the many processes a designer uses to make decisions. Imposing a path would only restrict the development. Given the current state of design knowledge, assistance is best provided by incorporating models that give the greatest freedom to the designer. The models should include consideration for the stages of the design process. Conceptual design, detailed design, and design for manufacturing each incorporate particular information and process. The types of tools and the information that is provided can affect the efficiency of the process.

The system proposed in this chapter is a model for developing computer-based design assistants. The model can be applied to any knowledge domain. While practical considerations limit the scope for development, through time and a concerted effort, individual systems can be linked to provide a more comprehensive design support tool.

The following chapters describe the development of such a system to assist in the early stages of cam mechanism design. The application illustrates how the general methodologies from chapter three can be directed to a specific domain and incorporated with the domain-specific information and procedures.

Chapter 5

Information Modeling in Conceptual Cam-Mechanism Design

5.1 Introduction

In many knowledge domains, models have been developed to assist the designer in performing analysis and optimization of a design alternative. The design process is then viewed as an iterative procedure of generating alternatives, analyzing them, and then evaluating them to select the best one. This is clearly seen in the domain of structural design where a part shape and material are selected, and then analyzed based on standard failure theories. The final design is selected based on functional performance and failure criteria. Tools such as finite element modeling have greatly assisted this process by automating some of the analysis. However, it can be seen that a designer experienced in the domain can greatly assist this process by applying background information and experience to wisely select the alternatives and reduce iterations. A naive designer, on the other hand, would clearly benefit from this information.

So then, what is the best approach for the naive designer encountering a design problem in a new knowledge domain? One approach would be to seek out all available information on the domain and study it to gain some form of proficiency before beginning the design. Another approach is to start directly into the design process and gain knowledge along the way. Clearly, neither of these approaches is ideal. It would be best if the naive designer had access to a model of the process for undertaking the design. Rather than overwhelming the designer with information all at once, the model would include information appropriate for the decision making at each stage of development.

Presented here is a model of the process for the conceptual design of cam mech-

anisms. The model includes information and techniques for designing the overall cam mechanism and synthesizing the cam profile. The focus is on the methodologies and considerations for the design process. As mentioned in the literature review, graphical and analytical techniques for synthesizing the cam profile are well developed. Details of these techniques will only be provided when appropriate. An example will be used throughout the discussion to clarify some of the points. The example considers the design of a cam mechanism to position a tube so that it can be filled with toothpaste. More details for the example will, of course, be presented along with the discussion.

5.2 Problem Confrontation and Clarifying Objectives

The problem confrontation can come in many forms. The designer may be presented with a set of specifications that delineates the performance for the design. Or the problem may be presented as vaguely as the toothpaste-tube-filling example in the introduction to this chapter. In any case, the designer must then decide how to get started. This is often the most daunting task for the naive designer. The first step for the designer is to clearly understand the objectives of the design problem. Whether or not detailed specifications are given, the designer will benefit by formulating a list of objectives. The objectives are general statements about the design, unlike the particular statements in the specification that bound the problem. Existing specifications may contain restrictions that unnecessarily bound the problem beyond the true objectives of the design.

The designer should develop a general statement that embodies the main objective for the design. Because we are dealing with cam mechanism design here, this main objective statement will include the purpose for cam mechanisms. As will be seen later, this is not to say that the problem should be so constrained, but it is necessary here to lead into the further development in this knowledge domain.

The purpose of a simple cam mechanism is to move an object through some prescribed motion.

The cam's rotation may directly move the object, or it may influence the motion of intermediate parts that function as an integrated machine. In this case, the object to be moved is the connecting intermediate part. The problem here is limited to simple cam mechanism design where the object is moved directly with the rotation of the cam. More complicated mechanisms that include combinations of cams and linkages require special consideration beyond the scope of the current topic. A discussion of these *cam-*

modulated linkages appears in Shooter, Tidwell, and Reinholtz (1994). However, many of the concepts presented here also apply to that problem.

Upon examination of the purpose of a simple cam mechanism, it is clear that it does not differentiate itself from that of a linkage mechanism, industrial automation, or even a programmable robot. Therefore, including the use of a cam mechanism in the overall objective statement is unnecessarily limiting. It will be left until later to decide if using a cam mechanism is the best alternative.

The main objective should be reduced to a statement presenting the movement of an object. In the example, the main objective can be reduced from “design a cam mechanism to position a tube so that it can be filled with toothpaste” to “move a tube so that it can be filled with toothpaste”. The statement includes the need for motion, a description of the object, and a reference to the purpose for the motion. Notice that this statement may also be unnecessarily limiting. It is assumed here that the tube must be moved into position to be filled. However, the overall goal is simply to fill the tube. This may be accomplished by moving the filling nozzle to the tube. For the sake of the current discussion on cam design methodology, consider that the design is restricted to moving the tube into position for filling.

5.2.1 Establishing Sub-Objectives

As presented in Chapter 3, the next step is to establish sub-objectives in support of the main objective. A good start for generating these statements is to consider the three keys in the main objective: the object being moved, the motion, and the need for the motion.

When considering the object being moved, it is helpful to include a description of the object and any considerations for the handling of the object. In the example, the object being moved is the tube. The tube may be made of thin aluminum or a flexible polymer. An objective may be to ensure the integrity of the tube. Supporting this statement could be the objective of preventing bending or kinking of the tube. These statements can go on and on. In formulating these sub-objectives, it is helpful to have the most complete description of the object as possible. Ideally, a good drawing describing the object is helpful in this stage as well as in later stages when designing the carrying part or follower.

The desired motion should be carefully considered. How must the object be moved to meet the main objective? This can start by considering the purpose of the motion. In the example, the tube is moved to the nozzle for filling and then, presumably, returned to

a position where it can be moved on for further operations. Another tube is then placed in position for filling, and the operation repeats. It is clear here that the tube must be kept stable for part of the movement so that it can be filled, and also held in position so that it can be removed to the next station. Included here may be the objective of doing these operations as fast as possible (ie. minimizing cycle time). In addition, filling the tube may require a limitation on the tube's shaking. Any thoughts or concerns regarding the motion should be written as an objective.

When considering the need for the motion, the general scheme of how this piece fits in with the rest of the operations should be considered. For example, the objective of timing this motion with other motions in the process can be critical. Knowledge of what is happening before, during and after this operation should be considered in the objectives. Environmental considerations should also be included. It is beneficial to have a drawing of the environment where the task will take place. This should include any equipment that is nearby. It may not be possible to have much detail in this early stage. However, general outlines can be helpful. The drawing should be seen as a dynamic document throughout the design process.

Mentioned here were just some of the considerations when establishing objectives. The list in Table 3.1 is helpful for stimulating thought when formulating objectives. The point is to keep the statements general at this stage. Its important at this point not to be concerned with how the objectives fit in with each other. It is best to generate a list of objectives and then arrange them in a tree of supporting objectives later.

5.2.2 Formulating an Objectives Tree

As presented in Chapter 3, some objectives will clearly present themselves as contributing to the performance of another objective. The objectives should then be organized in a tree or outline form that illustrates the connectivity of objectives. It has been suggested that weights be placed on objectives to signify relative importance. This can be a helpful procedure. However, care must be taken to avoid the false impression given by assigned numbers.

Figure 5.1 illustrates part of the objectives tree for the toothpaste example. Figure 5.2 is a drawing of the open tube that will be crimped at a later station. Figure 5.3 is a drawing of the environment. It is also helpful to illustrate the allotted space for the mechanism and any obstructions as shown in Figure 5.4. In general the drawings should

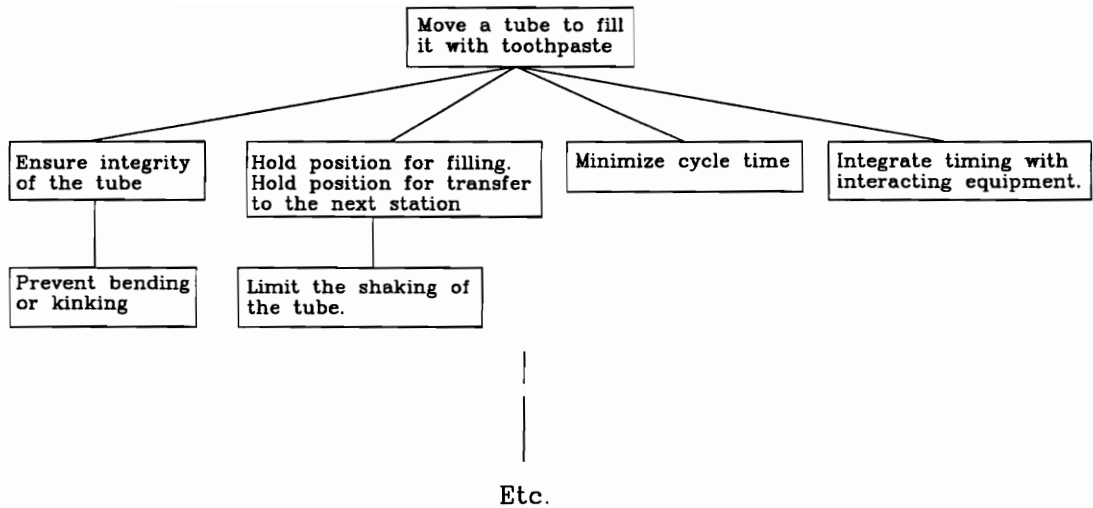


Figure 5.1: Partial Objective Tree for Toothpaste Example

include:

1. The object being moved.
 - (a) Necessary positions.
 - (b) Required orientations.
2. The environment
 - (a) Interacting equipment
 - (b) Areas of obstruction
 - (c) Areas that must be left clear
 - (d) Objects that enter the space
3. The space for the mechanism.
 - (a) Obstructions
 - (b) Driveshaft locations, if set

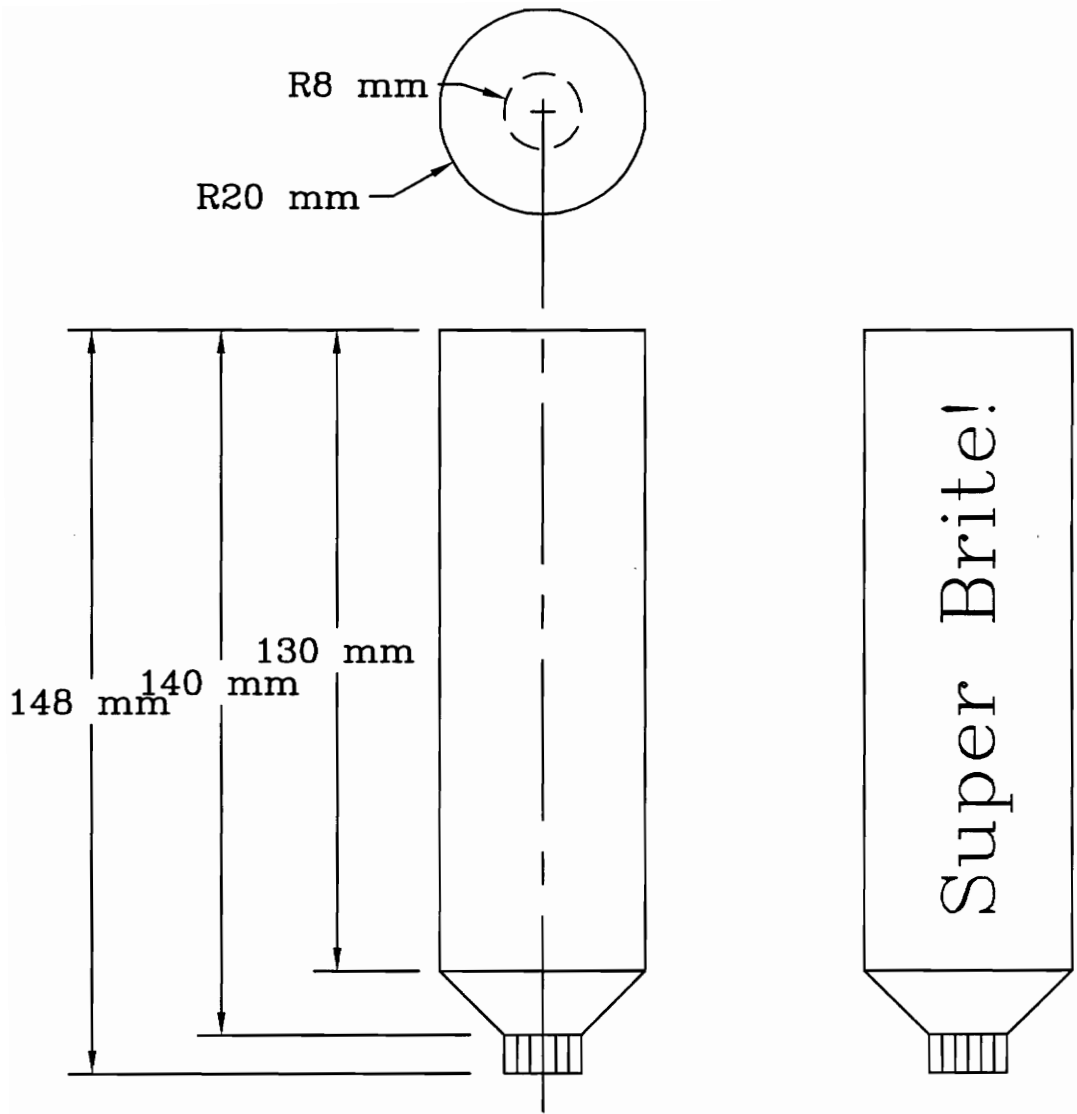


Figure 5.2: The Object to be Moved (Toothpaste Tube)

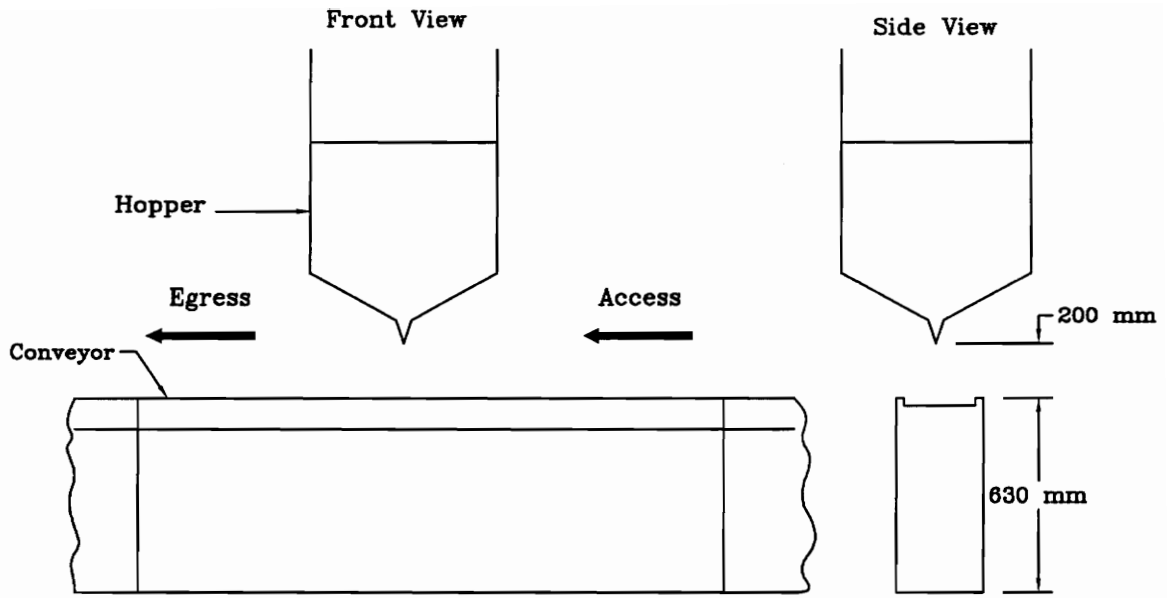


Figure 5.3: The Environment for the System

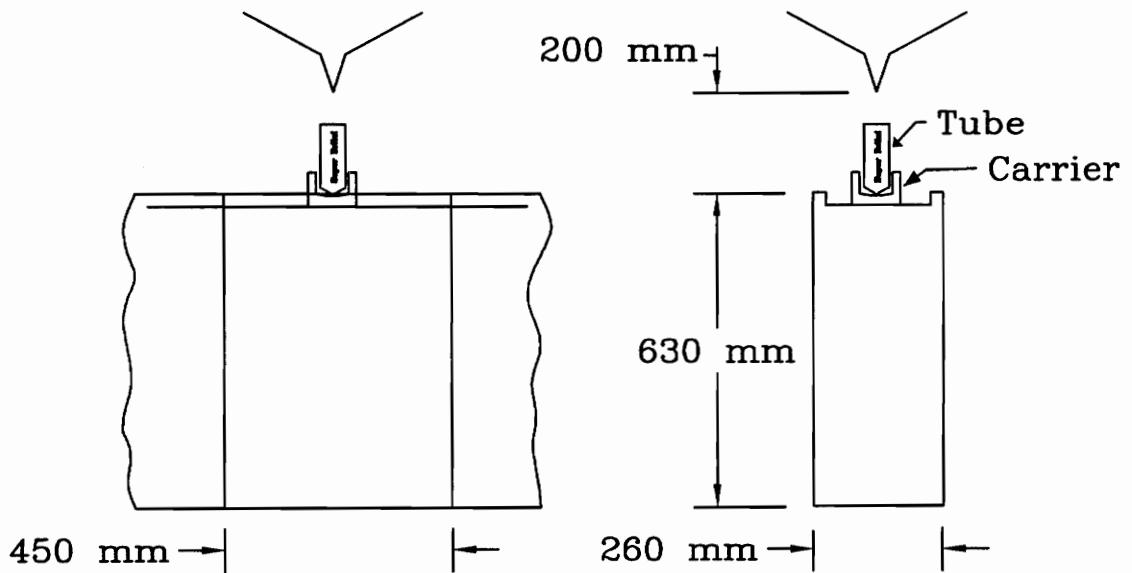


Figure 5.4: Details of the Mechanism Space

The drawings should include as much detail as possible. However, the designer should not be overly concerned at the lack of detail at this stage. The drawings are dynamic documents that will be updated as more information becomes available. Their purpose at this stage is to provide a visual scenario for the design.

5.3 Formulating Specifications

The list of objectives provide general statements for the goals of the design. In contrast, the specifications provide guidelines for the requirements of the design and bound the problem with constraints. The specifications seek to provide both qualitative and quantitative descriptions for the design.

There may be an existing set of specifications. The list of objectives should be compared to the specification list to ensure their compatibility. Often, it will be found that some specifications unnecessarily overconstrain the problem, or some factors are not emphasized enough. Reviewing the specifications in conjunction with the objectives will help to clarify and solidify the nature of the problem.

If specifications are not already made, the objectives provide a guideline for their development. Each objective that was stated in general terms should be developed to more qualitative and quantitative guidelines. The same list of considerations in preparing the objectives is helpful for preparing the specifications. The most important specification for cam mechanism design problems will involve the desired motion. In order to provide clear and concise descriptions of the motion, it is helpful to understand the language used.

5.3.1 Descriptions of Motion

There are two general categories of motion constraint. The first is termed *Critical Extreme Position (CEP)* motion. This is characterized by having the motion specified at the beginning and end positions of the body's travel. The motion between these end points is not defined. This gives the designer more freedom in developing the motion between the extreme positions. While the travelling motion is not directly specified, it is often governed by considerations of force and vibration.

Critical Path Motion (CPM) is characterized by having the traveling motion and one or more of its derivatives (velocity and acceleration) defined. The motion could be defined over all or part of the travel. In kinematic synthesis, the design of mechanisms

for CPM motion is often described as function generation because the output is a direct function of the input. The desired function could be complicated. However, it is often described by a simple motion such as a constant velocity segment or a drop function. The constant velocity is often specified in manufacturing situations where operations are performed on an object that is moving at a constant rate on a conveyor system. The drop function is characterized by an “instantaneous” change in position. This is often seen in triggering mechanisms.

The toothpaste example is best described as CEP motion. The tube must be moved to a position for filling and then return to the home position to continue on the conveyor. The extreme positions are further constrained in that the position must be held for some time duration. The holding position is often referred to as a *dwell*. Assume that filling the tube takes 0.7 seconds and that transfer of a full tube and a new tube requires a dwell of 0.4 seconds.

It is helpful when establishing the motion constraints to illustrate the needed motion on the drawing of the system. In the case of CEP motion, the object can be drawn at both ends of the motion. This is helpful for determining the distance of travel, often referred to as the *Stroke*. In the case of CPM motion, the object’s path can be illustrated on the drawing. Plots of the position, velocity and acceleration should be developed. Figure 5.5 shows the toothpaste tube at both extremes of motion. From the drawing it is clear that the tube must travel a vertical distance of 60 mm. It may be possible to reduce this distance by lowering the hopper. However, clearance must be allotted for access and egress of the tube to the station. For now, the distance will be specified as 60 mm. The resulting motion plot for position appears in Figure 5.6. It is desired to establish the total cycle time at 2.0 seconds.

5.3.2 Making the Specifications List

Generating the specification list follows the general procedure outlined in Chapter 3. However, there are specific considerations for the domain of cam design. As outlined above, a thorough description of the needed motion should be included. The presence of any particular motion segments and their durations should be noted. The required time for a cycle should also be listed. The actual cycle time can be influenced by several factors, so it is often beneficial to provide an acceptable range. Any known limitations on velocity and acceleration should be provided. In general, inertial forces act in proportion to

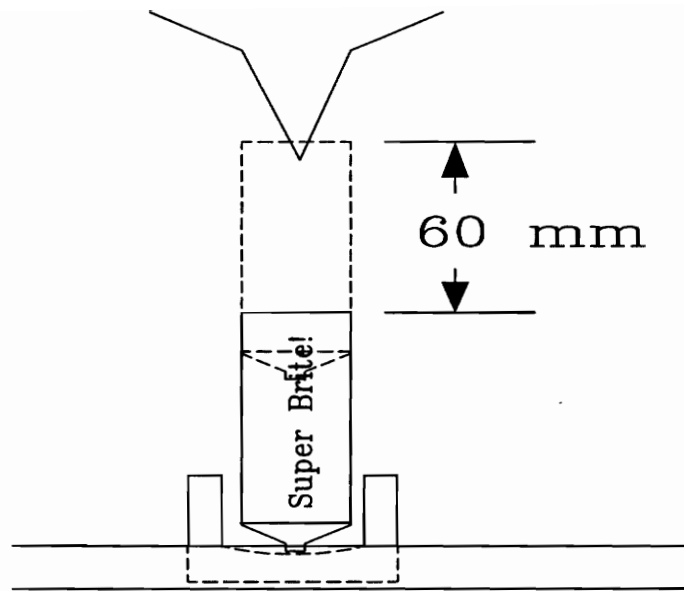


Figure 5.5: Toothpaste Tube at Two Critical Extreme Positions

acceleration. The kinetic energy of the system is related to the velocity and can influence the effect of vibrations. It is beneficial to minimize the peak acceleration and the peak velocity. As will be shown later, these parameters are governed by various motion types and the time for the motion (ie. cycle time). Testing or analysis can help determine limits for any of these values. However, absolute constraints are often difficult to establish at this early stage.

In general, the topics in the checklist of Table 3.1 should be considered when generating the specifications list. Along with the list of specifications, it is helpful to list the resources available for producing the system. Will this system be produced in house? How many will need to be built? Is this to be part of a mass-produced product or a small lot for in-house equipment? What are the shop facilities available? Who will be performing maintenance and repair? The answer to these questions can greatly facilitate decision-making when confronted with alternative solutions.

The specifications should be gathered and grouped in general categories for placement on the specification sheet. Each specification should then be recognized as a demand or a wish. Often naive designers do not recognize that most things are negotiable. Absolute demands are restrictions imposed by the purpose of the system and the environment.

