CHAPTER 1
EVOLUTION OF A SUCCESSFUL DESIGN

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1.1 EVOLUTION OF A DESIGN

Most likely you have, right at this moment, at least one machine design project in progress. Maybe you were the originator of the design, but I suspect you inherited this design from others. I further suspect that you have already identified elements of the design you feel could be improved. You might be under pressure from customer service or marketing to respond to some need for change. In responding successfully, either to your own observations for change or to those of others, the design will evolve. Recognizing that the evolutionary design process is decidedly complex, with a seemingly random sequence of steps, the primary purpose of *Standard Handbook of Machine Design* is to make the information you need as readily accessible and usable as possible.

As an example of how a design can evolve, and to provide perspective on how the information in this Handbook has traditionally been used, let me review for you a project I was given in my first job as a mechanical engineer. It involved the positioning of a microwave feed horn for a 30-ft-diameter antenna dish. The original design (not mine, by the way) called for a technician to climb up onto a platform, some 20 ft off the ground, near the backside of the feed horn. The technician had to loosen a half dozen bolts, rotate the feed horn manually, and then retighten the bolts. This design worked quite well until several systems were sold to a customer providing telecommunications along the Alaskan oil pipeline. Workers were not really safe going out in below 0°F weather, with snow and ice on everything. As a result of their concerns for safety, this customer asked that we provide remote positioning of the feed horn from the nearby control room.

The critical design requirement was that the positioning of the feed horn needed to be relatively precise. This meant that our design had to have as little backlash in the drive mechanism as possible. Being a young engineer, I was unaware of the wide variety of different drive systems, in particular their respective properties and capabilities. I asked one of the older engineers for some direction. He suggested I use a worm drive since it cannot be back driven, and loaned me his copy of Joseph Shigley's book, *Mechanical Engineering Design.* He said that Shigley's book (a precursor to this Handbook) had been his primary source of information about worm drives, and a wealth of other machine design information. As it turned out, the resulting design worked as required. It not only pleased our Alaskan customer but became a standard on all antenna systems.

I did not get a promotion as a result of the success of this new design, nor did I receive a raise. However, I was proud, and, as you can surmise, still am. I credit this successful design evolution to the material on worm drives in Shigley's book. And there is more to this story. The worm drive gearbox we ultimately purchased contained a plastic drive element. This allowed the backlash to be greater than what could be tolerated in positioning accuracy and did not provide the necessary strength to break the feed horn loose from a covering of ice. The original manufacturer of the gearbox refused to change this drive element to metal for the units we would be buying. If we made the change ourselves, they said, the warranty would be voided. However, after absorbing the wealth of information on worm drives in Shigley's book, I felt confident that we could make this substitution without endangering the reliability of the unit. Also, because of Joseph Shigley's reputation in the mechanical engineering community and the extensive list of references he cited, I never felt the need to consult other sources.

Another aspect of this story is also important to note. In addition to the information on worm drives, I also used Shigley's book to find comprehensive design information on the many other machine elements in the new design: gear train geometry, chain drives, couplings, roller bearings, bolted joints, welds, lubrication, corrosion, and the necessary stress and deformation calculations I needed to make. All this information, and much more, was contained in the First Edition of the *Standard Handbook of Machine Design,* which Joseph Shigley coauthored with Charles Mischke. Now in its Third Edition, this Handbook includes the information machine design engineers have come to trust. We hope you will find this information invaluable as you constantly strive to improve your designs, whether by your own initiatives, or for other reasons.

1.2 USING THE HANDBOOK

Once the chapters for this Third Edition of the Handbook were determined, we decided that these chapters should be organized into nine sections, denoted Parts 1 through 9. Each section focuses on a distinct collection of related material. For example, Part 3, "Gearing," contains chapters on spur gears, helical gears, bevel and hypoid gears, worm gearing, and power screws. However, each chapter stands on its own, providing direct access to a specific area of interest or need.

This Handbook is a unique reference, capturing the breadth and depth of what is currently known about each of these design element topics. The nine sections are

Part 1. Machine Elements in Motion

Part 2. Machine Elements That Absorb and Store Energy

Part 3. Gearing

Part 4. Power Transmission

Part 5. Bearings and Lubrication

Part 6. Fastening, Joining, and Connecting

Part 7. Load Capability Considerations

Part 8. Performance of Engineering Materials

Part 9. Classical Stress and Deformation Analysis

While there are many ways the nine sections could have been ordered, the order chosen for this Third Edition provides one sequence of steps to the evolutionary design process. For example, you might first consider the kinds of motions you need and how they might be accomplished. Part 1 might help you choose a classic mechanism or linkage, a cam, or maybe some arrangement of gears. Possibly your design needs to absorb or store energy, so the chapters included in Part 2 would provide the information you need. Depending on your design, Parts 3 and 4 cover virtually every type of gear set, drive type, coupling, and the common elements related to these devices. Part 5 covers how rotating elements might be supported, typically with either roller- or journal-type bearings. And if bearings are present, then lubrication and seals must be carefully considered.

Part 6 continues the design process to the consideration of how components will be assembled. Are there structural bolts, or just mechanical fasteners, or are parts to be welded? The coauthor of the chapter on welding is the well-known author of the preeminent book on welding, so this Handbook should provide all the information you need relative to this topic. The last chapter in this section presents the complex procedure necessary to maintain proper fits and tolerances, a full-time job in itself for some engineers. Everything an engineer needs to know about this area of manufacturing can be found in this Third Edition of the Handbook.

At some point, loads will be determined, both statically and dynamically; therefore, Part 7 contains the information you need to make decisions relative to the reliability of critical parts. Information on vibration, and just as important, its control, is provided in a chapter in this section. The selection of materials is covered in Part 8 and includes chapters on wear and corrosion. With regard to the problems of corrosion, one of the main components of a system I was responsible for failed due to excessive galvanic corrosion. The information contained in this Handbook helped me not make that mistake again.

The last section, Part 9, contains the classic information on stress and deformation calculations every