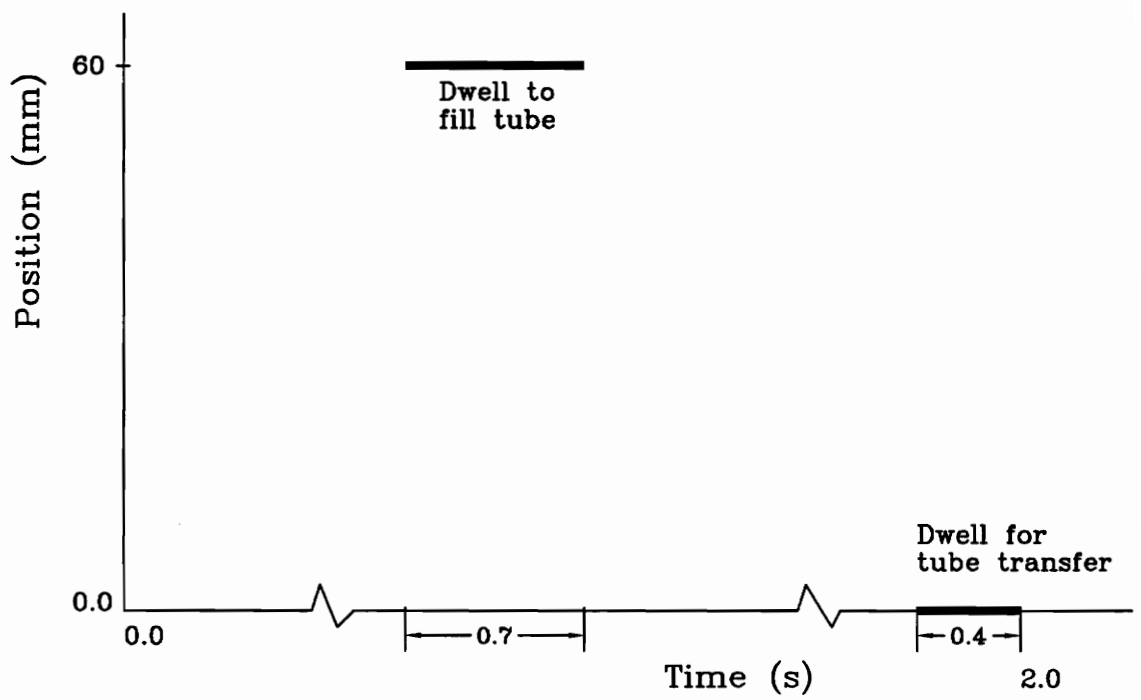


Figure 5.6: Incomplete Position Description for Toothpaste Tube CEP Motion (specified motion segments shown in bold, intermediate motions to be added)

The distance of travel and the dwell times in the toothpaste example are probably not negotiable without other design changes outside the realm of the current problem. These are limitations set by the purpose of the device. Often, restrictions such as the allotted space are not negotiable. Most mechanism design is restricted by spatial constraints. Care should then be given to other specifications that are listed as demands. Because the purpose of the specification list is to provide guidance for the design, the specifications described as “wishes” can be given weights to indicate their importance. These values should be viewed as guidelines rather than as absolute indications of relative importance. Figure 5.7 shows part of the specification sheet for the toothpaste example. In this example, the wishes are weighted on a five point scale, five being most important.

5.4 Using a Cam Mechanism vs. Other Choices

This dissertation focuses on providing assistance for the design of cam mechanisms. In the toothpaste example, it is assumed that the need is to move the tube to fill it. This, of course, is not the only possibility. One can abstract the problem in a broad number of directions. The true goal may be to develop any means resulting in a full tube. It can be beneficial to use the creative techniques such as brainstorming or any of the prescriptive models discussed in chapter 3 to generate possible alternatives. Because these creative approaches were discussed in chapter 3, they will not be presented here. The discussion will focus on cam mechanisms and reasons for using them.

Why use a cam mechanism rather than other alternatives? As mentioned previously, a linkage, industrial automation or a programmable robot could also be used to move an object through a prescribed motion. One must consider the advantages and disadvantages of each when choosing among alternatives.

A robot provides the most flexibility in providing any motion. By controlling any number of actuatable joints, the robot can move an object into any position and orientation in its workspace. This flexibility is costly. The mechanical design of the robot is complex and the motions must be controlled by computer. A robot should generally be considered for operations that require many different and complex motions to warrant the cost of a robot.

Industrial automation is a step down on the flexibility scale. Automation involves using combinations of actuators to move an object. The synchronization of these actuators is maintained by a programmable controller that monitors any number of switches and

Super Brite, Incorporated		Specification for a System to move a tube to be filled with toothpaste.		Established: June 1, 1995	
Changes	D W	Headings	Requirements	Responses	
	D D D	Kinematics	Required motion characterized as Critical Extreme Position Motion. Dwell time for filling tube = 0.7 seconds Dwell time for tube transfer = 0.4 seconds Stroke between positions is 60 mm		
	W5		Nominal cycle time set at 2.0 seconds - this operation is recognized as critical path, so all efforts should be made to reduce cycle time		
	D		Integrity of the tube must be maintained requiring smooth transition to dwell dwell positions		
	W3		Minimize peak accelerations (values to be determined by analysis)		
	W3		Minimize vibration that can cause spilling of toothpaste (analysis required)		
	D		Maintain vertical orientation of the tube		
	D D		Geometry	Space restrictions depicted on Drawing 231	
				Maintain clearance for access and egress to the station (Drawing 231)	
	D D D D D	Moved object geometry	Dimensions and description of tube in Drawing 232		
			Support must be provided to ensure integrity of the tube		
			Must ensure that the tube will not fall or spill		
			Empty tube weight for rise motion is 40 grams		
			Filled tube weight for fall motion is 220 grams		
	D W4 W4	Timing	Integrate timing with other stations		
			Use single power source to ensure timing integration in hardware		
			Utilize power shaft rotating at constant angular velocity		
	W3 W4	Forces	External forces limited to the contact of the tube and support		
			Imbalance by moving parts must not affect the stability of the tube		
		Power			
	D	Materials	Materials are limited by those accepted for food preparation environment in FDA Regulation 10429		
	D W5	Friction	Lubrication must be accepted by FDA Regulation 10430		
			Avoid all possible contamination of the product		
		Operation			

Figure 5.7: Sample Specification Sheet for Toothpaste Example

indicators. Combinations of logical indications from the switches compels the controller to activate the actuators. This type of automation provides flexibility in changing parts of the process without affecting others. However, programming the system can be complicated and failure of any sensor can debilitate the system.

5.4.1 Cams vs. Linkages

Both cams and linkages can be thought of as hard automation. The motion is “hard programmed” into the mechanism by specifying the geometry. They are the least flexible in that a desired change in the motion requires a new mechanism. However, repetitive actions can be performed at significantly higher speeds than with flexible automation or robots. They are often more reliable because they are less complex with little or no need for control.

The primary advantage of a cam over a linkage is that a cam can provide continuous precision for a desired motion. Provided spatial constraints allow it, the shape of the cam can be designed to place the follower exactly where it is wanted at any point in time. A linkage can only be synthesized for a limited number of precision points where the motion will be exactly as desired. Any position other than the precision points will have an error between the desired position and the actual position. If the desired motion must be produced exactly, then the only choice is a cam mechanism. If precision at a limited number of points is acceptable, then a linkage may be a better choice.

Another situation in which a cam has an advantage over a linkage is when the motion requires that the position be held in a dwell for a period of time. Linkages can be synthesized to approximate a dwell, but the procedure can be tedious and does not produce an exact hold of position. Dwells are very easily synthesized for cam mechanisms.

Before the explosive growth of computers, cams were used more often than linkages because cams were easier to synthesize. Graphical techniques to produce a cam for a desired motion are relatively straight forward. The greater difficulty in manufacturing a cam was accepted for the ease of design. Today, there are several computer programs to assist the designer in synthesizing linkages, which is a computationally intensive task. This now makes linkages a more attractive option.

There are other considerations for using cams rather than linkages. Cam mechanisms are generally more compact in design and have fewer moving parts. The most basic four-bar linkage requires more space. More complicated motions often require even more

links which adds to the needed space. Cams also have an advantage for dynamic balancing. Because the cam rotates on a fixed axis, any dynamic imbalance can be eliminated by applying a counterweight similar to balancing the tires on a car. Because linkages have links undergoing complex motions, they are not easily balanced.

Linkages have several advantages over cams. Cams are sensitive to the manufacturing accuracy of the cam contour. A small error on the cam profile can cause severe vibration in follower response. Slight manufacturing inaccuracies in linkages usually have little effect on output response.

Because of the sliding contact between the cam and follower, cam mechanisms require lubrication to reduce wear. Often, environmental restrictions can force the cam to be run dry, without lubrication. In such instances, the cams experience rapid wear which results in positional inaccuracies and noise. Linkages are often composed of revolute joints that can be achieved with sealed bearings. Wear is typically not a problem with linkages.

Traditionally, cams have been harder to manufacture than linkages. Cutting the precise contour required special equipment and training. The prevalence of CNC machines has alleviated this problem to some degree. Because linkages typically require more parts, the added complexity in linkage assembly may be considered in contrast to the added machining of a cam.

Consider the toothpaste tube filling example. The need for the two dwells in the motion strongly suggests using a cam mechanism rather than a linkage. However, the simple linear motion between the extreme positions could easily be produced with linear actuators and flexible automation control. The linear travel can be achieved quickly with a pneumatic cylinder. The extreme positions would be sustained with hard stops. An examination of this alternative, however, shows that a cam mechanism is the better choice. The pneumatic actuation requires hard stops at both extreme positions of travel. The hard stop does not provide a smooth transition to the dwell position. This abrupt halt can create enough force to jeopardize the integrity of the toothpaste tube and can create unwanted vibrations. The pneumatic cylinders do not provide for control of the motion in between the extremes. The cam mechanism provides for the dwells at the extremes and allows for control of the intermediate motion for limiting forces and vibrations.

5.5 Cam Mechanism Terminology

After determining that a cam mechanism is the most appropriate solution to the design problem, the design proceeds with methods particular to the realm of cam design. At this point it is helpful to review the terminology of cam mechanisms. This information can be found in any kinematics text but is presented here for convenience.

A simple cam mechanism has three basic components: the cam which is the driving element, the follower or driven element and the fixed frame which supports the system. Often there are additional elements such as a spring that is used to ensure that the follower maintains contact with the cam surface.

Cams can be designed in a multitude of shapes and sizes. A cam can operate in a plane or in three dimensional. Figure 5.8 shows a spatial cam where the axis of the cam is not perpendicular to the plane of motion, several cylinder cams and a disk cam. Spatial cams have rare applications and are not often used. Cylinder cams are formed by cutting a groove to guide the path of a follower. By far the most prevalent type of cam is the disk cam that produces planar motion. It is this type of cam on which this dissertation focuses.

Followers are classified by the type of motion they produce, their shape and, in some cases, their position with respect to the cam. Figure 5.9 illustrates the four basic follower types considered in this dissertation: the translating flat-faced follower, oscillating flat-faced follower, translating roller follower, and oscillating roller follower. In the case of the translating roller follower, the location of the roller is described as being radial (along the radial line) or offset some distance from the radial line. Followers can be made in any desired shape. However, these types are by far the most common.

The cam and follower must be supported by bearings as part of the constructional form or frame. There are essentially three types of frames: dual support, cantilever, and a combination of the two as shown in Figure 5.10. The dual support provides for the simplest bearing arrangements. It also allows the highest speeds for a given load and gives the greatest rigidity because each member is straddled by a pair of bearings. Difficulties with the dual support lie in obtaining rigidity in the frame and ensuring accurate alignment. Access is not as easy for inspection and repair. Cantilevered construction is more convenient for assembly and repair, but less rigid. Lack of support is often compensated by using larger shafts and pre-loaded bearings. It may be beneficial to use a combination of the two types where the cam may be dual supported and the follower cantilevered. This

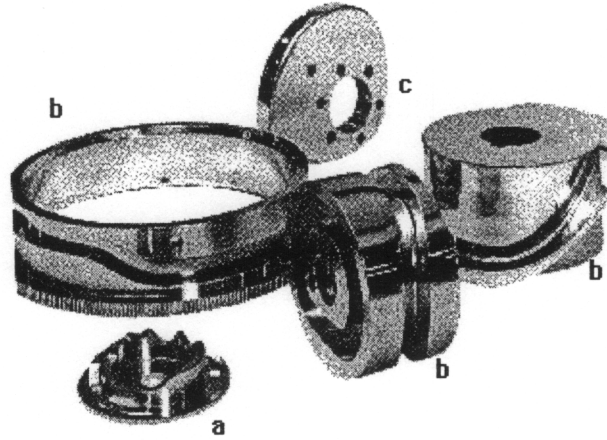
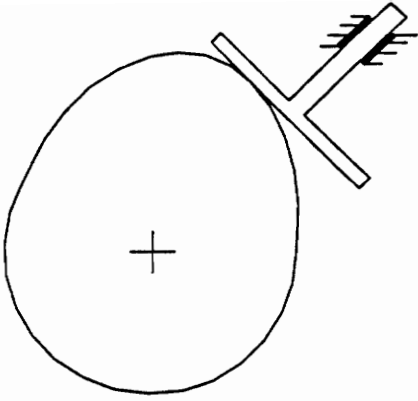


Figure 5.8: Types of Cams (a: spatial cam; b,c,d: cylinder cams; e: disk cam), Norton (1992)

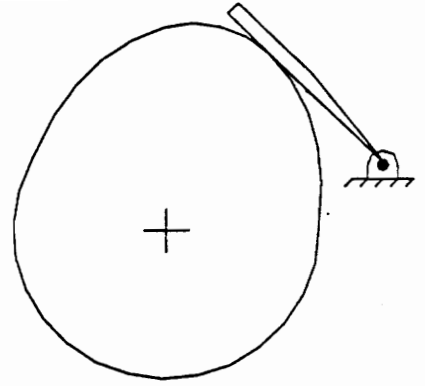
gives the cam the necessary support and allows access to the follower for maintenance and repair.

5.5.1 Cam Mechanism Nomenclature

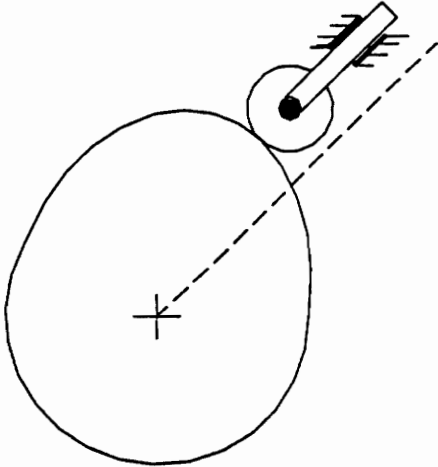
Figure 5.11 illustrates a disk cam with common nomenclature. The *cam profile* describes the contour of the cam. The synthesized cam profile defines the resulting motion of the follower. In the case of a roller follower, an imaginary curve called the *pitch curve* describes the path of the center of the roller. The *base circle* is the smallest circle tangent to the cam surface about the center of rotation of the cam. The base circle provides the starting point for the cam profile synthesis, thereby governing the size of the cam. The cam and shaft may be cut from one piece of stock. Often, however the cam is attached to the shaft with a *hub* that is keyed to the shaft. The *key* is nothing more than a piece of material that fits in a groove in the hub and the shaft. The distance between the two extreme positions of the follower is termed the *stroke*. A characteristic that often governs the cam profile synthesis is the *pressure angle*. The pressure angle is the angle between



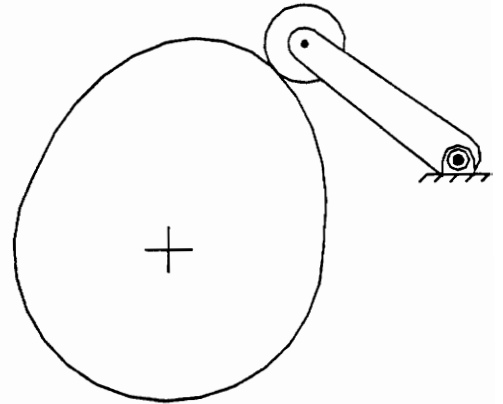
Translating Flat-faced Follower



Oscillating Flat-faced Follower



Translating Roller Follower



Oscillating Roller Follower

Figure 5.9: Common Follower Types

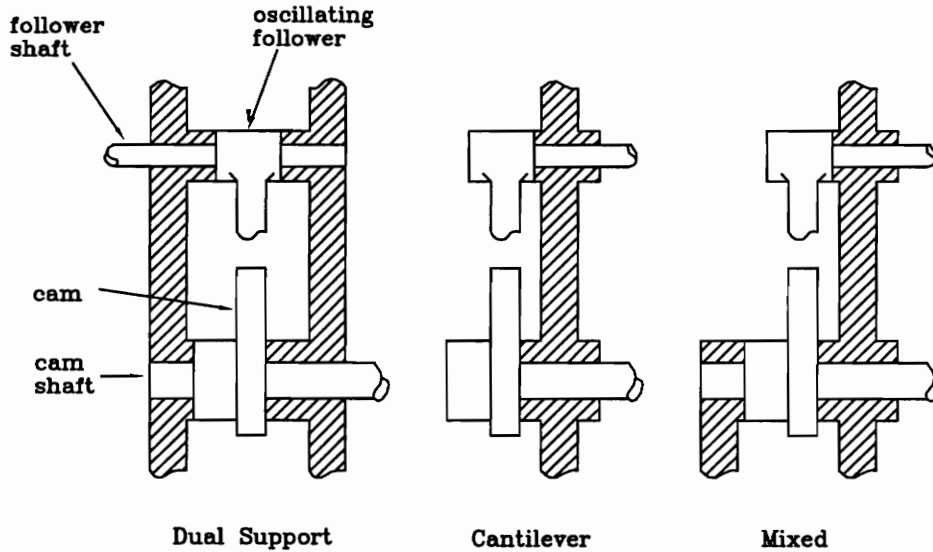


Figure 5.10: Cam Mechanism Support Frames

the direction of motion of the follower and the *common normal* between the cam and follower. The common normal can always be drawn through the point of contact between the cam and follower and the center of curvature of the follower surface. For roller followers, the center of curvature is the center of the roller. The center of curvature for a flatfaced follower lies at infinity, so the common normal is perpendicular to the flat face.

5.6 Formulating the Motion Program

The required motion for a cam mechanism is often an under-defined problem. Usually only part of the motion cycle is specified, giving the designer freedom to generate the remaining motion to best suit the dynamic constraints. Often, it is the motion program that has the greatest effect on the dynamic performance of the cam mechanism. Formulating the motion program often involves an iterative procedure between specifying motion types, selecting follower types and cam characteristics.

There are several factors that influence the motion program formulation. Foremost, it is important that the function be continuous through the first and second derivatives

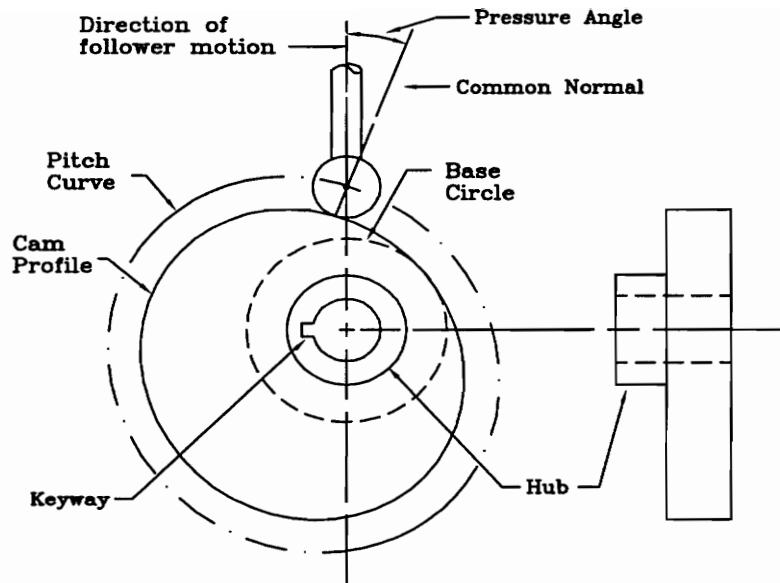


Figure 5.11: Cam Mechanism Nomenclature

of displacement (velocity and acceleration) across the entire interval (360 degree rotation of the cam). Ensuring this eliminates the possibility of having infinite jerk (the third derivative of displacement). Areas with infinite jerk will undergo extreme impacts between the cam and follower which increases wear and may result in unwanted dynamic effects. The areas of greatest concern for producing infinite jerk occurs at the junctions between motion specifications. Techniques for avoiding infinite jerk will be presented later.

It is also best to have a smooth jerk profile throughout the cycle because discontinuities in the jerk function tend to excite vibratory behavior in the follower train. While it may not be possible to eliminate these discontinuities, it is desirable to minimize them.

It is desirable to minimize magnitudes of peak acceleration and peak velocity. Dynamic forces are directly related to acceleration. Kinetic energy is directly related to velocity. This is especially important in multi-dwell mechanisms where vibrations can affect the dwell position. This becomes even more critical when the follower mass is very large.

Another consideration is to avoid taking the acceleration to zero unnecessarily. The only justification for taking acceleration to zero is to connect to a zero acceleration curve such as a dwell or constant velocity or a need to change sign.

Because these factors are co-dependent, the designer must try many possibilities

and select the best one by making compromises.

5.6.1 Types of Motion Programs

It is often helpful to characterize the desired motion program because different types lend themselves to selection of particular motion curves. The first type is simple Rise-Fall motion. If the specification calls for Critical Extreme Position (CEP) motion with no dwell, it is often better to consider a linkage. The linkage can be a crank-rocker four-bar or a slider crank depending on whether the desired motion is oscillating or translating respectively. The Rise-Fall motion does not warrant the added complications of a cam mechanism. If the required motion is Critical Path Motion (CPM), however, the cam mechanism does have an advantage in that it can produce the desired function exactly. This is especially true if the displacement derivatives are defined over an interval. It is very difficult to synthesize linkages for specified derivatives of displacement.

Another common type of motion is Rise-Fall-Dwell, or Single-Dwell, motion. In this case using a linkage is not an option. The curve selection must ensure smooth transition to the dwell. Also, in changing directions from rise to fall, one should ensure that there is not an unnecessary return to zero acceleration.

Rise-Dwell-Fall-Dwell motion is characterized by dwells at both extreme positions. This requires a smooth transition to and from the dwells at four junction points. Included in this category are any number of multi-dwell situations. Although it is rare that multiple dwells are required.

The final type of motion is generally referred to as Custom Motion. In this category falls situations such as periods of constant velocity or drop functions. These programs can take on any level of complexity. Often, following the guidelines above can assist in formulating these complex systems.

5.6.2 Motion Curves

There are many types of curves that can be used to fill in unspecified portions of the motion program. Traditionally, these curves have used trigonometric functions and polynomials. More recent research has focused on the generation of more complex motions using B-Splines. However, the use of trigonometric functions and polynomials is still more prevalent. Presented here are some of the most common motion curves that can be used to adequately handle the large majority of desired motion programs.

Harmonic Motion

Figure 5.12 illustrates assorted segments of harmonic. Segments H-1 and H-2 are useful for the rise while H-3 and H-4 provide motion for the fall of the follower. These four segments combine to make a complete cycle. Because two segments make a rise or a fall, these curves are referred to as Half Harmonics. H-5 and H-6 illustrate the same complete harmonic cycle broken into two parts. They are often referred to as Full Harmonics. Upon study of the curves, it is clear that H-1 and H-2 combine to form H-5, and H-3 and H-4 combine to form H-6.

In the curves, S signifies position, V signifies velocity and A signifies acceleration. The position, velocity and acceleration equations are given as a function of the cam's rotation, θ . The equations require that θ must be given in radians. The abscissa is provided in relation to the rotation of the cam so that the motion program can be generated without consideration of the angular velocity of the cam. For a cam rotating at a constant angular velocity, there is a linear relationship between time and cam rotation.

The same curves may be used for translating or oscillating motion. In the case of translating motion, the position, S, would be in units of distance such as millimeters, velocity would be in units of distance/radian, and acceleration would be distance/radian². In the case of oscillating motion, the position, S, would be described with units of degrees or radians. The velocity and acceleration would also use these units. It is important to note that the same curves can be used directly for oscillating motion. Often the naive designer attempts to convert the oscillating motion to some linear correspondent. This is not only unnecessary effort, but results in undesirable motion programs.

Examination of the harmonic curves provides insight that can be helpful when generating a motion program. The acceleration is proportional to the displacement and in the opposite direction. The acceleration is smooth and continuous, and provides one of the lowest peak accelerations of the alternatives yet to be discussed.

In all of the curves, the velocity and acceleration on the end points do not correspond. That is, when the velocity is zero, the acceleration is finite, and vice versa. Therefore, harmonic motion will never provide a smooth transition to or from a dwell. Because a dwell exhibits zero velocity and acceleration, there will always be a disjoint transition or discontinuity when attempting to blend a dwell with a harmonic curve. This produces infinite jerk and causes high impact loads. Figure 5.13 illustrates this point where an H-5 rise is used to join with a dwell, and an H-6 fall connects to the bottom dwell. In

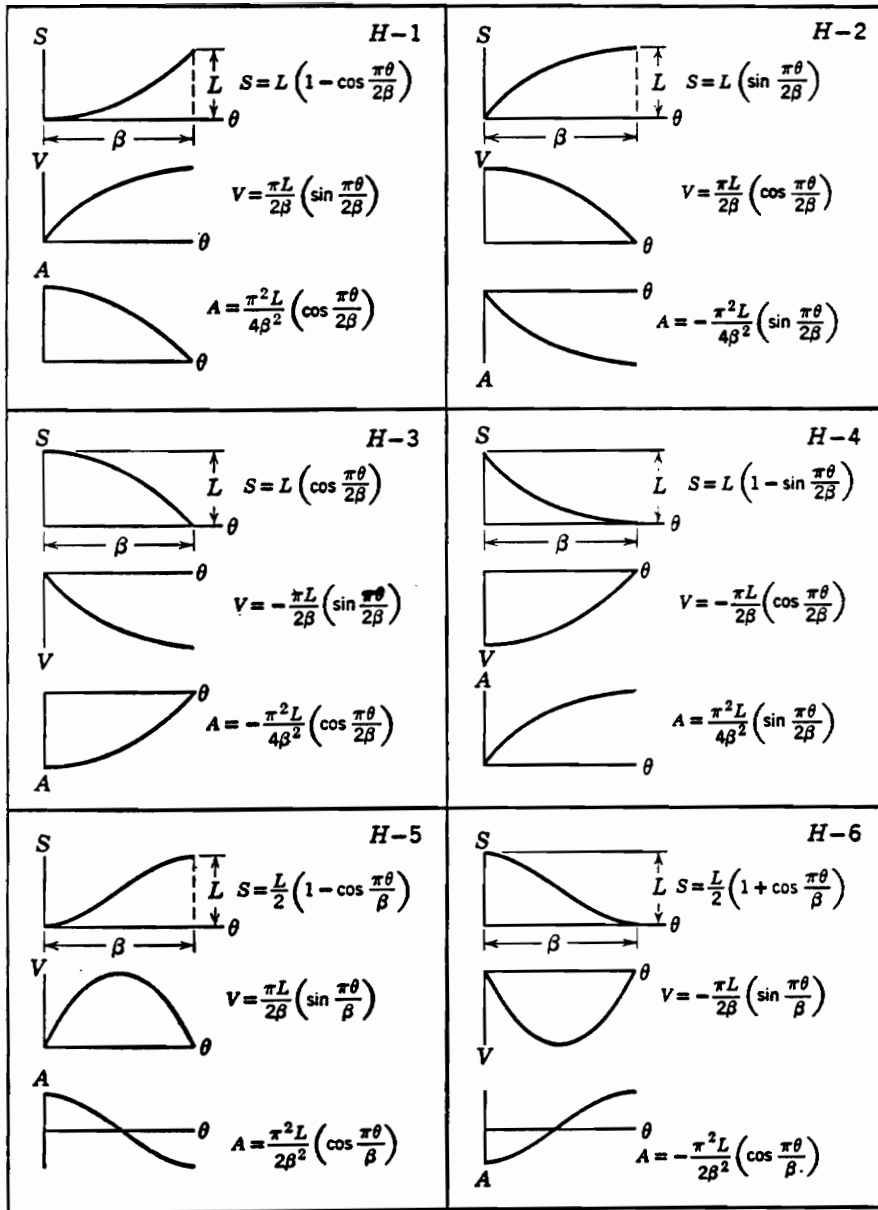


Figure 5.12: Harmonic Motion Curves (Mabie and Reinholtz, 1986)

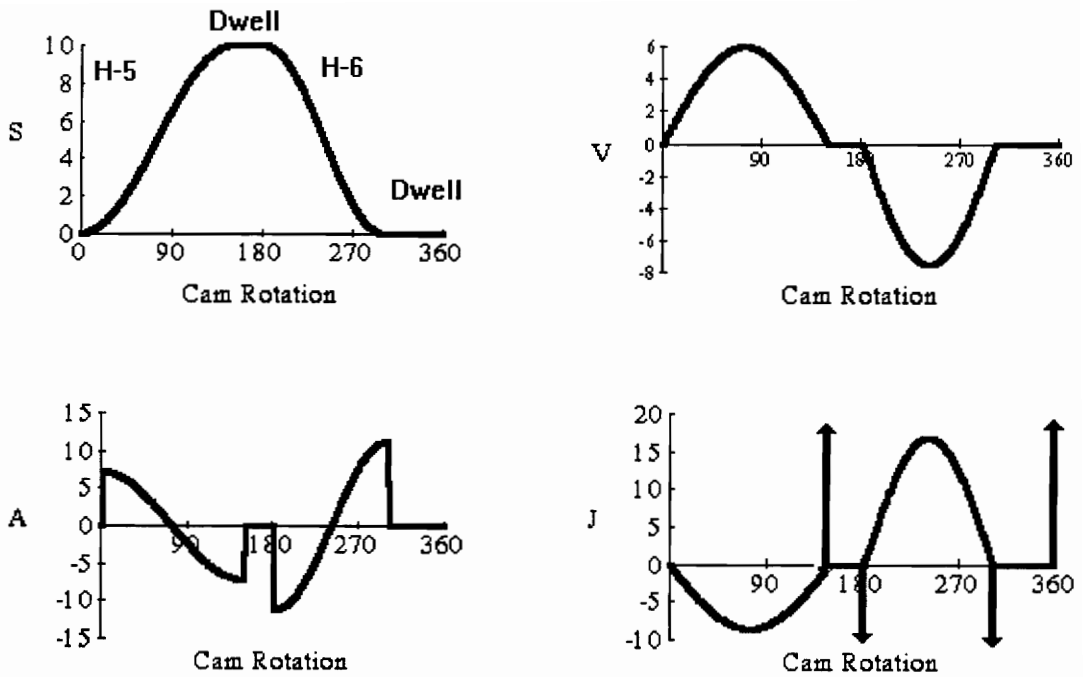


Figure 5.13: Rise-Dwell-Fall-Dwell Motion Exhibits Infinite Jerk When Using Harmonic Motion Curves

fact, there are four junctions where the motion program exhibits infinite jerk because of discontinuities in acceleration: H-5 to Dwell, Dwell to H-6, H-6 to Dwell, and Dwell to H-5. The last junction discontinuity is important because the operation of the cam is cyclical, and the ends of the plots at 360 degrees must join with the beginnings of the plots at zero degrees. This example illustrates that harmonic motion curves should NOT be used for Rise-Dwell-Fall-Dwell motion. The harmonic motion curves can be used for part of Rise-Fall-Dwell motion, but should not connect to the dwell.

Harmonic motion curves are best used for Rise-Fall motion or for connecting to a constant velocity segment. As previously noted, a cam is often not the best alternative for Rise-Fall CEP motion. However, using harmonic motion for this case provides smooth motion throughout the cycle. The resulting cam with a translating flat-faced follower producing harmonic motion would be in the shape of a circle. The shaft would be located off-center by an amount equal to half of the desired stroke. This special type of cam is called an *eccentric* cam.

Cycloidal Motion

Figure 5.14 illustrate the complete cycle of cycloidal motion broken into six segments similar to those for harmonic motion. Cycloidal motion is characterized by exceptionally smooth transitions. When comparing the velocity plots of cycloidal motion with those of harmonic motion, it is clear that the cycloidal motion provides a smoother transition. This makes cycloidal curves a better choice for high speed applications. A drawback is that cycloidal motion exhibits large magnitudes of peak acceleration and peak velocity.

Examination of the full cycloidal motion segments C-5 and C-6 indicates that the velocity and acceleration are zero at both ends of the interval. Therefore, cycloidal motion is a good choice for transitioning to and from a dwell. Cycloidal motion curves should be considered for Rise-Dwell-Fall-Dwell motion programs. The resulting jerk does not match directly, but is finite in magnitude.

Cycloidal motion should not be used for Rise-Fall motion programs or the Rise-Fall portion of a Rise-Fall-Dwell program. Examination of the end of the C-2 curve and the beginning of the C-3 curve shows that the velocities and accelerations will match at zero. However, the slope of the acceleration C-2 curve is positive at the end point and the slope of the acceleration C-3 curve is negative at the beginning. The negative acceleration during the C-2 curve is unnecessarily brought back to zero only to return in the negative direction for the C-3 curve. This unnecessary return to zero results in high pressure angles and should be avoided.

When considering Rise-Fall-Dwell motion, a beneficial combination results from joining the dwells with the half-cycloidal motion curves and using the half-harmonic motion curves for transitioning from the rise to the fall.

Modified Trapezoidal Acceleration Motion

Many motion curves have been formulated by combining various trigonometric functions to produce desirable dynamics. Often, designers want to control the acceleration of the motion because of its effect on forces. The velocity and position of the curve are obtained by integrating the acceleration. One of these curves that has proven most useful is the modified trapezoidal acceleration curve shown in Figure 5.15. This motion curve is formulated by combining portions of a sinusoidal acceleration and trapezoidal shaped acceleration. The mathematical formulation for these curves is complicated and is not important for this discussion. A detailed formulation is presented in Norton (1993).

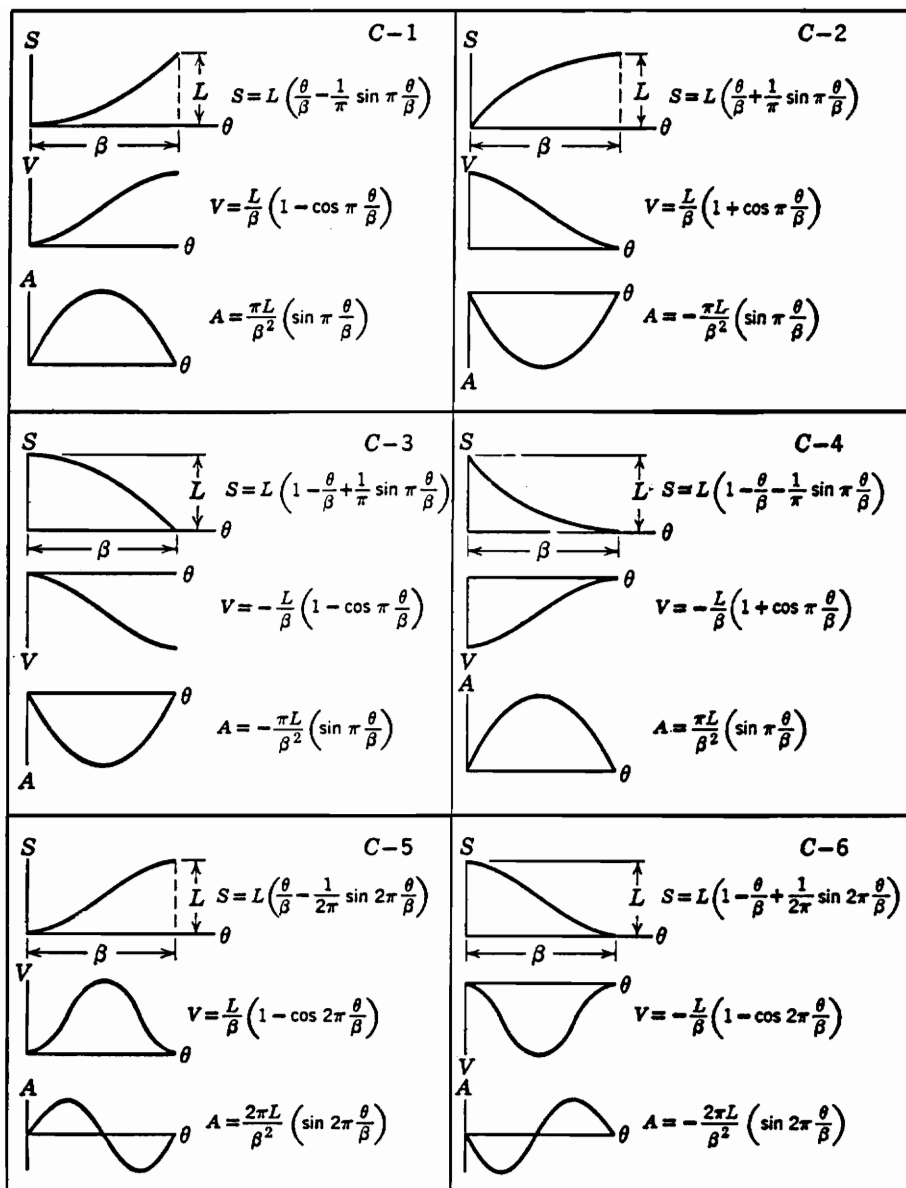


Figure 5.14: Cycloidal Motion (Mabie and Reinholtz, 1986)

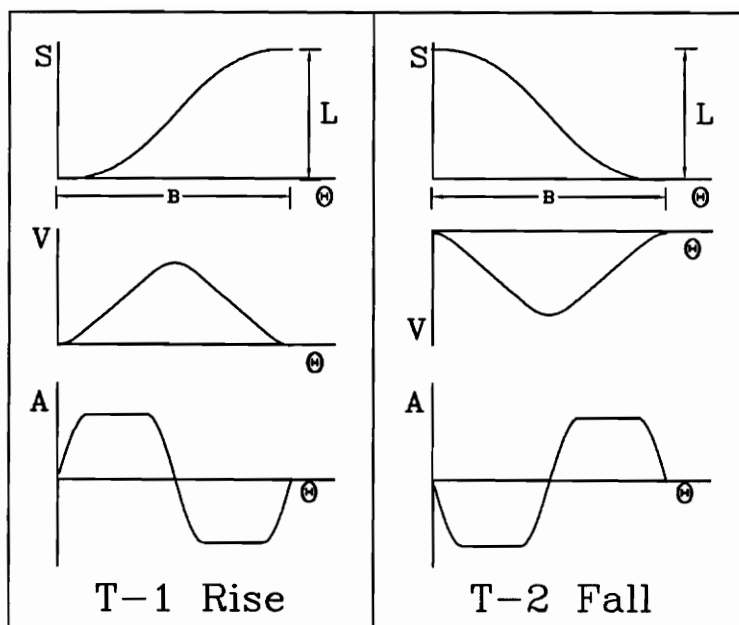


Figure 5.15: Modified Trapezoidal Acceleration Motion

Modified trapezoidal acceleration motion has the primary advantage of relatively low peak acceleration with reasonably rapid and smooth transitions at the beginning and end of the interval. The magnitude of the peak acceleration is found to be (Norton, 1993):

$$A_{peak} = \frac{4.8812L}{\beta^2} \quad (5.1)$$

where L is the stroke of the follower and β is the length of the interval of motion.

This peak acceleration compares favorably with that of cycloidal motion for equal displacement and angular rotations of the cam where

$$A_{peak} = \frac{2\pi L}{\beta^2} \quad (5.2)$$

The modified trapezoidal acceleration motion results in a 22% decrease in peak acceleration over the cycloidal motion. The resulting dynamic characteristics make this one of the best choices for Rise-Dwell-Fall-Dwell motion programs. Because the curves were developed for this application, the cycle is broken into two parts: rise and fall. The curves were not developed for Rise-Fall motion and would result in unnecessarily

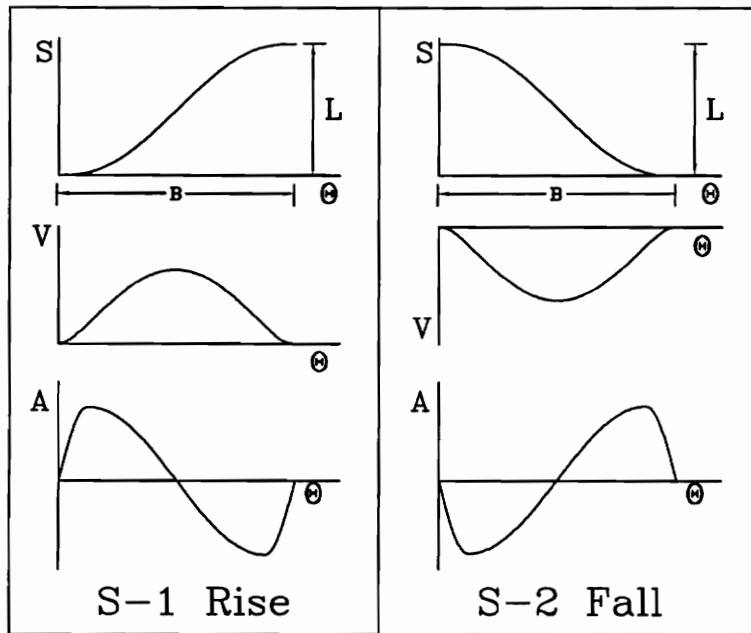


Figure 5.16: Modified Sinusoidal Acceleration Motion

bringing the acceleration to zero.

Modified Sinusoidal Acceleration Motion

The modified sinusoidal acceleration curves shown in Figure 5.16 are formulated by combining two different sinusoids to make the acceleration curve. This curve was also formulated for the Rise-Dwell-Fall-Dwell motion program. The modified sinusoidal acceleration motion curve provides less ragged jerk than the modified trapezoid resulting in smoother motion. The peak acceleration of the modified sinusoid is higher at $5.528L/\beta^2$. The peak velocity is lower with $1.7596L/\beta$ compared to $2L/\beta$ for the modified trapezoid and cycloidal motion. The modified sinusoidal acceleration motion is best suited for situations where vibrations are more important than inertial forces. This curve is only suitable for Rise-Dwell-Fall-Dwell motion programs.

Eighth-Degree Polynomial Motion

Polynomial curves can be the most versatile for generating motion programs because they can be tailored to most any customized design specification. The polynomials are formulated by specifying the boundary conditions at the end points of the interval. There is no control between the boundary conditions. The order of the polynomial is based on the number of boundary conditions.

While there are many polynomial curves that can be generated, the eighth-degree polynomial motion curve shown in Figure 5.17 is a good alternative to be included with the others mentioned previously. Examination of the acceleration shows that the acceleration is zero at the beginning of the rise, P-1, but finite and negative at the end. The fall, P-2, shows a finite and negative acceleration at the beginning and zero at the end. This makes this curve an ideal choice for the Rise-Fall-Dwell motion program. The transition from rise to fall is made without unnecessarily returning to zero. This curve would not be a good choice for Rise-Fall motion because the junction from fall to rise (at the end of the cycle) would unnecessarily bring the acceleration to zero.

5.6.3 Summary of Motion Curves and Comparisons

It is clear from the previous discussion that some curves are better suited than others for a desire motion program type. Formulating a motion program involves selecting among alternatives and manipulating parameters to best fit the design specifications. Many motion programs may be acceptable for a given design. Formulating the best motion program requires consideration of many factors beyond peak velocity and acceleration, but this information provides a start. Table 5.1 provides data that is useful when formulating a motion program by comparing peak values for velocity, acceleration and jerk. Other considerations will be presented in later sections.

5.7 Curve Matching to Avoid Infinite Jerk

Smooth operation of the cam mechanism requires that the jerk remain finite throughout the cycle. Typically, infinite jerk occurs at the junctions between the motion curves. Avoiding infinite jerk requires that the velocities and accelerations of the two curves match at the junction. If the velocities and accelerations match at a junction by definition of the curves, nothing need be done. (This frequently occurs when $V = A = 0$ at the

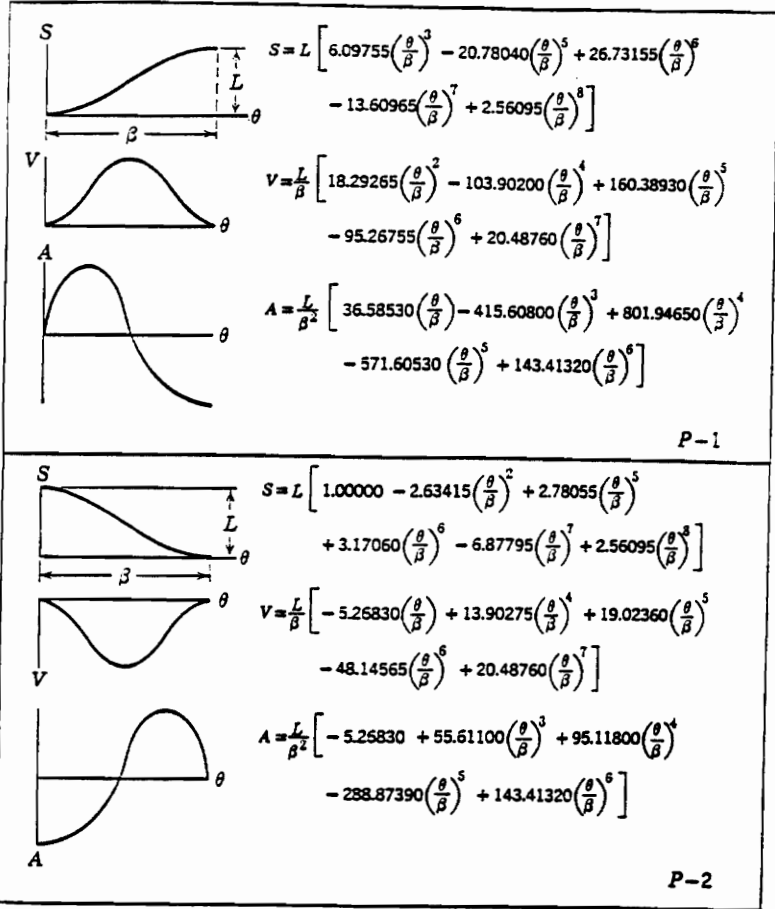


Figure 5.17: Eighth-Degree Polynomial Motion (Mabie and Reinholtz, 1986)

Table 5.1: Summary of Velocity, Acceleration and Jerk Factors

Program	Max. Veloc.	Max. Accel.	Max. Jerk	Comments
Harmonic Disp.	$1.571L/\beta$	$4.945L/\beta^2$	Infinite	Rise-Fall and Custom
Cycloidal Disp.	$2.000L/\beta$	$6.283L/\beta^2$	$40L/\beta^3$	Double Dwell and Custom
Mod. Trap. Accel.	$2.000L/\beta$	$4.888L/\beta^2$	$61L/\beta^3$	Double Dwell
Mod. Sin. Accel.	$1.760L/\beta$	$5.528L/\beta^2$	$69L/\beta^3$	Double Dwell
8th Deg. Poly.	$1.763L/\beta$	$5.268L/\beta^2$	Infinite	Single Dwell and Custom

junction.) If the velocities and accelerations do not match, then it must be determined if it is possible for parameters to be selected such that the curves can match. The curves can be made to match if both end points have a finite, non-zero value of the same sign for the corresponding velocity and acceleration. If the end point of one curve is finite in velocity or acceleration and the joining end point of the other curve is zero, then the curves will never match. The curve selection must then be reconsidered.

The junctions are made to match by establishing the parametric equation of both curves at the junction and setting them equal. It is then possible to establish a relationship between the strokes of each curve and the cam rotations over the intervals of each curve. All junctions must be considered simultaneously because of interdependence of the parameters. The curve matching process is best illustrated by example.

Figure 5.18 shows a Rise-Fall-Dwell motion program where a C-1 half-cycloidal rise passes to an H-2 half-harmonic rise to a P-2 eighth-degree polynomial fall and then to the dwell. Examination of the junctions between the curves reveals the following:

C-1 to H-2: Velocities must be made to match

H-2 to P-2: Accelerations must be made to match

P-2 to Dwell: Velocities and accelerations match at zero

Dwell to C-1: Velocities and acceleration match at zero

It is then necessary to establish parameters such that the following governing equations are satisfied.

$$\begin{aligned} V_{C-1(end)} &= V_{H-2(beginning)} \\ \frac{2L_1}{\beta_1} &= \frac{\pi L_2}{2\beta_2} \end{aligned} \quad (5.3)$$

$$\begin{aligned} A_{H-2(end)} &= A_{P-2(beginning)} \\ \frac{-\pi^2 L_2}{4\beta_2^2} &= \frac{-5.2683L_3}{\beta_3^2} \end{aligned} \quad (5.4)$$

$$L_1 + L_2 - L_3 = 0 \quad (5.5)$$

$$B_1 + B_2 + B_3 + B_4 = 360 \quad (5.6)$$

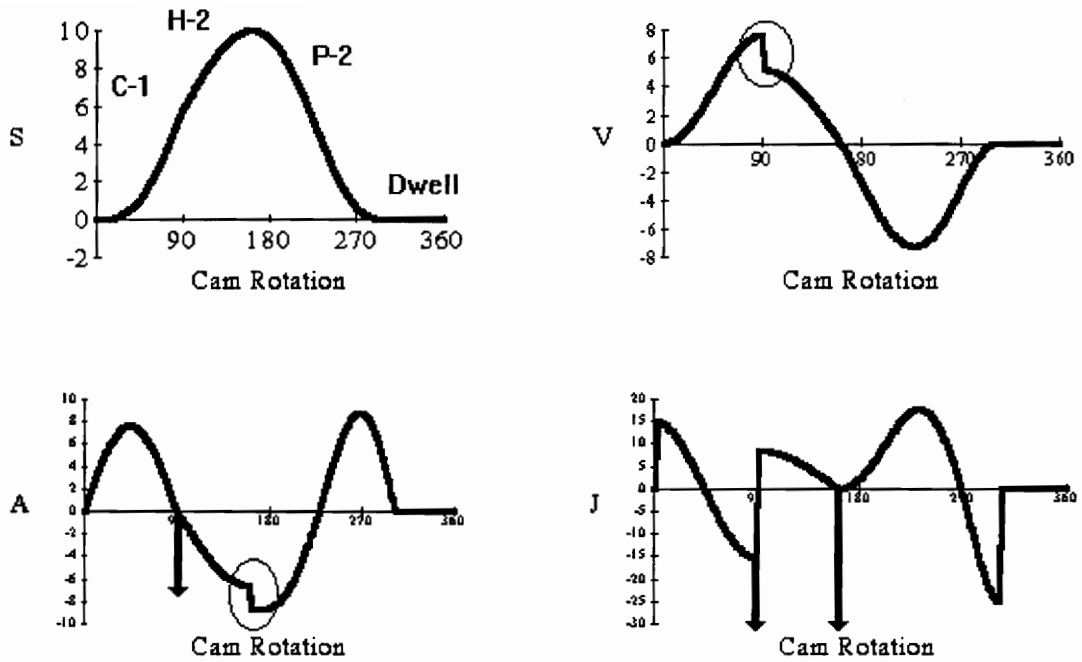


Figure 5.18: Curvematching Example to Avoid Infinite Jerk at the Junctions

Equations 5.3 and 5.4 are formulated by normalizing the relevant equation from the motion curve segments. For example, in equation 5.4, the junction is at the beginning of the P-2 curve. Therefore, the equation is obtained by using a value of zero for θ and entering the accompanying cam rotation and stroke, β_3 and L_3 respectively.

The last two equations ensure that the total rising stroke and the total falling stroke are equal and that the sum of the rotations of all of the intervals equals 360 degrees or 2π radians. There are four governing equations and seven unknowns ($L_1, \beta_1, L_2, \beta_2, L_3, \beta_3, \beta_4$). The designer may select values for three of these. The equations will govern the values for the remaining four. The designer's choices are restricted, however. The designer cannot select values for all three curve strokes (L_1, L_2 and L_3) because they are governed by equation 5.5. Note that L_4 does not appear in the equations or the list of selectable parameters because the stroke of a dwell is zero.

Values for all of the parameters in a governing equation can not be selected and set because they would not satisfy the equation. Therefore, there are three guidelines for selecting parameters when curve matching:

1. All of the strokes (L's) cannot be selected

2. All of the rotations of the intervals (β 's) cannot be selected
3. All of the parameters at a governing junction cannot be selected

5.8 Selecting Follower Type and Cam Size

The motion program must be formulated in conjunction with considerations for selecting the follower type and cam size. As was shown, the type of motion program that is required (Rise-Fall, Rise-Fall-Dwell, etc.) helps govern the decision for selecting the motion curve types. The values for the parameters of the curves tends to be governed by desired attributes of the cam mechanism.

5.8.1 Selecting the Follower Type

Follower types are characterized by the type of motion (translating or oscillating) and the follower shape (flatfaced or roller). The choice of translating or oscillating follower is frequently governed by the design requirements. It is often readily apparent whether the follower should be translating or oscillating. However, there are some additional considerations. A translating follower has sliding contact between the follower and the guide. The friction from this sliding contact must be considered. Also, the guide must remain true (no bends or kinks) to allow the follower to slide freely. The area must be well lubricated and the guide must be strong enough to remain true through the desired lifecycle of the mechanism.

In the case of a translating roller follower, special care must be given to aligning the roller with the direction of the velocity of the cam surface as shown in Figure 5.19. Misalignment can greatly reduce the life of the follower and the cam, as well as induce unwanted dynamic effects. Aligning the roller can be time consuming during installation and maintenance. The follower must be designed to preserve alignment. This can be accomplished using a keyway or by using two guides.

It may be advantageous to approximate a linear motion using an oscillating follower with a long rocker arm. An oscillating follower uses a revolute joint rather than sliding contact so that lubrication is simplified. Alignment concerns are greatly reduced because the alignment is dependent on the design of the rocker arm rather than installation. It is also more difficult for an oscillating follower to become misaligned during operation.

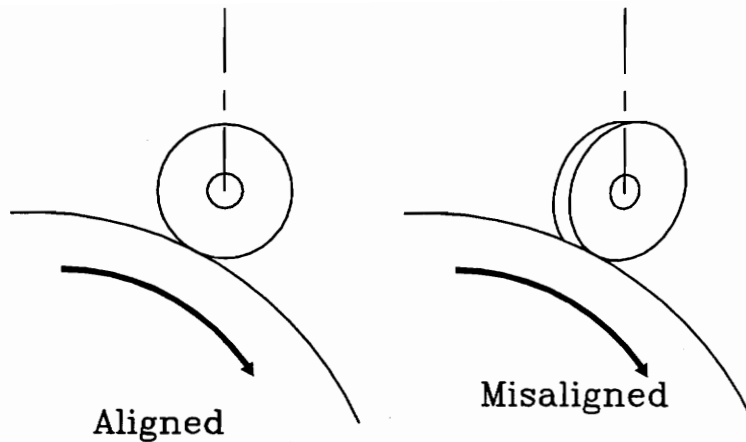


Figure 5.19: Proper Alignment of Roller Followers

An oscillating follower also eliminates the problem of binding in the guides that is often associated with a translating follower.

There are several factors to consider when deciding on a flatfaced or roller follower. Some of these are linked to the motion program formulation and will be discussed in detail in the next section. One of the advantages for a roller follower is that it will accommodate a negative radius of curvature (concave section) in the cam contour. As long as the radius of concavity is larger than the roller, the roller can follow the contour. A flatfaced follower cannot follow the contour of the concave area so a negative radius of curvature is not permissible. The existence of a negative radius of curvature of the cam surface for a flatfaced follower is called *undercutting*. A roller follower, then, has greater freedom in formulating the motion program because it can accommodate concavities. The equations for radius of curvature will be presented later.

Roller followers are also widely available commercially in many materials and sizes. This greatly reduces the cost of manufacture as well as maintenance and repair. A disadvantage of roller followers is that they must be aligned as mentioned previously. They may also be more complex and have more parts. The roller is an intermediate part between the cam and the arm of the follower. The shaft connecting the roller to the arm must be able to carry the static and dynamic loads to reduce failure and fatigue.

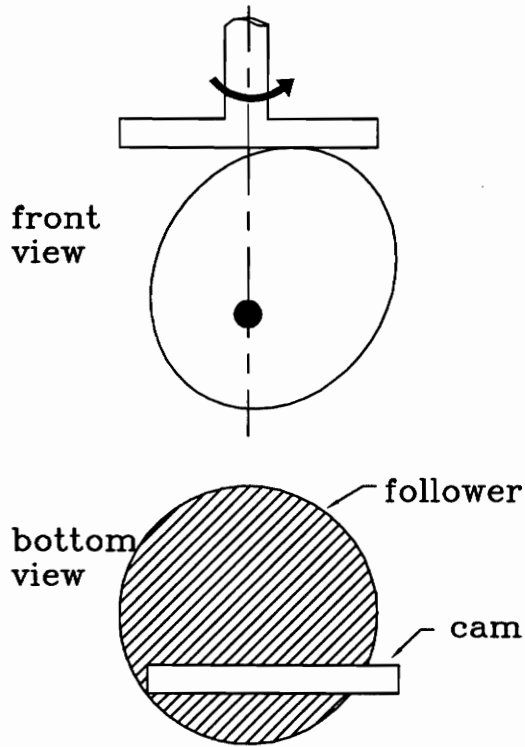


Figure 5.20: Flatfaced Follower Rotating Freely to Reduce Wear

Flatfaced followers are often custom designed for the desired application. The lot size should be large enough to warrant this expense. Flatfaced followers often require less space than roller followers. Alignment is not a problem. In fact, often flatfaced followers are allowed to rotate freely about the axis of motion to distribute the wear as shown in Figure 5.20.

5.9 Equations Governing Motion Program, Follower Type and Cam Size

One of the primary considerations when formulating the motion program is the effect on the pressure angle. The pressure angle represents the difference between the direction of force and the direction the follower wants to go. Only that portion of the force transmitted

from the cam that lies in the direction of motion of the follower assists that motion. The transverse portion of the force negatively affects the motion of the follower, induces stresses on the follower arm, and can cause the follower to bind in the guides. While the limit for the maximum pressure angle must be determined by analyzing each design problem, a general guideline often cited in the literature is to limit the maximum pressure angle to 30 degrees.

5.9.1 Pressure Angle and Translating Roller Followers

Equation 5.7 is used to calculate the pressure angle, α , for a translating roller follower. This equation was derived using techniques of conjugate geometry as presented by Shooter, West and Reinholtz (1995). The derivation for this and other equations is well developed and will not be shown here. The variables are clarified in Figure 5.21.

$$\alpha = \pi - \tan^{-1} \left(\frac{V(\theta) - E}{R(\theta)} \right) \quad (5.7)$$

where

$V(\theta)$ is the velocity of the follower from the motion program

E is the offset distance (sometimes termed the eccentricity) measured positive toward the left

$R(\theta)$ is the rise of the follower ($R(\theta) = B + S(\theta)$) where B is the base circle radius and $S(\theta)$ is the position of the follower from the motion program.

It is clear from equation 5.7 that the velocity from the motion program, the follower offset, and the base circle radius all influence the pressure angle. The maximum pressure angle can be reduced by decreasing the maximum velocity in the motion program and by increasing the base circle radius. The velocity can be affected by manipulating parameters in the motion program. Of course, the base circle radius may be limited by the available space, and a larger cam often increases cost.

Typically, it is desirable to offset the roller toward the approaching cam profile (right if cam spin is ccw, left if cw) to alter the pressure angle. This has the effect of reducing the pressure angle on the rise motion and increasing the pressure angle on the fall as shown in Figure 5.22. Disk cams tend to do work on the follower during the rise stroke. The

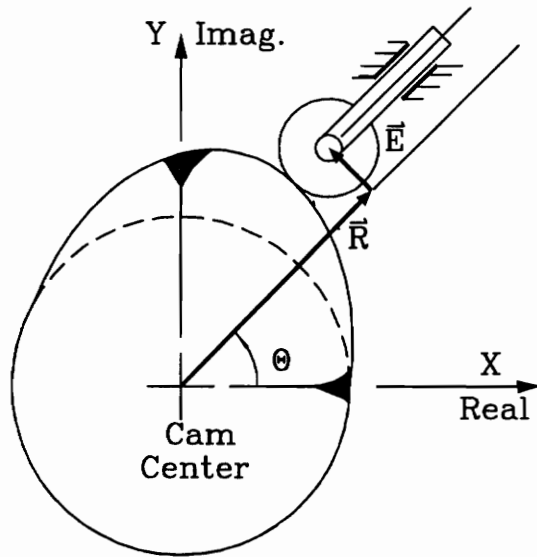


Figure 5.21: Translating Roller Follower

fall is typically enacted by gravity or a spring in which case the cam merely reacts against this force. For this reason, a higher pressure angle is usually more tolerable on the falling stroke. Adding an offset is also beneficial when the motion program is asymmetrical and significant differences exist between the maximum and minimum pressure angles on rise and fall. Adding an offset can balance the pressure angles and create a smoother running cam.

5.9.2 Pressure Angle and Oscillating Roller Followers

Equation 5.8 is used to calculate the pressure angle, α , for an oscillating roller follower (Shooter, West, Reinholtz, 1995). The variables are clarified in Figure 5.23.

$$\alpha = \frac{\pi}{2} - \tan^{-1} \left[\frac{C \sin \phi}{-(C \cos \phi + R(1 + \omega(\theta)))} \right] \quad (5.8)$$

where

C is the distance from the cam pivot to the follower arm pivot

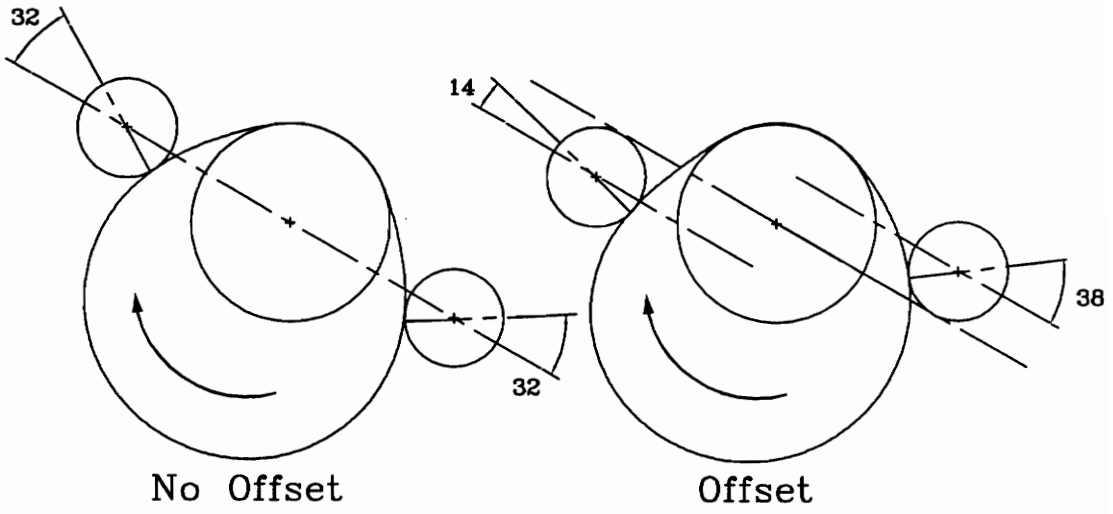


Figure 5.22: Effect of The Offset On The Pressure Angle

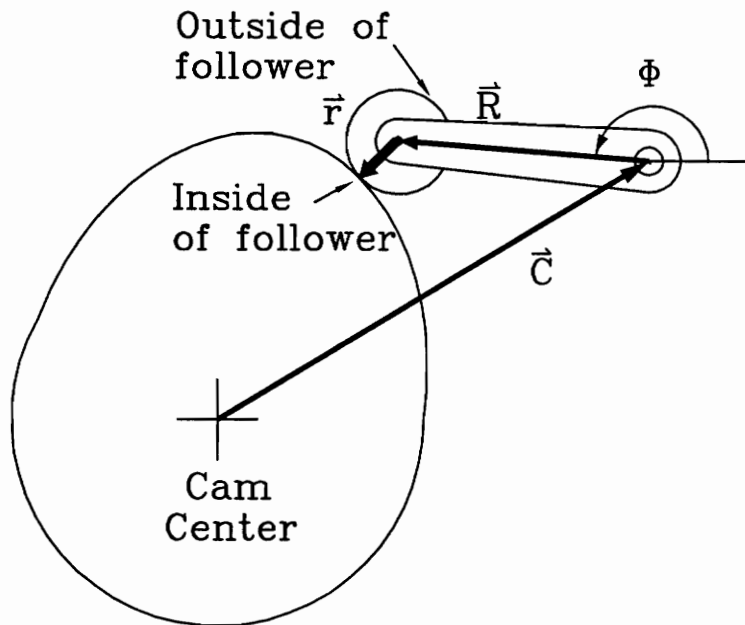


Figure 5.23: Oscillating Roller Follower

R is the length of the follower arm

ϕ is the angular displacement of the follower measured counter-clockwise from the horizontal

$\omega(\theta)$ is the angular velocity of the follower obtained from the motion program

The motion program describes the angular displacement of the follower from its home position resting on the base circle. The angular displacement in the motion program is denoted as γ to distinguish it from the angle ϕ . ϕ is then found from the equation:

$$\phi(\theta) = \pi - \cos^{-1} \left[\frac{C^2 + R^2 - (B + r)^2}{2CR} \right] - \gamma(\theta) \quad (5.9)$$

where the additional parameters

B is the base circle radius

r is the roller radius

$\gamma(\theta)$ is the angular displacement from the motion program.

Note that the negative sign was placed on the denominator of the fraction in equation 5.8. This ensures that the value results in the correct quadrant and produces the cam profile on the inside of the follower. The other value will produce a cam profile on the outside of the follower. While this is mathematically correct, it is not the desired result. This is clarified in Figure 5.23

Examination of equation 5.8 reveals that the pressure angle can be reduced by increasing the distance between the cam pivot and the follower pivot, C, increasing the length of the follower arm, R, and increasing the base circle radius, B. These parameters, of course, are limited by space and cost. Decreasing the maximum velocity will also decrease the pressure angle.

For oscillating roller followers, a well-accepted guideline is to keep the pressure angle under 35 degrees. It is often beneficial to select the parameters so that the pressure angle places the follower arm in tension rather than compression for the follower rise. This prevents the effects of buckling.

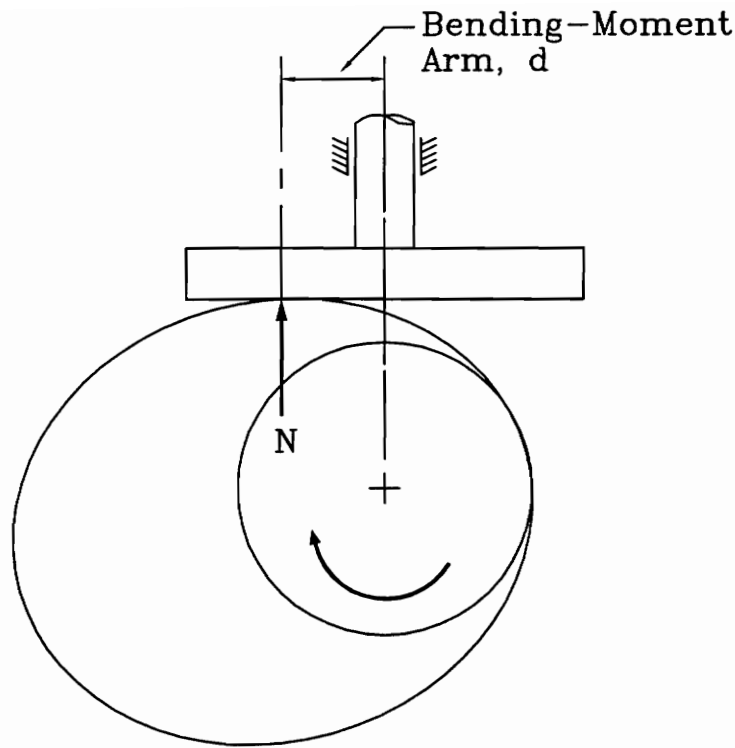


Figure 5.24: Bending Moment on Translating Flatfaced Followers

5.9.3 Bending Moment and Translating Flatfaced Followers

For translating flatfaced followers the pressure angle is constant. If the follower stem is perpendicular to the flat face, then the pressure angle is zero. However, there exists a bending moment on the follower stem that is analogous to the pressure angle as shown in Figure 5.24. The force transmitted from the cam to the follower must be perpendicular to follower face. This force is offset a distance, d , from the follower stem. The magnitude of d changes throughout the motion program. Derivations from conjugate geometry show that d is directly related to the velocity (Shooter, West and Reinholtz, 1995). The conjugate geometry approach neglects friction.

$$d = V(\theta) \quad (5.10)$$

Equation 5.10 indicates that the point of contact between the cam and the follower is known directly from the motion program. The maximum bending moment arm, d , is simply the maximum positive velocity on one side of the follower stem and the minimum velocity on the other side. The value of d can give an indication of the bending moment on the follower stem that can cause it to bind. As with the pressure angle, the bending

moment is more of a concern on the rising stroke. Therefore, it may be beneficial to move the stem to reduce the magnitude of d during the rise. It is also clear that the minimum width of the flatfaced follower, W_{min} , can be found as:

$$W_{min} = V_{max} - V_{min} \quad (5.11)$$

Usually the follower face is designed slightly larger to ensure that the follower does not gouge the cam at the corner of the follower face. It may seem strange at first to accept that a distance is equal to a velocity. However, a quick review of the units will show that this is true as long as the cam rotation is measured in radians.

5.9.4 Bending Moment and Oscillating Flatfaced Followers

The bending moment is not a problem for oscillating flatfaced followers. The pivot arm is often designed so that a line along the flat face passes through the follower bearing. This results in the force always acting in the direction of the velocity of the follower. This provides maximum efficiency and is one of the primary benefits of using an oscillating flatfaced follower.

The length of the follower arm, L , can be calculated using equation 5.12 which was, again, derived using conjugate geometry (Shooter, West and Reinholtz, 1995). The variables are clarified in Figure 5.25.

$$L = \frac{-C \cos \phi}{1 + \omega(\theta)} \quad (5.12)$$

where

C is the distance from the cam pivot to the follower pivot

ϕ is the angular displacement measured counterclockwise from the horizontal

ω is the angular velocity from the motion program

The motion program describes the angular displacement of the follower from its home position resting on the base circle. The angular displacement in the motion program is denoted as γ to distinguish it from the angle ϕ . The value of ϕ is then found from the equation:

$$\phi = \pi - \sin^{-1} \left(\frac{B}{C} \right) - \gamma(\theta) \quad (5.13)$$

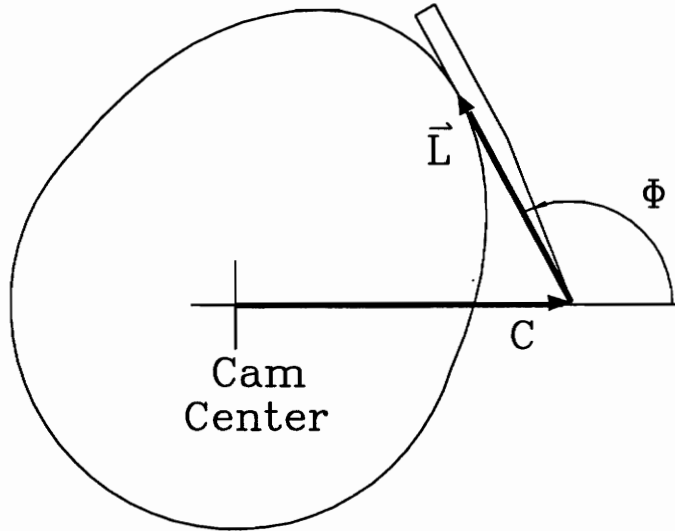


Figure 5.25: Oscillating Flatfaced Follower

where the additional parameters:

B is the base circle radius

$\gamma(\theta)$ is the angular displacement from the motion program.

5.9.5 Cam Profile Shape and Size

It has been shown that increasing the base circle radius tends to decrease the maximum pressure angle. The maximum base-circle radius is often often limited by space constraints and cost. Having a base circle that is small has other adverse effects. Exploring these effects relates to the radius of curvature of the cam profile.

Radius of Curvature and Translating Flatfaced Followers

The radius of curvature, ρ , for a disk cam and translating flatfaced follower can be found from equation 5.14 (Norton, 1993).

$$\rho = B + S + A \quad (5.14)$$

where

B is the base circle radius

S is the position of the follower specified in the motion program

A is the acceleration of the follower specified in the motion program

A flatfaced follower cannot accommodate a negative radius of curvature. The flat face cannot follow the contour. Examination of equation 5.14 indicates that the radius of curvature, ρ , can only become negative from the effects of the acceleration. The worst case for undercutting will occur when the acceleration is at its peak negative value. The actual minimum base circle radius can be calculated using equation 5.14.

$$B_{min} = \rho_{min} - S_{atA_{min}} - A_{min} \quad (5.15)$$

The minimum radius of curvature, ρ_{min} , is a design consideration. Contact stresses may be a consideration in selecting a minimum allowable radius of curvature.

Radius of Curvature and Roller Followers

Roller followers can allow a negative radius of curvature because the roller may fit into the concave section. However, a roller follower will be unable to follow the cam profile if there is a radius of curvature in the concave region less than the roller radius.

A general guideline is that the radius of curvature should be two or three time larger than the radius of the roller. The radius of curvature, ρ , for a roller follower can be found from equation 5.16.

$$\rho = \frac{[(B + S)^2 + V^2]^{1.5}}{(B + S)^2 + 2V^2 - A(B + S)} \quad (5.16)$$

If a positive radius of curvature of the pitch surface is equal to or less than the roller radius the cam profile will become pointed. This point is called a *cuspl* and the effect is called *undercutting*. Figure 5.26 shows the effect of undercutting on the cam profile.

Sizing Disk Cams and Oscillating Followers

When selecting parameters for oscillating followers, the designer must consider the effects on pressure angle and undercutting. In addition to specifying the base circle radius and

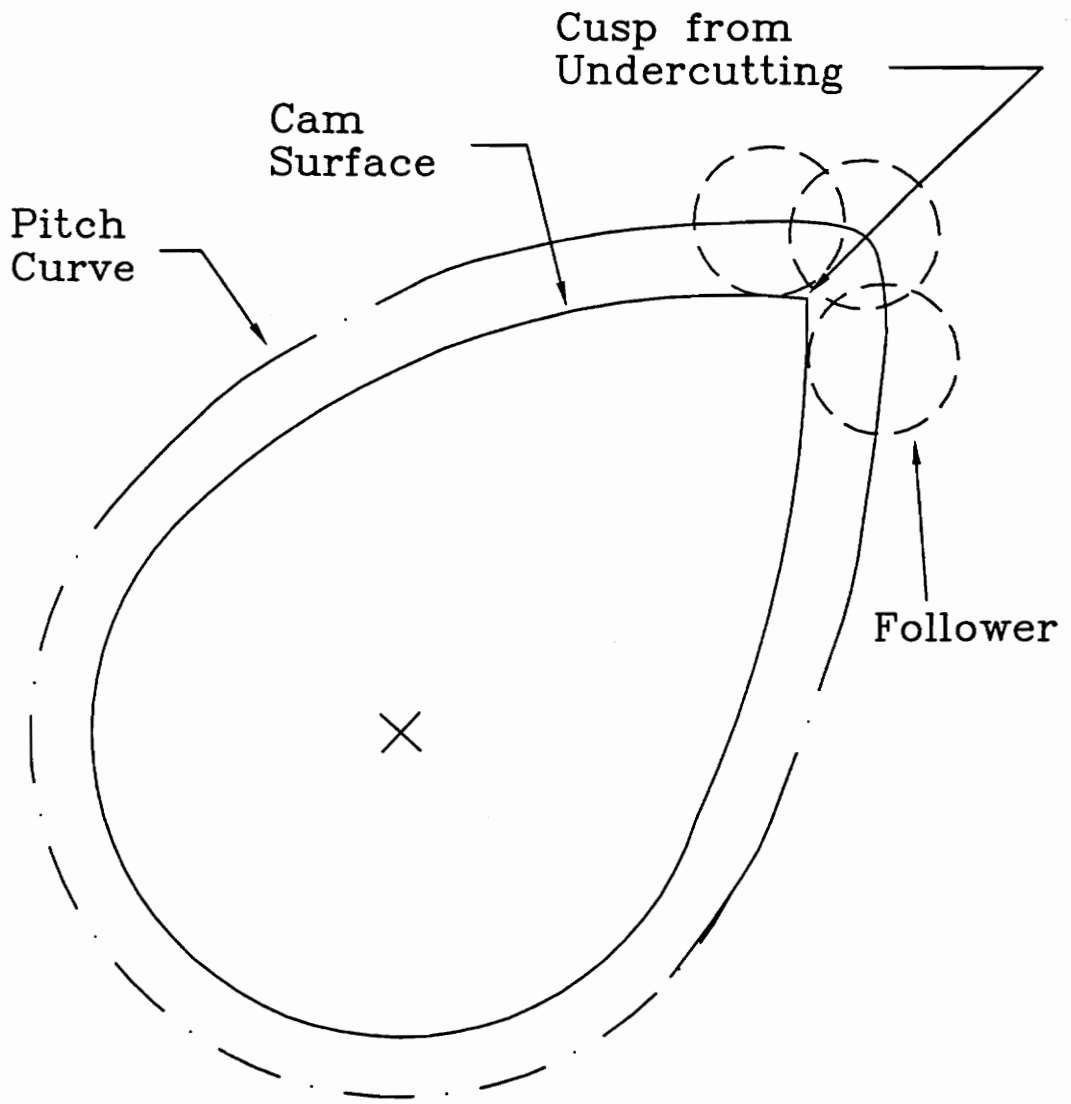


Figure 5.26: Undercutting Caused by Roller Radius Equalling the Radius of Curvature

the roller radius, the designer must specify the distance between the cam pivot and the follower pivot and the length of the follower arm. It is clear that the distance between the pivots must be larger than the base circle radius plus the stroke in order for the cam to rotate completely. Using a pivot distance of at least 1.5 times the sum of the base circle and the stroke tends to provide the needed space for good motion of the follower. The follower pivot can be placed on a different vertical level than the cam pivot. This can be helpful if the space for the mechanism is restrictive. However, the resulting cam profile and relative motion of the follower is unaffected as long as the distances stay greater than the stroke of the oscillating follower.

The length of the follower arm for oscillating flatfaced followers is not a parameter that the designer can select. It is best if the length of the follower arm for oscillating roller followers should be selected such that the arm is in tension throughout the rise of the follower (Molian, 1968). Maintaining tension also requires that the follower pivot be placed on the right for cams spinning counter-clockwise and on the left for cams spinning clockwise. The minimum arm length, R_{min} can be calculated from equation 5.17.

$$R_{min} = \left[(B + r)^2 + C^2 - \frac{(B + r)}{h} \right]^{.5} \quad (5.17)$$

where

B is the base circle radius

r is the roller radius

C is the distance between the pivots

h is the height of the follower pivot relative to the cam pivot

5.10 Toothpaste Example

Revisiting the example problem of moving a tube to fill it with toothpaste will help to clarify some of the issues presented in the past several sections. It has been established that the type of motion program desired for filling the tube with toothpaste is a Rise-Dwell-Fall-Dwell type. From the discussion, the best choices for providing the rise and fall motion are the full cycloidal, modified trapezoidal acceleration and modified sinusoidal acceleration. This can also be referenced in Table 5.1.

First, consider the rise motion. During the rise, the tube is empty so there is little internal support to maintain the integrity of the tube. The tube would tend to bend more from force than vibration. Examination of Table 5.1 shows that the modified trapezoidal acceleration would provide the lowest peak magnitude of acceleration and, therefore, the lowest forces.

During the fall, the tube is full and under internal pressure, so there is more support for the tube. Of greater concern is the effect of vibrations on this full tube. The curve with the lowest peak velocity is the modified sinusoidal curve. The jerk function should also be considered. While all three curves avoid infinite jerk at the junctions by matching the velocity and acceleration with the dwell, the cycloidal curve provides a smoother jerk function. Table 5.1 indicates a peak magnitude of jerk 58% of that of the modified sinusoidal acceleration curve. This smoother jerk function makes the cycloidal fall appear more appealing than the modified sine function. The first option to explore is the modified trapezoidal acceleration rise, dwell, cycloidal fall, dwell.

Selecting parameters

The established specifications require a total stroke of 60 mm, dwell for 0.7 seconds at the top extreme position and dwell for 0.4 seconds at the low position. The total cycle time must not exceed 2.0 seconds, and it is desirable to reduce it. A cycle time of 2.0 seconds means that the cam must spin only at 30 rpm. This is a low-speed operation. Some operations may require cam speed of greater than 1000 rpm. The specifications do not constrain how the time must be divided between the rise and fall. It may prove more beneficial to not divide the time evenly.

When synthesizing the motion program, it is often easier to think in terms of the cam rotation rather than time. The time can easily be converted to cam rotation. The first motion program to explore is given in Table 5.2.

This results in the plots shown in Figure 5.27. Analysis of the plots shows that the maximum acceleration for the rise is (146.7 mm/rad^2) and the fall is 188.6 mm/rad^2 . Also notice that the jerk function is jagged for the rise, but smooth for the fall. The jerk function for the fall exhibits a finite jump in jerk at the beginning and end of the cycloidal segment. Reducing the magnitude of this jump in jerk may be beneficial to settling the toothpaste in the tube. This can be accomplished by reducing the time for the rise and increase the time for the fall. Several iterations of this results in the motion program

Table 5.2: First Motion Program Considered for Toothpaste Example

Segment	Motion Type	Time (s)	Cam Rotation (deg)
1 Rise	Mod. Trap. Accel.	0.45	81
2	Dwell	0.7	126
3 Fall	Cycloidal	0.45	81
4	Dwell	0.4	72

Table 5.3: Final Motion Program Considered for Toothpaste Example

Segment	Motion Type	Time (s)	Cam Rotation (deg)
1 Rise	Mod. Trap. Accel.	0.417	75
2	Dwell	0.7	126
3 Fall	Cycloidal	0.483	87
4	Dwell	0.4	72

shown in Table 5.3 and the plots in Figure 5.28. This shows a more even proportion of acceleration for the rise and fall and provides a smaller magnitude of jump in the jerk function for the fall.

Selecting Follower Type and Cam Size

Because the hopper can be located over the tube at the station, it is assumed that a translating follower will provide the most direct motion. However, there are other reasons not to choose an oscillating follower. The first is that it is best to maintain the orientation of the tube. Using an oscillating follower would require that the tube orientation change with the angular position of the follower. Making the follower arm large would reduce this tilt of the tube. There is also the issue of space. It may be possible to contain the cam and translating follower inside the conveyor structure. The follower shaft can rise up from the conveyor and return below to provide free space for the exchange of tubes. In this way, it will not interfere with any of the free space that must surround the station. An oscillating follower would stand out to the side, and the cam would have to rise above the surface of the conveyor.

Should the follower be a roller or flatfaced? Using a roller follower has the advantage of being a stock component available from a supplier. This is advantageous for

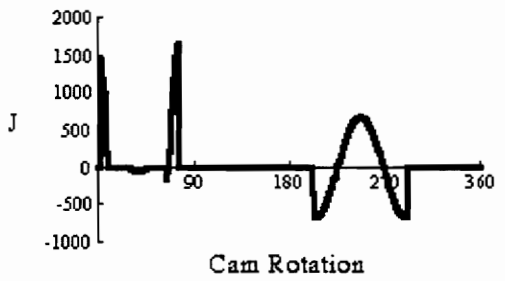
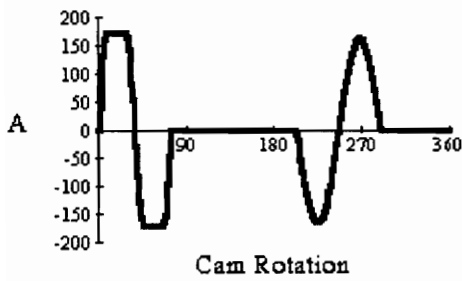
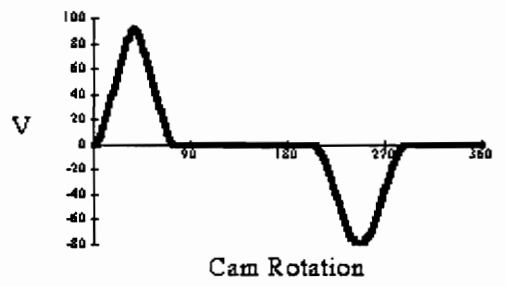
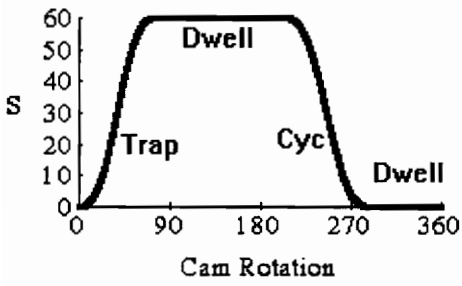
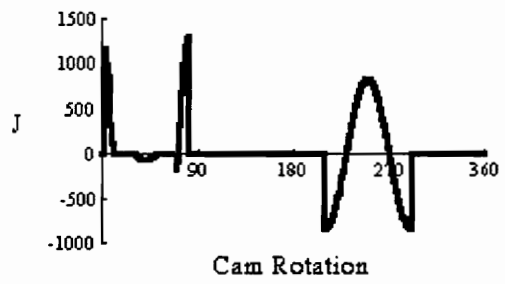
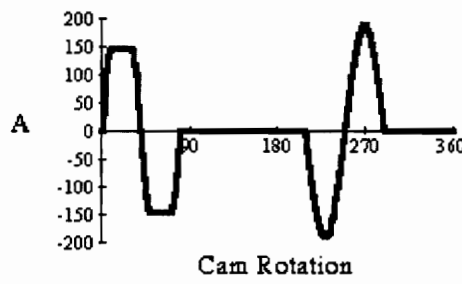
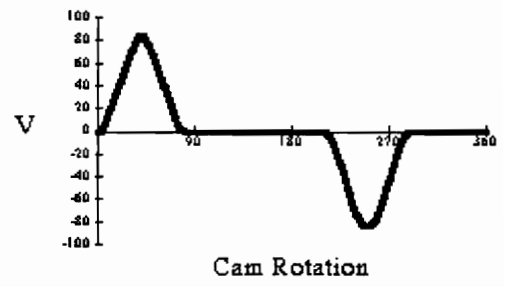
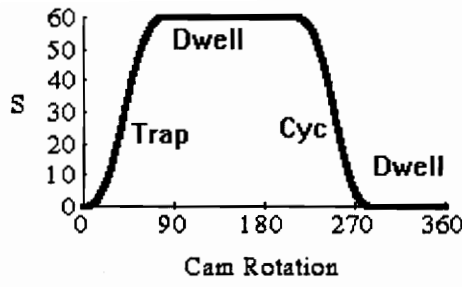


Figure 5.28: Plot of the Final Motion Program

assembly and maintenance. Flatfaced followers would have to be custom designed and built. Although the initial thought is to use a roller follower, use of the flatfaced follower will be explored.

Considering the motion program and equation 5.10, the minimum width of the follower must be 91.61 mm on the left of a centered stem and 79.0 mm to the right for a total width of 170.6 mm. It would be prudent to add 5 mm to both sides to prevent gouging. This gives a follower width of 180.6 mm. This would be a fairly large follower. The mass would be significant and would add to the required input torque on the motor. Analysis shows that a base circle radius of 150 mm would be needed to avoid a negative radius of curvature. This means that the total width of the cam at its largest point would be 360 mm. This is a significant portion of the available space of 450 mm in width. The resulting cam does not produce a smooth profile. The transitions to the dwells have a tight radius of curvature.

In light of these figures, a translating roller follower appears more appealing. A few iterations of parameters show that a translating roller follower with a base circle radius of 125 mm, roller radius of 15 mm and zero offset will have a negative radius of curvature. This, however, is not a problem for the roller follower. The maximum pressure angle is found to be 30.84 degrees on the rise side and 27.38 degrees on the fall. This pressure angle is higher than the guideline maximum of 30 degrees. If the follower is offset toward the rise 15 mm, the resulting maximum pressure angles are 26.5 degrees on the rise side and 31.71 degrees on the fall. The offset has the effect of reducing the pressure angle on the rise at the cost of increasing it on the fall. However, the fall is not as critical because less force will be on the follower.

It is decided to pursue a translating roller follower with the following dimensions:

Base Circle Radius, $B = 125.0$ mm

Roller Radius, $r = 15.0$ mm

Offset, $d = 15.0$ mm to rise (left)

5.11 Cam Profile Synthesis

Techniques for synthesizing the cam profile are well developed. Graphical techniques are intuitive and help the designer visualize the problem. However, graphical synthesis is time

consuming and does not lend itself to iteration. Analytical techniques allow the designer to explore many alternatives with the aid of a computer. Many techniques for deriving the governing equations for the cam profile have been developed. Conjugate geometry has been shown to be a unified approach that can be applied to any cam and follower arrangement (Shooter, West, Reinholtz, 1995). The derivations will not be presented here. However, the resulting vector equations appear in Figure 5.29. This figure provides the vector equation for the cam profile \mathbf{P} and the equation for the common normal expressed as a unit vector. The designer will find that all but one parameter will be known. The equation for the unknown parameter is found by techniques of conjugate geometry and is also provided.

The resulting disk cam for the toothpaste example is synthesized with these equations and is shown in Figure 5.30.

5.12 Considerations Beyond Synthesizing the Cam Profile

The focus of this dissertation is to model the cam mechanism design process from inception through synthesizing the cam profile. Later stages of design will undoubtedly affect the design. Presented here were the common considerations for reaching the profile synthesis stage. After the desired cam profile has been synthesized, there are several more considerations for the designer. Among these are the detailed design, manufacturing, and maintenance planning.

The detailed design phase involves the selection of actual parts, materials, and dimensions. Material selection and dimensioning will be governed by the operating environment and strength of materials calculations. The designer will have to consider the materials for the cam, follower and support frames. The width of the cam, hub size, shaft size and means of attaching the cam to the shaft will need to be considered. The details of the follower shape and size will also need to be considered along with the details of the support frame. A spring for maintaining contact between the cam and follower must be selected. The means of lubrication must be devised. The designer will have to seek suppliers by examining catalogs and talking to sales people. This process will likely require some iteration through the earlier stages of design.

The techniques for manufacture and assembly will need to be considered. If the mechanism is part of a mass-produced item, detailed manufacturing and assembly plans will be essential. Because of the wear involved in cam mechanisms, a maintenance plan

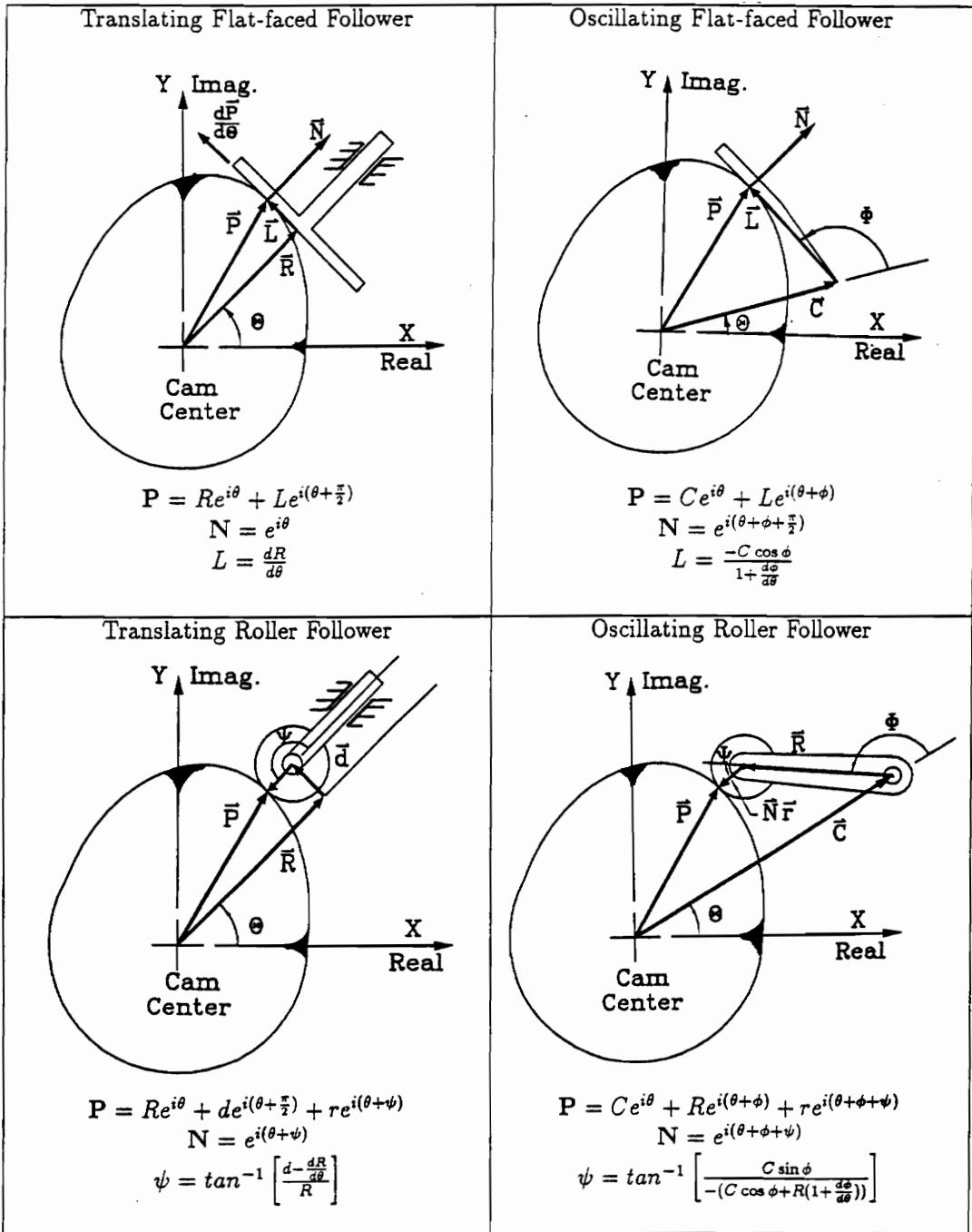


Figure 5.29: Synthesis Equations for Disk Cam and Four Common Followers

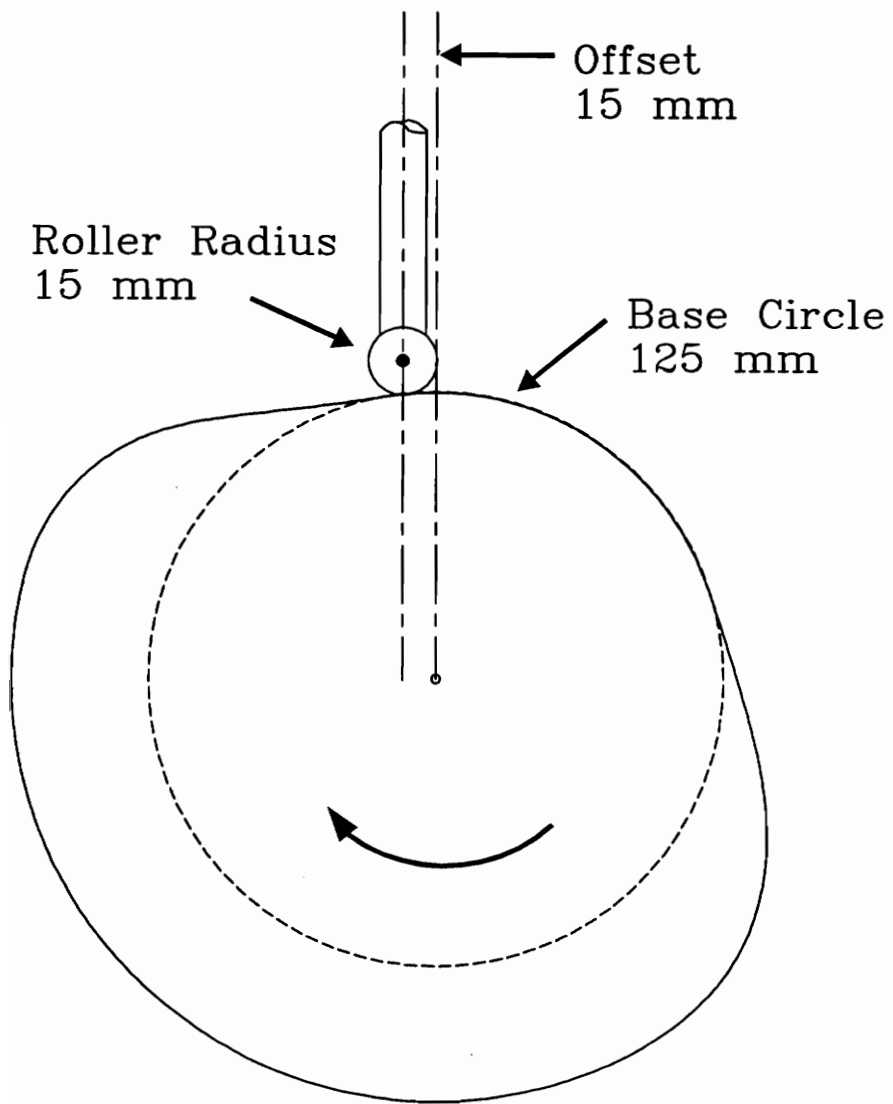


Figure 5.30: Cam for Toothpaste Tube Filling Example

should also be developed. Each of these tasks will require significant effort and thought.

5.13 Conclusions

This chapter provides a model for carrying out the conceptual design process for cam mechanisms. Embodied in this model is information and procedures to assist the designer in decision making. Governing equations have been presenting along with considerations for manipulating the parameters to best suit the design problem. Following these guidelines and considering the offered information will assist the designer throughout the conceptual design of cam mechanisms.

Chapter 6

AutoCam: A Modular Decision Support System for Conceptual Cam Design

6.1 Introduction

The previous Chapter presented a detailed description of the information model for conceptual cam mechanism design. That model describes the information in the form of facts, heuristics, calculations and procedures. This Chapter describes the realization of that model in a computer system named AutoCam. Presented here are the general system layout and some of the more interesting details of each of the modules. Included is a description of the system performance and capabilities.

6.2 General System Layout

AutoCam is a modular design assistant operating under the Windows environment for the personal computer. The system was developed using Microsoft Visual Basic. Dynamic Data Exchange (DDE) capabilities were exploited for linking the windows graphical user interface to the AutoCad drafting environment and the Microsoft Word word processor. A diagram of the system is shown in Figure 6.1.

A detailed information system is linked to the modules. The designer can access the information system in several ways. The most direct method is by using the mouse to select **Help** on a pull-down menu. The system will then direct the designer to a contents screen or allow access for a search of keywords. The designer also has access to context-

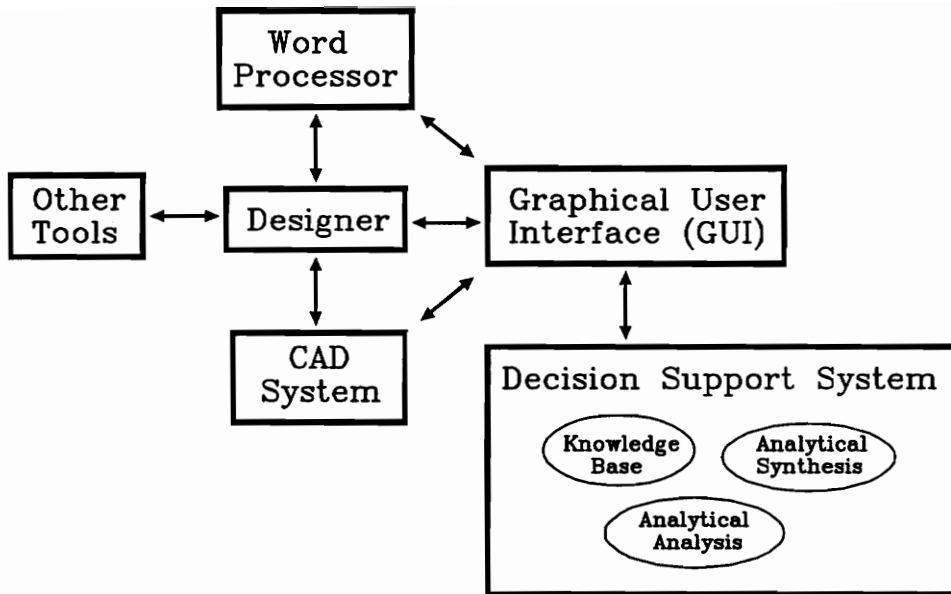


Figure 6.1: AutoCam System Model

sensitive information by pressing the F1 key when the mouse has highlighted a portion of the screen. An information screen pertinent to the present state of the system is presented to the designer.

Figure 6.2 illustrates a complete modular system for cam mechanism design. The completed system will assist the designer throughout the development from the problem confrontation and clarifying objectives through synthesizing the cam profile, detailed design and formulation of a manufacturing and maintenance plan. This Chapter describes the conceptual design which encompasses the first four modules:

Module 1: Clarifying Objectives

Module 2: Formulating Specifications

Module 3: Establishing Motion Specifications

Module 4: Cam Profile Synthesis

The other modules have not yet been developed. Their development is included as future work.

<u>INPUTS</u>		<u>OUTPUTS</u>
User Queries CAD Drawings	Module 1 Objectives	Objective Statements Objective Tree
User Queries CAD Drawings	Module 2 Specifications	Specification List Timing Diagram Drawing of Allotted Space Recommended Mechanism
CAD Interaction Assumed Cam	Module 3 Motions	Motion Specifications Follower Motion
Outputs from Module 3	Module 4 Synthesis	Complete Motion Program Cam and Follower Arrangement Synthesized Cam Profile
Outputs from Module 4 CAD Drawings	Module 5 Dimensions	Cam Width Follower Size and Shape Spring Size and Shape
Outputs from Module 5 Materials	Module 6 Dynamics	Forces Vibrations
Frame Types Bearings Fasteners Shafts	Module 7 Form Design	Assembly Drawing of All Components
CAD Drawing	Module 8 Detail Design	Working Drawing
Outputs from Modules 7,8 User Queries	Module 9 Manufacture	CNC Code (Cutting Edge) Manufacturing Plan
User Queries	Module 10 Maintenance	List of Replacement Items Preventive Maintenance Plan

Figure 6.2: Extended AutoCam System Modules

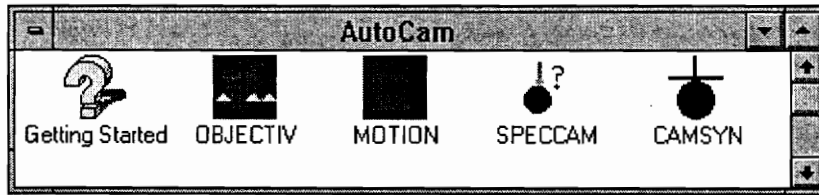


Figure 6.3: AutoCam Workgroup

6.3 Getting Started

The designer may begin a project by selecting the “Getting Started” icon in the AutoCam workgroup shown in Figure 6.3. This initiates the information system in the Getting Started information group. Here, the designer has access to information on the AutoCam system layout and its basic operations. Other topics include:

- Brief introduction to design methodology
- Cam mechanism terminology
- Why use a cam mechanism
- Cams vs. linkages
- System limitations

The last item is important. Often software programs describe their capabilities, but do not highlight the limitations. It is important for the designer to be aware of what the program cannot do. The system is limited to the conceptual design of cam mechanisms. It provides assistance and information useful for the early development of a cam mechanism. It does not provide detailed dynamic analysis, optimization, or strength of materials calculations. The system is limited to the synthesis of disk cams with the simple follower types described in the previous Chapter. It provides information and manipulation of the five common motion curves also presented in the previous Chapter. The system is capable of assisting the designer in developing preliminary working drawings of the cam mechanism, its environment and the motion program.

Figure 6.4 shows the information system screen for introducing the designer to cam mechanism terminology. Notice that the words *follower* and *frame* are underlined (they

are also colored green). This indicates that these words can be selected by the designer for further clarification. If the designer were to click the mouse over the word follower, a screen describing the follower types is brought forward. This hypertext action allows the designer the freedom to explore relevant topics as desired.

6.4 ObjectCam - Establishing and Clarifying Objectives

ObjectCam assists the designer in formulating a list of objective statements for the design. The objectives can be organized in an objectives tree where subordinate objectives support higher-level objectives.

Figure 6.5 shows the main menu window with the objectives for the toothpaste tube filling example from Chapter 5. On the left of the window is the “Objective Tree of Names”. Here the designer can organize the objectives into the tree format. Listed in the tree is only the referral name for the objective. The buttons below the tree are used for organizing the objectives. The designer can add or remove an objective from the tree. Objectives can also be moved to new positions. Branches of the tree can be expanded to show all subordinate objectives or collapsed to show only the top level. The right and left arrows are used to reduce or increase the level of an objective to indicate subordination.

To the right of the tree is the “Objective Card”. The card shows the name of the objective and the date it was established. The main body of the card is a text window where the designer can write any desired description for the objective. The designer can access the cards by highlighting the title in the objectives tree.

The “File” pull-down menu provides standard file manipulation controls. The “Edit” pull-down menu provides common Cut, Copy, Paste and Delete features for editing the objectives. The “Help” pull-down menu provides access to the information system. The designer can access the main menu for the ObjectCam module or perform a search of keywords. There is also a description of the operation of the module and the functionality of the command buttons.

The contents of the information system for ObjectCam contains the following topics, the details of which appear in Chapters 3 and 5. Figure 6.6 shows the information system window for establishing sub-objectives.

- The importance of formulating objectives
- The main objective

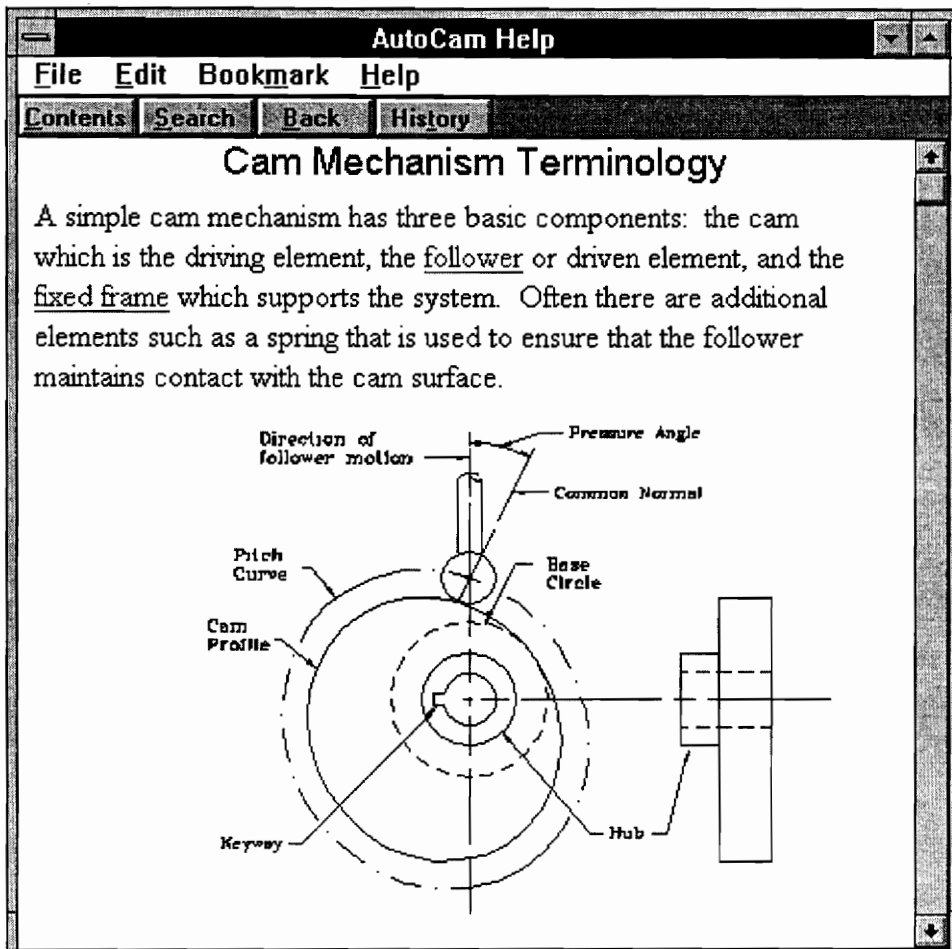


Figure 6.4: AutoCam Information System - Cam Terminology Screen

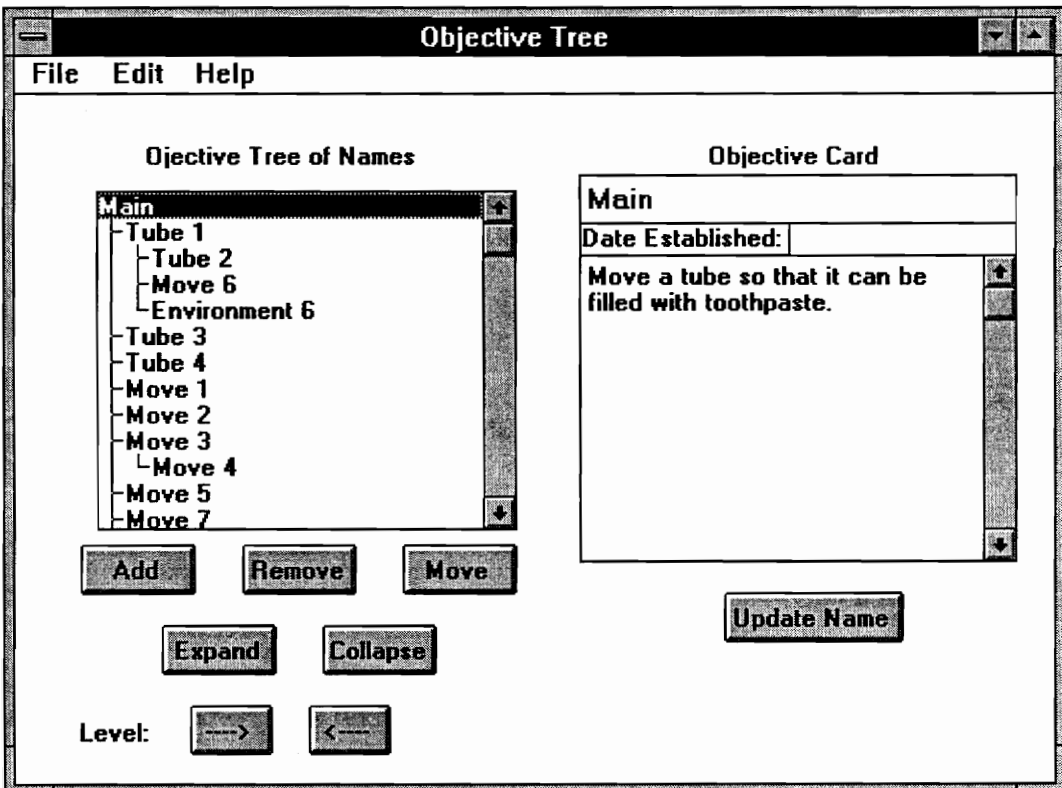


Figure 6.5: ObjectCam - Main Window

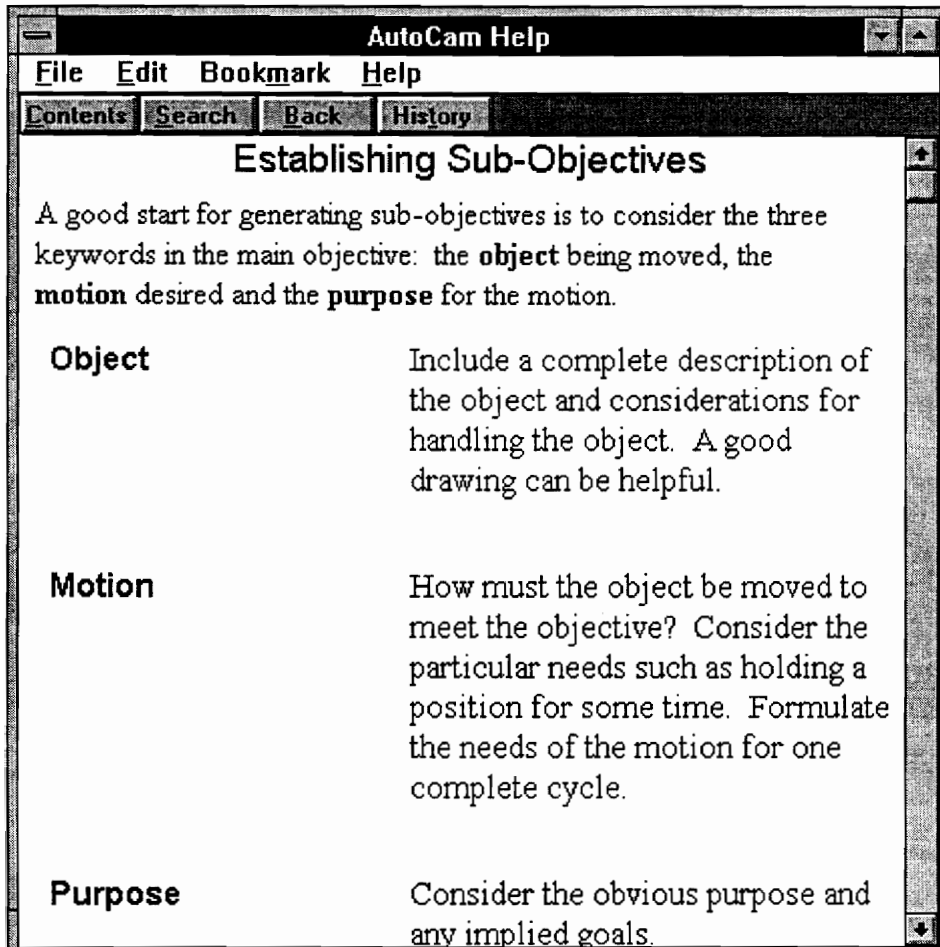


Figure 6.6: Information System - Establishing Sub-Objectives

- Establishing sub-objectives
- Formulating an objectives tree

6.5 SpecCam - Formulating Specifications

When the designer activates the SpecCam module from the AutoCam group, a small window is created that will remain *always on top* of other open windows. The SpecCam window contains three drop-down menus: SpecSheet, DrawSpecs, and Help.

Under SpecSheet the designer can create a new specification sheet or open an existing one. The module then opens the Word word processor and accesses a template for a standard specification sheet. The specification sheet is laid out in the manner presented in Chapter 5. The template is shown in Figure 6.7. The Headings section of the specification template contains the suggested topics for consideration; the designer may add or delete these headings from the list. The headings help provide a reminder of topics to consider for the specifications.

The designer can access the information system through the Help pull-down menu where the contents page for the SpecCam module can be called or a search of keywords can be performed. The SpecCam contents contains the following topics for making specifications:

- The importance of specifications
- The specification sheet
- The specification check list (describes all of the topic headings on the specification sheet)
- Formulating a project timeline
- Specification drawings
- Example specification sheet

The DrawSpecs pull-down menu accesses the AutoCad drafting environment. As discussed in Chapter 5, the drawings help to clarify the specifications. Although the drawings may be rudimentary at this stage, they should be viewed as dynamic documents to be updated throughout the design of the cam mechanism.

Company Name:	Specification for a Cam Design for:	Date:
---------------	--	-------

Changes	D W	Headings	Requirements	Responses
		Kinematics		
		Geometry		
		Moved object geometry		
		Timing		
		Forces		
		Power		
		Materials		
		Friction		
		Operation		
		Environ- ment		
		Production		
		Assembly		
		Mainten- ance		
		Transport		
		Safety		
		Ergonom- ics		
		Costs		
		Schedules		

Figure 6.7: SpecCam - Specification Template

The designer can access the information system for guidance on the specification drawings. Four drawings should be made:

1. The object being moved
2. The system environment showing interacting parts and machines
3. The mechanism environment highlighting the allotted space for the mechanism
4. The motion description illustrating the specified positions and/or orientations of the moved object.

The information system describes the aspects to consider for each of these drawings and provides examples.

6.6 MotionCam - Formulating Specifications for the Motion Program

Traditionally the specifications for the motion program of the follower have been developed with plots of position, velocity, and/or acceleration as a function of the cam's rotation. The designer would have to correlate desired motions with any drawings of the system. MotionCam facilitates the development of the motion specifications by providing an integrated environment with the AutoCad drafting package.

When MotionCam is activated by selecting its icon in the AutoCam group, AutoCad is started with the small MotionCam window in always-on-top mode. The designer can then open the motion description drawing produced from the guidelines in the SpecCam module or start a new drawing. The pull-down menu item MotionSpecs can then be used to open a window illustrating the specifications shown in Figure 6.8. The designer can select a motion specification type and place an icon on the drawing to indicate the position for the specification. An accompanying window prompts the designer for information on the specification. The dwell, constant velocity and drop specifications were described in Chapter 5. The Start, Return, and Pivot specifications are presented below.

6.6.1 Start

When the start specification is selected, the designer is prompted to enter either the total cycle time for the motion or the angular velocity of the cam. The two are related by the

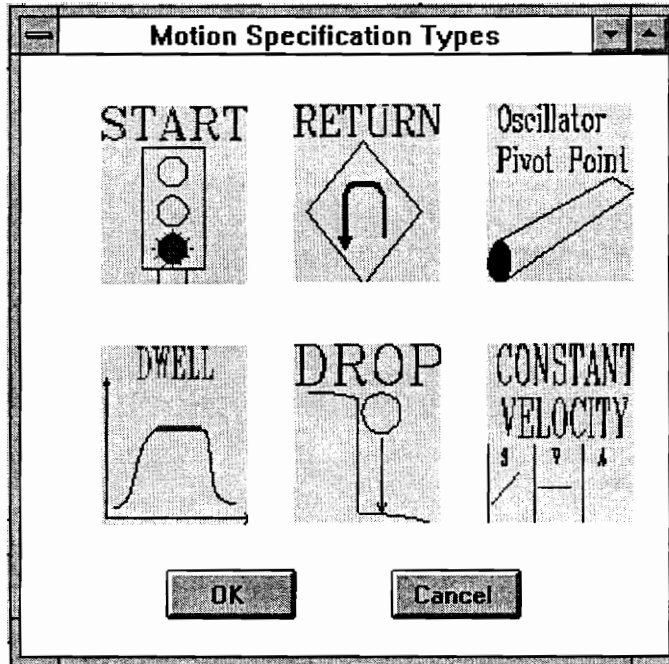


Figure 6.8: Motion Specifications Window

equation:

$$cycle\ time = \frac{60}{\omega} \quad (6.1)$$

where

ω is the angular velocity in rpm and the cycle time is in seconds

The designer then places the start icon on the drawing where the motion of the object will begin.

6.6.2 Return

When the return specification is selected, the designer is prompted for the rise time to reach the return position or the angular rotation of the cam at this position in degrees. The two are related by the equation:

$$cam\ rotation = \frac{risetime}{cycletime} 360 \quad (6.2)$$

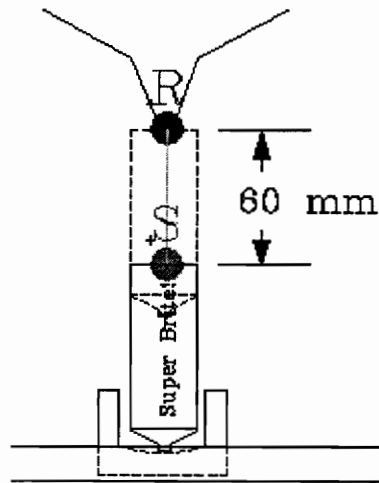


Figure 6.9: Start and Return Position Icons

The designer then places the return icon on the drawing at the return point for the object. Figure 6.9 illustrates the toothpaste example from Chapter 5 with the start and return positions identified with icons.

6.6.3 Pivot Point

It is necessary to establish a pivot point when using an oscillating follower. The pivot point defines the center of the arc along which the follower will move. The location of the pivot point has additional ramifications which will be discussed more in the next section on logical operations.

6.6.4 Logical Operations

The effort in programming this module was focused on logical operations in placing icons and producing the motion specification plot. After the designer establishes the start and return points, a decision must be made whether to pursue a translating follower or an oscillating follower. The program prompts the designer for this decision. Two points define a line on which the other specifications must lie. If the user selects translation for

the motion, then the program draws a line indicating the path of the object and calculates the follower stroke as the distance between the start and return icons.

If the user selects oscillating motion, the designer is prompted to select a third specification or a dummy point. Three points define an arc. The program then draws the arc for the path of the motion of the follower and places the pivot point icon at the center. The stroke is calculated as the angle between the start and return icons about the pivot point.

This is not the only mode for creating the arc motion of an oscillating follower. If the designer selects the pivot point specification, one other specification must be chosen before the program reacts. Two points establish the radius of the circle for the arc. The program then draws a semicircle through the specification point. The next specification must fall on this semicircle. If the next specification completes the start-return pair, the semicircle is removed and an arc is drawn to indicate the path of the follower.

The designer is warned that care must be taken in locating the specification points. For a translating follower, the icon can be placed in any consistent location on the moving object. For oscillating followers, the points need to be located at the intended connection between the follower and the moving object. Otherwise, the pivot point will be incorrectly positioned. The designer may choose to move the pivot point, but this will effect the arc representing the path of the follower.

The program ensures that other specifications lie on the established path of the follower. When a specification point is selected, the program searches for the closest point on the path and then places the icon. If placing an icon results in one on top of another, the program offsets the new icon. This is shown in Figure 6.10 where the dwells for the toothpaste tube are at the extreme positions. This figure illustrates the complete specification drawing for the toothpaste example.

6.6.5 Viewing the Specifications

By selecting the **View** pull-down menu, the designer can view the specifications as a plot or in a table. Figure 6.11 shows the resulting specification plot for the toothpaste example. The return point is indicated by a circle. This example specifies the cycle time, the stroke and the dwells at the extreme positions. The motion between the specifications is developed in the CamSyn module.

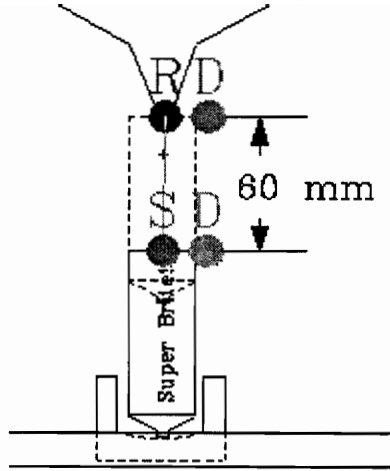


Figure 6.10: Complete Motion Specifications for Toothpaste Example

6.6.6 Comments on MotionCam

The MotionCam module demonstrates the ability of computer aided design to establish new methodologies. Traditionally, the designer would make the specification not independently of the drawing. Some intuitive feel for the connection of the motion specifications to the actual problem can be lost. MotionCam brings the two together and frees the designer from the mundane tasks such as measuring the stroke. The designer is free to focus on what the mechanism is supposed to do.

The designer has access to the information system in the MotionCam module through the **Help** pull-down window and in a context-sensitive mode. The user can highlight an item in the window and press F1 to directly call the information. For example, the designer can directly access information on the dwell specification by highlighting the dwell specification picture and pressing F1. Figure 6.12 shows the information system window describing the dwell motion specification. If the designer selects the words with dashed underlines, a pop-up window arises to give more information. After establishing the motion specifications, the designer can save them so that they can be used in the CamSyn module.

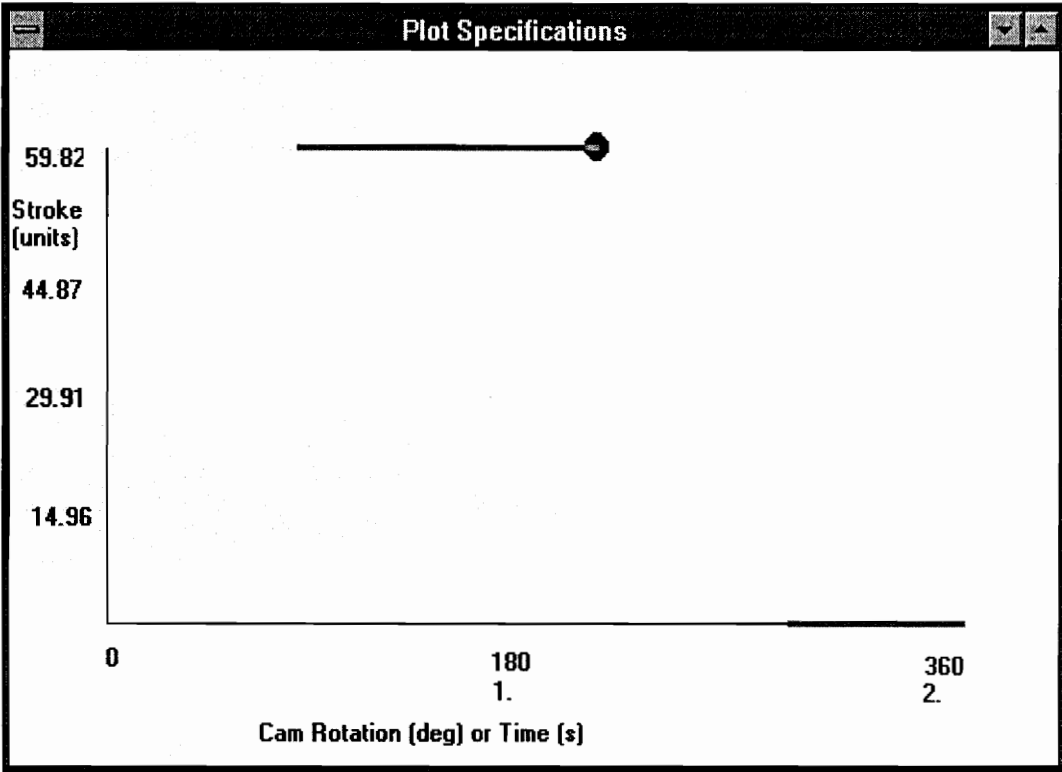


Figure 6.11: Motion Specifications Plot for Toothpaste Example

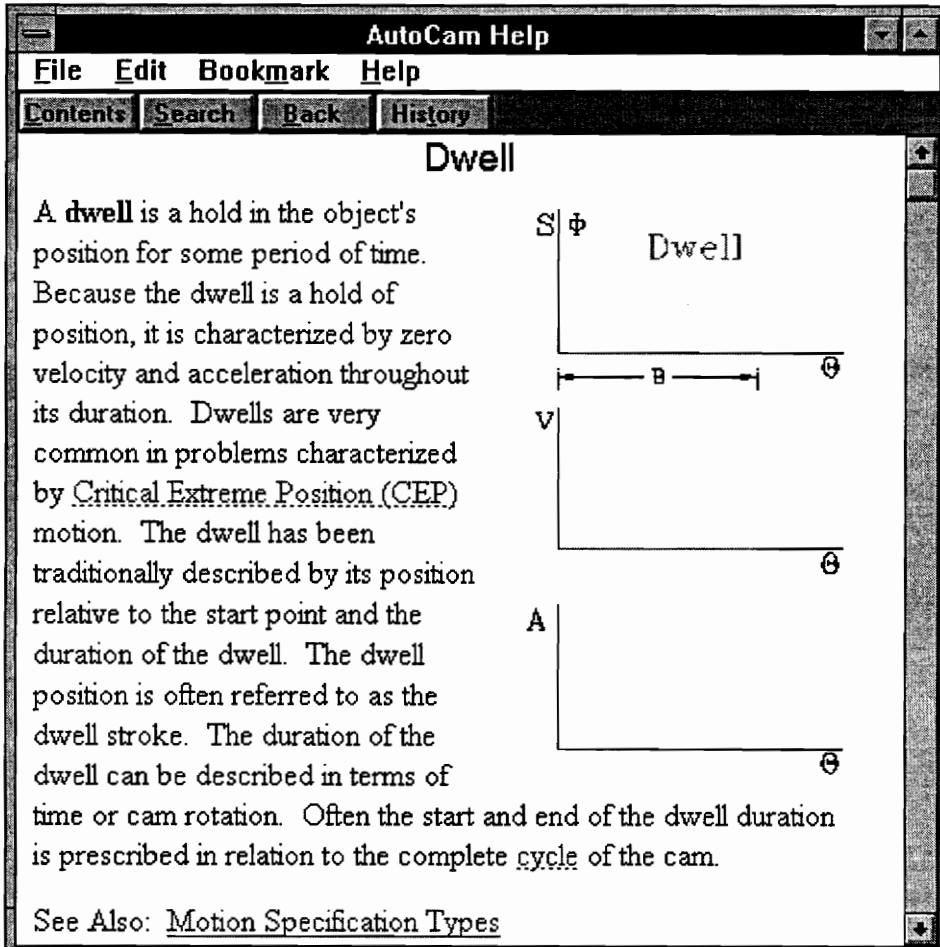


Figure 6.12: Information System - Dwell Motion Specification

6.7 CamSyn - Motion Program Formulation and Cam Profile Synthesis

A large portion of the software development effort was devoted to the CamSyn module. The CamSyn module assists the designer in formulating the motion program, selecting the follower type, sizing the cam mechanism and synthesizing the cam profile. This module employs a large number of analytical techniques in addition to providing access to useful information. The designer can import the motion specifications from the MotionCam module or establish them in CamSyn.

Figure 6.13 shows the main window for the CamSyn module. The designer can follow the design process across the pull-down menus from left to right:

1. Program Type
2. Motion Curves
3. Analysis
4. Make Cams
5. Call AutoCad
6. Help - access the information system

The body of the window contains dialog boxes and information. Through an input window in the upper left portion of the screen, the user can enter the angular velocity of the cam in magnitude and direction. Below that is a group of information reminders to inform the designer of the motion program type, the total stroke of the follower and the total time, or cycle time. The main focus within the window is the grid for the motion program. As the designer establishes motion curves for segments of the motion program, the information is included in the grid. The designer can add, delete or insert new segments with the buttons to the right of the grid. The grid will give the information on the motion curves in terms of the cam rotation (degrees) or time. Clicking on the toggle button specifies which format is displayed. The View Motion button can be used to view plots of the motion program for position, velocity, acceleration and jerk.

A description of the capabilities of the module follows in a logical order for the design development. The process does not have to proceed in this linear fashion, but it is useful to present it this way for clarity.

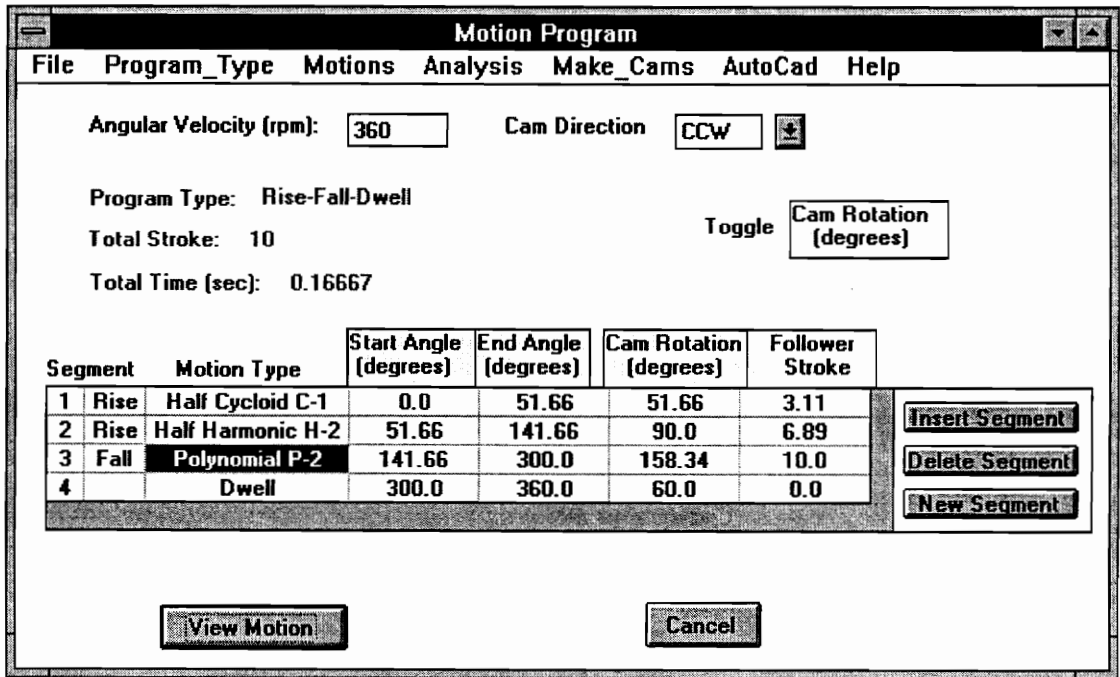


Figure 6.13: Main Window for the CamSyn Module

6.7.1 Program Types

When the designer accesses the “Program Types” pull-down menu, four choices are available for selection: Rise-Dwell-Fall-Dwell, Rise-Fall-Dwell, Rise-Fall, and Custom. These motion program types were described in Chapter 5 and won’t be repeated here. When the designer selects a program type, a window pops up for additional information. The details of the window depend on the program type. For example, the Rise-Dwell-Fall-Dwell window is shown in Figure 6.14. The designer enters a value for the total stroke of the follower and information on the starting and ending points of the dwells. The information can be entered as a rotation of the cam in degrees or as a time. When the designer clicks on the OK button, the system updates the motion grid with the information, placing the dwells in the proper positions. The designer can access information on the motion program types by pressing the F1 button when the mouse is highlighting a menu item. It should be noted that selecting a program type is not necessary if the designer used the MotionCam module and imports the specifications. The grid would be filled with this information automatically.

Rise-Dwell-Fall-Dwell

Total Rise:

Dwell 1 Start Angle	<input type="text" value="150"/>	Dwell 2 Start Angle	<input type="text" value="310"/>
Dwell 1 Start Time	<input type="text" value="0.06944"/>	Dwell 2 Start Time	<input type="text" value="0.14352"/>
Dwell 1 End Angle	<input type="text" value="200"/>	Dwell 2 End Angle	<input type="text" value="360"/>
Dwell 1 End Time	<input type="text" value="0.09259"/>	Dwell 2 End Time	<input type="text" value="0.16667"/>

Figure 6.14: Rise-Dwell-Fall-Dwell Dialog Window

6.7.2 Motion Curves

The designer can then proceed to fill in the remaining segments of the motion program by accessing the “Motions” pull-down menu. The choices are:

- Harmonic Motion
- Cycloidal Motion
- Eighth Degree Polynomial
- Modified Trapezoidal Acceleration
- Modified Sinusoidal Acceleration
- Dwell
- Constant Velocity
- Drop Function

Selecting a motion curve calls the appropriate dialog window. The dialog window shows each of the portions of the motion curve as was presented in Chapter 5. The harmonic motion dialog window is shown in Figure 6.15. The designer can access the information system by pressing F1 while this window is active. This will directly call information on harmonic motion. The designer can then access information on comparisons of other motions or any other desired topic. When the designer selects one of the portions of the motion curve, a new window will open with dialog boxes for information on the curve such as the follower stroke during the motion and the motion curve’s beginning and end points. Again, the designer can enter this information in degrees of cam rotation or time. The CamSyn module will handle unit conversions. When the designer clicks on the OK button, the main window returns with the motion curve information entered in the grid. In this fashion, the designer can enter a complete motion program for further exploration.

6.7.3 Viewing the Motion Plots

The CamSyn program contains all of the accompanying equations for the motions. When the designer clicks on the “View Motion” button, the CamSyn program uses these equations to formulate the position, velocity, acceleration and jerk plots for the complete motion

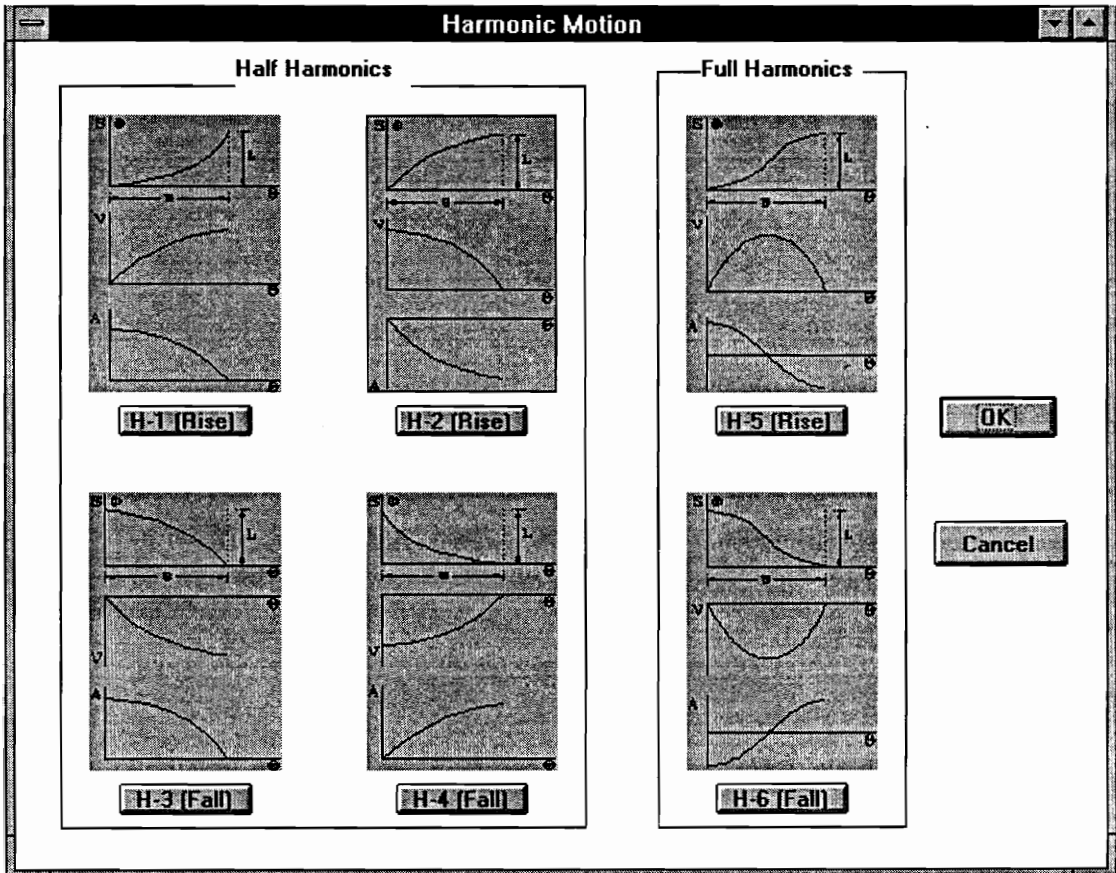


Figure 6.15: Harmonic Motion Dialog Window

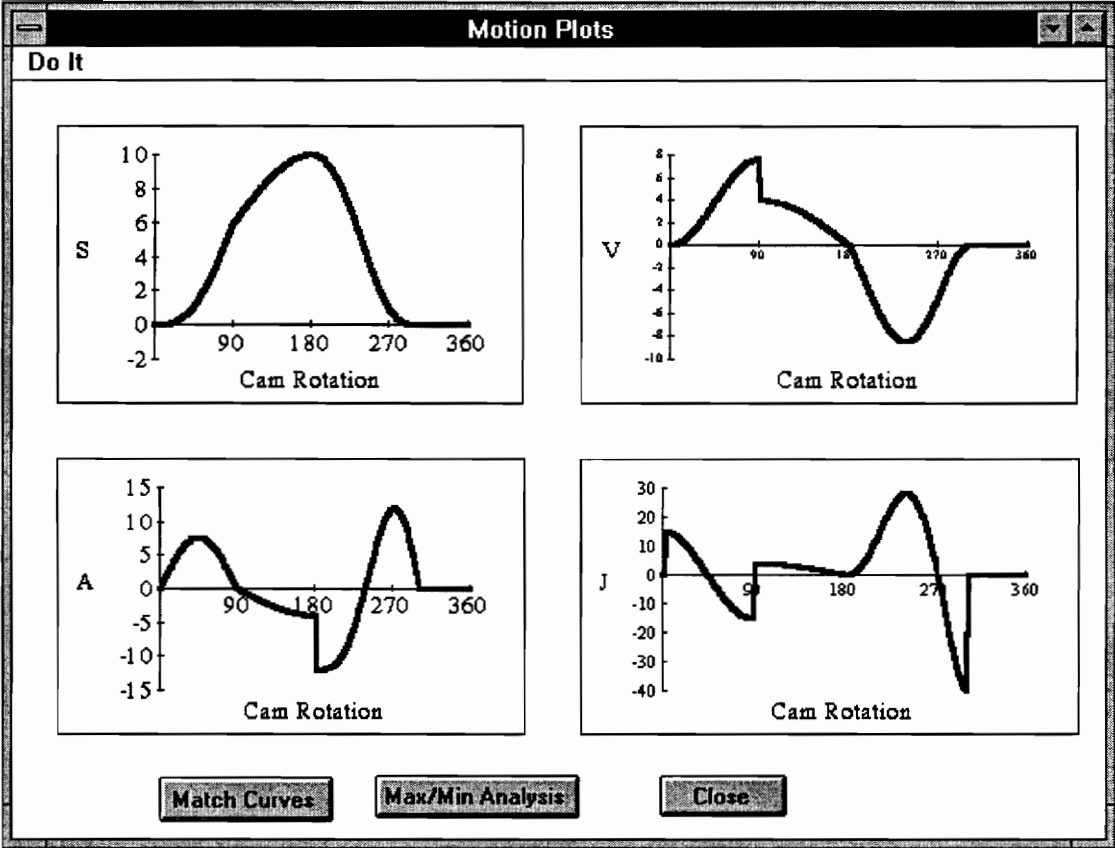


Figure 6.16: Plots for Motion Program

program. All of the calculations are done in the background. The designer views the plots as shown in Figure 6.16. The designer can get details on values for each of the plots by clicking the “Max/Min Analysis” button.

The motion program for the plots in Figure 6.16 is shown in Table 6.1.

6.7.4 Curve Matching

As can be seen in Figure 6.16, the parameters entered by the designer do not result in a smooth motion program. Infinite jerk results at the junction between the Half Cycloidal Rise, C-1, and the Half Harmonic Rise, H-2, because the velocities do not match. The accelerations do not match at the junction between the H-2 curve and the Eighth-Degree Polynomial Fall, P-2. It is important to eliminate the infinite jerk by manipulating the

Table 6.1: Motion Program Accompanying Plots

Segment	Motion Type	Cam Rotation (deg)	Stroke
1 Rise	Cycloidal C-1	90	6
2 Rise	Harmonic H-2	90	4
3 Fall	Polynomial P-2	120	10
4	Dwell	60	0

cam rotation and stroke values for the curves. The process for accomplishing this was presented in section 5.7.

Performing the curve matching can be cumbersome and time consuming for the designer. The CamSyn module automates this process. This is significant because most of the cam synthesis packages discussed in the literature review do not consider the curve matching. It is usually left to the designer. The curve matching capabilities of CamSyn are significant and warrant some detailed discussion.

Much of the operation is hidden to the designer. If the motion program contains infinite jerk, the designer can eliminate it by clicking on the “Match Curves” button to activate the curve matching algorithm.

Look-up Table

The CamSyn program begins by obtaining information about the curves’ beginning and end points for each junction by employing a look-up table. The look-up table includes the equations for the velocity and acceleration at the beginning and end of each curve. An examination of these equations indicates that only one will produce a non-zero value. Only the equations that produce a non-zero value can be used for the governing equation. The table also contains the partial derivatives of the governing equation with respect to the cam rotation, β , and the stroke, L . An example of a look-up table entry is shown in Table 6.2 for the Half Harmonic, H-2, motion curve.

The CamSyn Program obtains the motion curve information for each junction of the motion program and then classifies the junction according to the following rules.

1. Never Match: This is indicated by the velocity or acceleration of one of the curves having an equation for its value, while the other curve has a zero value or an equation of the opposite sign.

Table 6.2: Look-Up Table Entry for Harmonic Motion, H-2

Motion Curve	Velocity	Acceleration	$\frac{\delta F}{\delta L}$	$\frac{\delta F}{\delta \beta}$
H -2 (beginning)	$\frac{\pi L}{2\beta}$	0	$\frac{\pi}{2\beta}$	$\frac{-\pi L}{2\beta^2}$
H-2 (end)	0	$\frac{-\pi^2 L}{4\beta^2}$	$\frac{-\pi^2}{4\beta^2}$	$\frac{\pi^2 L}{2\beta^3}$

2. Always Match: This is indicated by both curves having a zero value for velocity and acceleration.
3. Can Match: This is indicated by the curves both having an equation of the same sign for the corresponding velocity or the acceleration.

If the program finds junctions that will never match, it lists these junctions in a table and alerts the designer. The designer should select new motion curves to eliminate the problem. However, the designer may choose to continue the process with these curves. In which case, the program ignores the offending junction.

As shown in section 5.7, the junctions that always match do not produce a governing equation. The junctions that can match produce a governing equation, and the CamSyn program collects these. Section 5.7 also showed that an equation is needed to ensure that the sum of the strokes is zero and an equation is needed to ensure that the sum of the cam rotations is 360 degrees.

The example in Table 6.1 results in the following junction information:

C-1 to H-2: Velocities must be made to match

H-2 to P-2: Acceleration must be made to match

P-2 to Dwell: Velocities and Accelerations match at zero

Dwell to C-1: Velocities and Accelerations match at zero

This leads to a total of four governing equations and seven unknowns ($L_1, \beta_1, L_2, \beta_2, L_3, \beta_3, \beta_4$). The stroke for the dwell, L_4 is always zero. The designer may select three

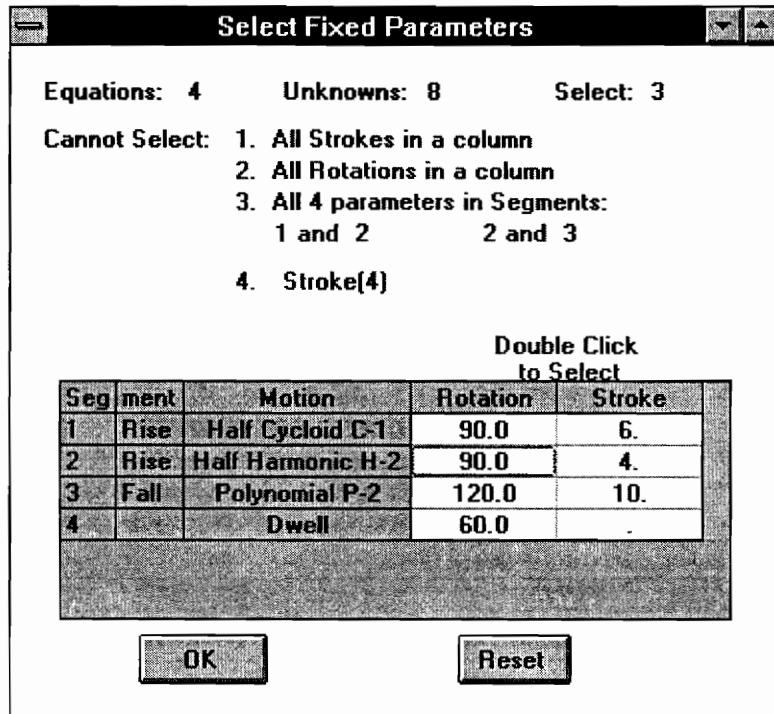


Figure 6.17: Window for Selecting Fixed Parameters in a Curve Match

of these and the program will solve for the others from the governing equations. Figure 6.17 shows the window where the designer can select the three parameters to keep fixed. Included above the grid are the instructions from section 5.7 for making the selections.

Solving the Governing Equations for the Unknown Parameters

The program employs a modified multivariable Newton-Raphson technique to iteratively solve for the unknown variables. The governing equations must be written as a function that can be driven to zero. The equations for the example in Table 6.1 are as follows:

$$\begin{aligned}
 f(1) &= V_{C-1(end)} - V_{H-2(beginning)} \\
 f(1) &= \frac{2L_1}{\beta_1} - \frac{\pi L_2}{2\beta_2}
 \end{aligned} \tag{6.3}$$

$$\begin{aligned}
f(2) &= A_{H-2(end)} - A_{P-2(beginning)} \\
f(2) &= \frac{-\pi^2 L_2}{4\beta_2^2} - \frac{-5.2683L_3}{\beta_3^2}
\end{aligned} \tag{6.4}$$

$$f(3) = L_1 + L_2 - L_3 \tag{6.5}$$

$$f(4) = B_1 + B_2 + B_3 + B_4 - 360 \tag{6.6}$$

The modified multivariable Newton-Raphson routine also uses the slope of the functions to assist the iterations. This can be formulated as a matrix equation using the partial derivatives of the functions with respect to the cam rotation and stroke parameters as follows:

$$\begin{bmatrix} f(1) \\ f(2) \\ \vdots \\ f(n-1) \\ f(n) \end{bmatrix} = \begin{bmatrix} \frac{\delta f(1)}{\delta L_1} & \frac{\delta f(1)}{\delta \beta_1} & -\frac{\delta f(1)}{\delta L_2} & -\frac{\delta f(1)}{\delta \beta_2} & 0 & 0 & 0 & \dots \\ 0 & 0 & \frac{\delta f(2)}{\delta L_2} & \frac{\delta f(2)}{\delta \beta_2} & -\frac{\delta f(2)}{\delta L_3} & -\frac{\delta f(2)}{\delta \beta_3} & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 1 & 0 & -1 & 0 & -1 & \dots \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & \dots \end{bmatrix} \begin{bmatrix} \Delta L_1 \\ \Delta \beta_1 \\ \Delta L_2 \\ \Delta \beta_2 \\ \vdots \end{bmatrix} \tag{6.7}$$

or

$$[F] = \left[\frac{\delta F}{\delta \xi} \right] [\Delta \xi] \tag{6.8}$$

where ξ represents the vector for the change in motion parameters.

The program uses the partial derivative expressions from the look-up table to formulate this matrix equation. The vector for the change in motion parameters is then obtained by solving for $\Delta \xi$.

$$[\Delta \xi] = \left[\frac{\delta F}{\delta \xi} \right]^{-1} [F] \tag{6.9}$$

The result from equation 6.9 is added to the previous value for the parameters. The iterative method steps through these equations until

$$f(1) + f(2) + \dots + f(n) < 0.0001 \tag{6.10}$$

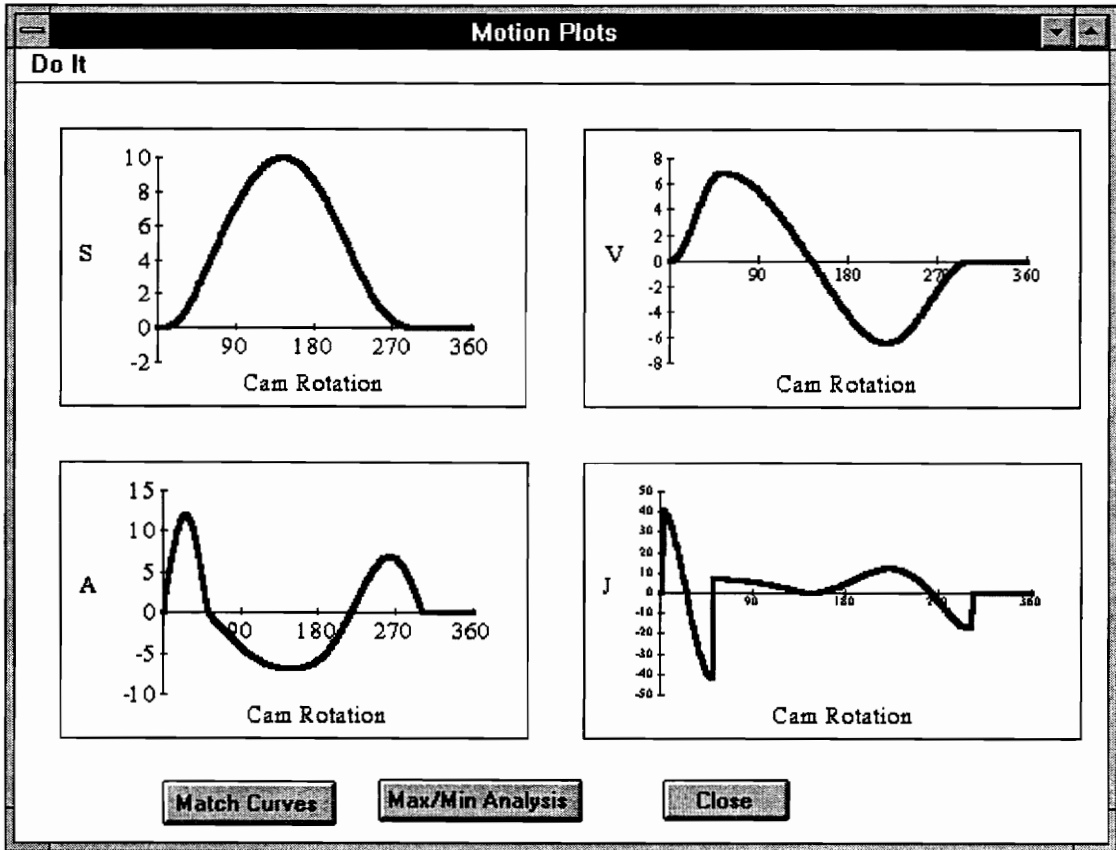


Figure 6.18: Plots for Motion Program After the Matching Algorithm

Updating

After the CamSyn program solves for the new motion curve parameters, it re-calculates the curves and creates a new plot. It also updates the table on the main window. The matched curve for the example is shown in Figure 6.18. The results will be different depending on which parameters the designer chooses to hold fixed in the curve-matching algorithm. The designer can save the resulting motion program and try others.

6.7.5 Selecting Follower Type

After formulating the motion program, the designer can select the follower type under the "Make Cams" pull-down menu. A window is opened showing the possible follower types discussed earlier in the dissertation. The designer can highlight any of the drawings

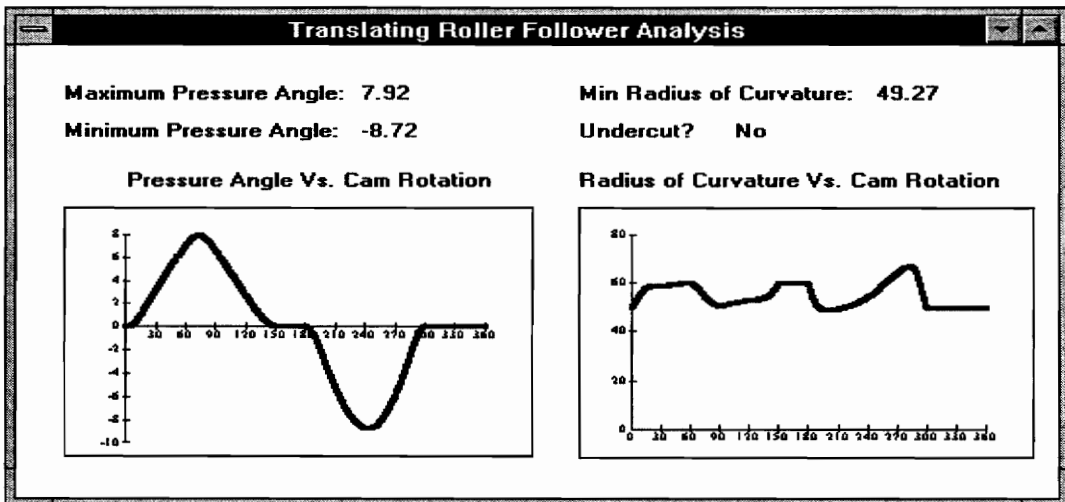


Figure 6.19: Analysis Window for a Translating Roller Follower

and press the F1 key to access the information system. When the designer selects a follower type, another window is opened to get information on the fixed parameters for the follower. For example, a translating roller follower requires the setting of the base circle radius, roller radius and follower offset. The designer can also enter a name for this arrangement so that it can easily be recalled later among the many alternatives explored. Again, the designer has access to the information system to explore the implications of the parameters.

6.7.6 Cam Analysis

After the follower type is selected, the designer can analyze the resulting mechanism by selecting “Cam Analysis” under the “Analysis” pull-down menu. Figure 6.19 illustrates the analysis window for a translating roller follower. At the top is listed the maximum and minimum pressure angles. The pressure angle is plotted as a function of the cam rotation below. Next to this is a plot of the radius of curvature. The program determines if there is undercutting. The designer can access the information system by highlighting one of the plots and pressing F1. Figure 6.20 shows the information system window describing the radius of curvature for a translating flatfaced follower.

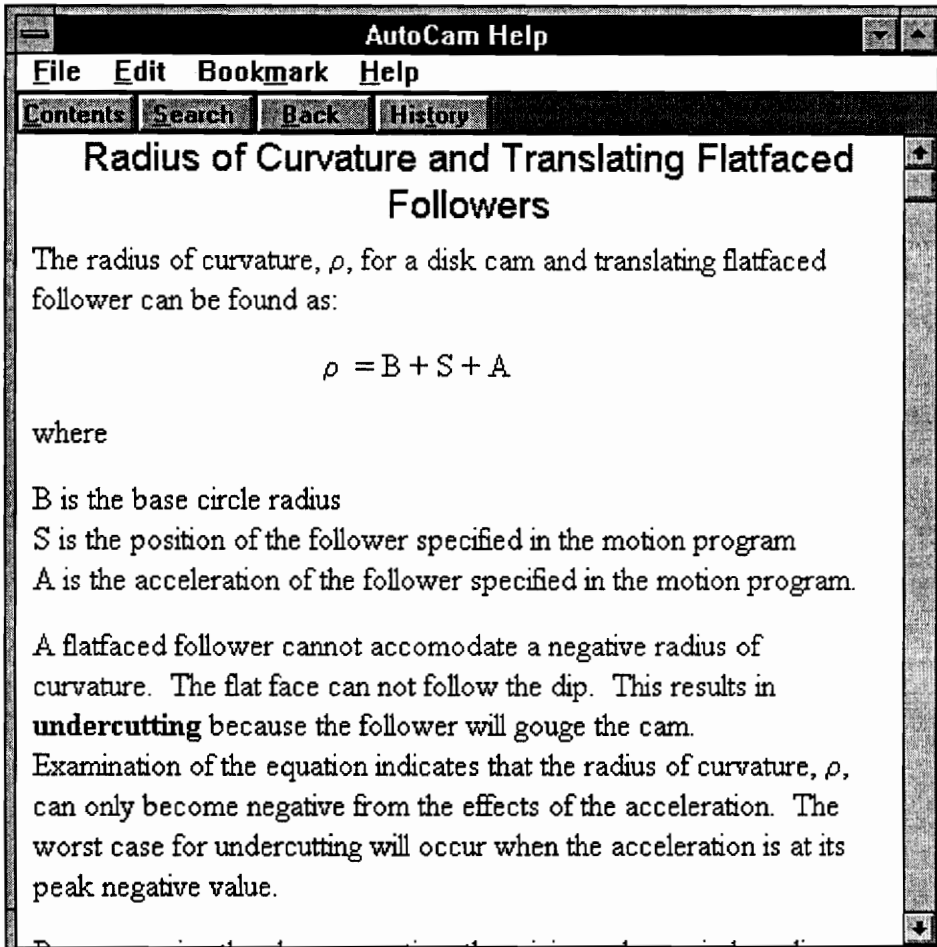


Figure 6.20: Information System - Radius of Curvature

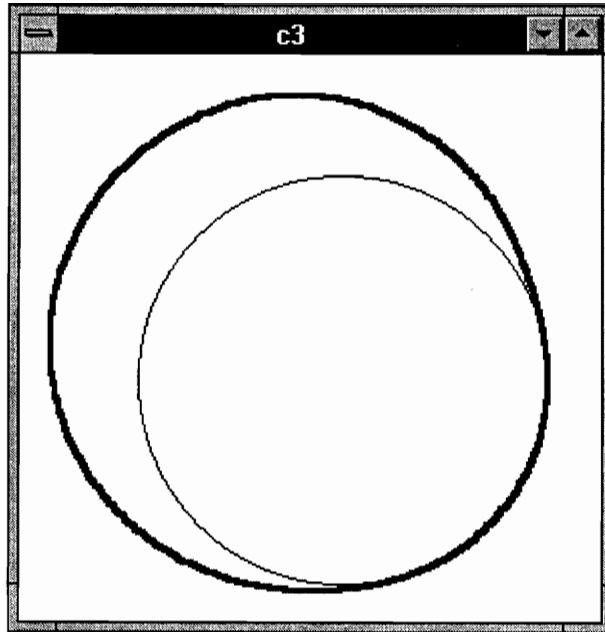


Figure 6.21: Plot of a Cam Profile

6.7.7 Cam Profile Synthesis

CamSyn will synthesize the cam profile using the equations derived by conjugate geometry that were presented in section 5.9. The designer can simultaneously plot several different cams in open windows for comparisons. The cam profile changes color for each segment of the motion program so that the designer can see the effect of the transitions. A resulting cam profile is shown in Figure 6.21. The name that the designer assigned to the cam-and-follower arrangement appears in the top of the window.

6.7.8 Integration of CamSyn with AutoCad

When the designer has selected an appropriate cam mechanism, AutoCad can be called by selecting the AutoCad pull-down menu. The designer can open a drawing of the system environment and select the location for the cam. The CamSyn program will draw the cam at the specified location and to the specified scale. The designer can then add details to the design. Having the detailed cam profile in the system drawing is an advantage for continuing the design process. The designer can correctly see the space the cam mechanism will take. Figure 6.22 shows the resulting cam from the toothpaste example in the system environment.

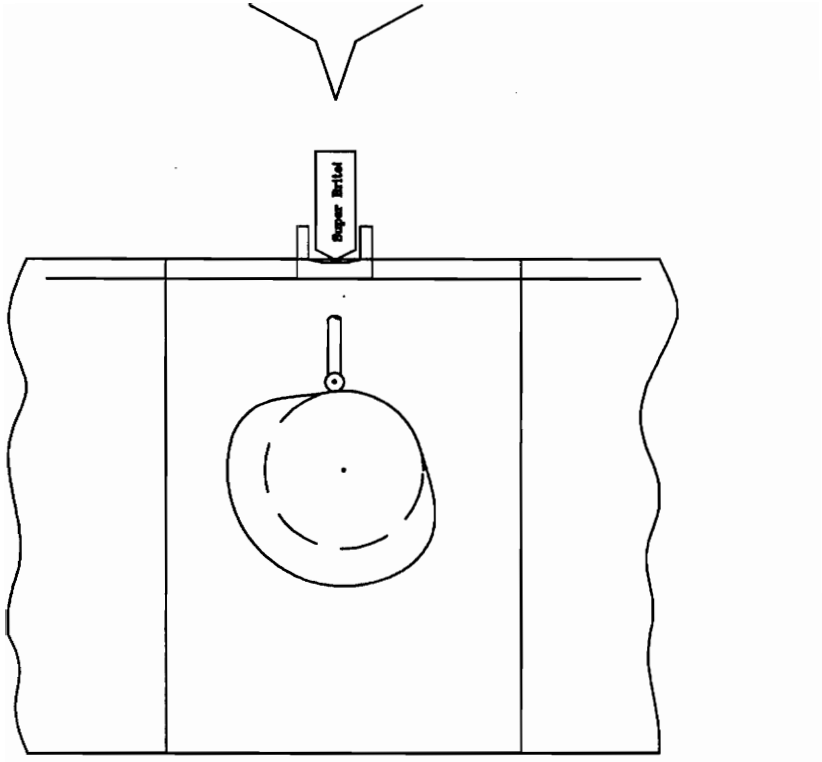


Figure 6.22: Cam Profile in AutoCad Drawing

6.8 Conclusions

The AutoCam system assists the designer through the conceptual design of cam mechanisms. Because conceptual design involves an initial exploration, the system limits the details and provides general information useful to that task. It transcends the general design methodologies by embodying them in a model that is useful to the designer. The designer can decide whether or not to follow the methodology. AutoCam also demonstrates the utility of integrating design methodologies with domain-specific tasks. The true benefit of any software system is to free the designer from the need to perform mundane, routine tasks and calculations. This allows the designer to focus on decision-making. In this manner, the strengths of both the computer and the designer are exploited.

The AutoCam system assumes that a cam mechanism is desired. There are other possible alternatives. Although the information system provides information as to why a cam mechanism may be desired and compares cams to linkages, the AutoCam system does not assist in the decision-making process that can result in exploring a cam mechanism as an alternative. Future development would include a module that would assist the designer in exploring alternatives beyond cam mechanisms. This module would describe creative techniques and assist in organizing alternatives. A long term goal would include the development of other systems that link to AutoCam. Ideas for these include systems for assisting in the design of linkages, industrial automation and robots.

Chapter 7

Conclusions and Recommendations

The field of design theory and methodology is in its infancy. While the act of design is as ancient as the invention of the wheel, our present understanding of the process is minute. Design is a human endeavor. The activities of design are, therefore, greatly influenced by the participating individuals and their culture. These influences must be considered in the formulation of theories and methodologies for design. Researchers have approached the design process from many vantage points. Some perform protocol studies of the act of design to gain insight to this complicated process. Others produce prescriptive models and methodologies on their view of how design should be performed. The artificial intelligence community seeks to emulate the design process in the computer environment. Each of these groups is working towards the goal of formulating a unified theory for design. As yet, none has been produced.

Chapter 3 of this dissertation discussed several theories and methodologies that have been proposed for the design process. These ranged from the very structured approach of Pahl and Beitz to the open, creative techniques of Tuomaala and French. The results of protocol studies suggest that none of these methodologies are followed by practicing engineers. This does not eliminate the potential benefit of such methodologies. One must then consider why these prior approaches are not used. While there are many possible considerations, two factors seem clear. First, the designers may not be aware of the methodologies and their benefits. These methodologies are relatively new. The engineering educational structure is just beginning to incorporate more design in the curriculum, so there are many engineers who have not been exposed to these methods. The second reason is that the methods are incompatible with the designers' background and culture. One cannot expect a designer to use a structured methodology when his personal approach is more free flowing. There is a need to educate designers about the

different design methodologies and their utility. In so doing, the designers will then be free to operate in a manner that best suits their background and culture.

Practicing designers are not as concerned with design theories and methodologies as they are with gaining practical assistance with their problems. The explosive growth in computer technology has greatly influenced the design environment. A plethora of tools are available to assist in specific aspects of the engineering enterprise. Many of these focus on domain-specific analysis tasks. However, general tools such as word processors, spreadsheets and computer aided drafting have gained wide acceptance. An examination of the successful tools provides insight for developing new systems to assist designers with the design enterprise.

While there is yet no universally accepted approach to design, tools can still be developed to provide assistance to designers. Presented in this dissertation is a model for their development. This model applies the theories of design methodology and popular general tools with domain-specific assistance across the many stages of design. The model capitalizes the strengths of the computer and the designer. The computer is used to perform routine and time-consuming analytical tasks. It also stores and presents useful information. This enables the designer to quickly generate and explore many alternatives and assists the designer's decision making. The general design methodologies are combined with domain-specific processes to provide the greatest utility to the designer, as well as inform him of alternative approaches to design.

This model was demonstrated for the conceptual design of cam mechanisms. The conceptual design stage is the least understood of the many stages of design, and also has the fewest tools to support the designer. Yet, decisions made during this stage have the greatest effect on the life-cycle cost and success of the design. The model incorporates methodologies for establishing objectives and formulating specifications with special consideration for the issues in cam mechanism design. It also focuses on the specific tasks and information needed to synthesize a workable cam profile. Careful thought was given to the information and processes needed for the conceptual stage of cam mechanism design. The model is intended to be useful without overwhelming the designer with details that are better considered in later stages of the design.

The model was used to develop a computer system for assisting designers with the conceptual design of cam mechanisms. The modular system, named AutoCam, provides assistance for design tasks from clarifying objectives to synthesizing the cam profile. It combines many task-specific computations with generalized tools such as the Word

word processor and the AutoCad drafting environment. It incorporates a context sensitive information system so that the designer can access pertinent information useful for the present stage of design. The modular nature of the system gives the designer the freedom to access the tools in the most suitable fashion.

The results of this dissertation are significant to both design theory and methodology and the domain of cam mechanism design. The general model suggests an approach for developing tools to assist designers with the design enterprise. These tools were developed with the recognition of the available design theories and methodologies; it capitalizes on the strengths of the computer and the designer.

There are several significant contributions to cam mechanism design as a result of this work. Much of the literature on cam design has focused on graphical and analytical techniques for synthesizing the cam profile. Little information was available for assisting the decisions that lead up to the cam profile synthesis. The information on cam mechanisms contained in Chapter 5 was compiled from many sources. This dissertation serves as a single source for information and processes pertinent to the conceptual design of cam mechanisms.

An area of noteworthy contribution is in developing the motion program. Several sources present the possible motion curves, but little information was available for selecting among the alternatives. Yet, it is the motion program that will have the greatest effect on the dynamic performance of the cam mechanism. The best single-source reference on this subject was Norton (1992), but his discussion is not as complete as that presented here.

The Motion module of the AutoCam system demonstrates how technology can influence the methods employed in design. Traditionally the specifications for the motion program were formulated by the designer. By considering the needs of the system, the specified motions would be generated and plotted. A drawing of the system is typically used as a reference to calculate the needed information. The Motion module automates this process by interacting directly with the designer and the CAD system. By employing icons at desired locations and providing requested information, the designer directs the Motion module to create the motion specification plots. This process frees the designer from performing routine calculations and permits the exploration of alternative approaches. The Motion module demonstrates the benefit of adding "intelligence" to the CAD software.

When generating the motion program, it is important to combine the motion curves such that the motion is smooth and continuous so that infinite jerk is avoided. Few texts

on kinematics or cam mechanisms provide adequate information on this process. Most of the cam synthesis packages do not consider curve matching, but simply synthesize the cam profile for the motion program entered. Any further consideration is left to the designer. One notable exception is a system developed at Purdue University that was described by Lin, Chang and Wang (1988) and Lin and Wang (1988). They automated the curve matching for the motion program on a limited scale by incorporating an expert system. They employed an extensive notation scheme to record the matchability of each motion curve segment with each of the other possibilities. The governing equation for each possible match was also stored. This resulted in a massive amount of stored information. Their formulation was such that adding only one motion curve segment would increase the needed connectivity information by a factor of two.

The curvematching algorithm employed in the AutoCam system presented here uses a look-up table of information about the end points of the motion curve segments. It then employs simple rules to determine curve compatibility. The algorithm formulates the governing equations and iteratively solves them to produce values for the parameters to avoid infinite jerk. The AutoCam algorithm allows the designer the greatest freedom in selecting the free parameters of the governing equations. The Purdue system does not allow the designer to select the fixed parameters. Another significant advantage of the AutoCam algorithm is the ease of adding new motion curves. The addition of new motion curves to the system only requires that the end point information be added to the look-up table. No other connectivity information is needed.

The integration of the system with the AutoCad drafting environment and the Word word processor is beneficial to the designer. The cam profile can be drawn directly in the desired position on the system drawing. This provides detail for further development in later stages of the design process. Having the specification sheet as a Word document is also beneficial for editing, distribution and the development of reports. Integrating new tools with popular software will add to the utility and help ensure its use.

7.1 Contributions from this Research

This research resulted in significant contributions to both fields of design theory and methodology and cam mechanism design. The main contribution to the field of design theory and methodology was the formulation of a system model for developing computer tools for assisting design. The model emphasizes the incorporation of general methodolo-

gies for the complete design process along with domain-specific techniques and computational support. The modular system does not impose a direct methodology, but supports a methodical approach if the designer wishes to follow it. Also, the modules support the iterative nature of design. The system includes a context-sensitive information system that provides background information appropriate for assisting decision making at the present stage of development. The information system should be accessible but should not be imposed on the designer. The general system model also specifies integration with commonly used tools in design such as computer aided drafting packages. Smooth integration with other software packages will ensure the overall utility of the system.

At the present time, a universal methodology that is applicable to all areas of design has not emerged. However, great contributions to design can be made by developing methodologies and computer systems specific to a given knowledge domain. This was demonstrated in this dissertation by applying the general system model to the domain of cam mechanism design. This dissertation describes a formal methodology for cam mechanism design. Previously, no methodology existed. Texts on cam mechanism design focused on particular aspects of cam mechanism design with the greatest concentration on techniques for generating the cam profile. Information useful for assisting in the decision making throughout the cam mechanism design process was scattered. No single source provided a complete and organized presentation of the issues in cam mechanism design. This dissertation has gathered and organized useful information for cam mechanism design and included it in a methodology.

The process of developing a computer system and formulating automated assistance tools resulted in several new contributions to cam mechanism design directly. First, is the recognition of the issues in formulating objectives and specifications that are particular to cam mechanism design. This had never before been presented. Another contribution resulted from the development of the motion specification module. By directing the formulation of the motion specifications on an actual drawing of the desired system and its environment, the module demonstrates the use of current technology to influence design techniques. The development of an automated approach for performing the curve matching when formulating the motion program is another direct contribution to cam mechanism design. It resulted in a set of rules and guidelines for establishing the governing equations and selecting parameters to remain fixed when solving the equations. This information is very useful, but had not been presented in the past.

The resulting AutoCam system itself is a significant contribution to both design

theory and methodology and cam mechanism design. AutoCam provides assistance in the design of cam mechanisms from the point of clarifying objectives to generating the cam profile. There had previously been no other system of such scope. The modules that assist in formulating objectives and establishing specifications also contribute to design theory and methodology. There had previously been no tools developed that assisted in formulating objectives and organizing an objectives tree. This module in itself could be distributed and used for formulating objectives for any type of design.

Overall, this dissertation demonstrates the benefits that can be obtained by developing models for domain-specific design processes. A concerted effort to adopt this methodology across many fields of engineering will inevitably improve the design enterprise.

7.2 Closing Statement

An examination of the research and development efforts in engineering over the past four decades shows a tremendous increase in models, algorithms and tools focused on engineering science and analysis. These efforts have greatly influenced the rapid advancement of technology. A similar effort is just beginning in the area of design theory and methodology and engineering synthesis. While a unified theory on design applicable across all knowledge domains is not readily apparent, a concerted effort of development by researchers in their areas of expertise would greatly improve the design process. This dissertation is a step toward that goal.

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Vita

Steven Bryan Shooter was born in Woodbury, New Jersey on November 6, 1965. He earned a bachelors degree in Mechanical Engineering from Virginia Polytechnic Institute and State University (Virginia Tech) in May of 1988. Upon graduation he worked for Sony Music Corporation as a Process Engineer in their first compact disk plant.

Steve returned to Virginia Tech in the fall of 1989 to pursue a Master of Science in Mechanical Engineering. His masters thesis was entitled *The Conceptual Design of Manipulators for Limited Access Workspaces*. His efforts were the seeds for the development of a robot for steam generator maintenance in nuclear power plants. Twenty four of the robots have been used in operations by the sponsor, BWNT.

After a brief hiatus when Steve and his wife, Catherine, backpacked through Europe, Steve began his Ph.D. with an interest in design methodology prompted by his experience from his masters degree. While working on his Ph.D., Steve served as an Instructor in the Department of Mechanical Engineering teaching the junior-level class in kinematics and dynamics of machinery. During this time, Steve also founded the Virginia Tech student chapter of the American Society for Engineering Education (ASEE).

Steve will finish the requirements for the degree of Doctor of Philosophy in Mechanical Engineering in August of 1995. He will then join the faculty in the Department of Mechanical Engineering at Bucknell University as an Assistant Professor in the fall semester.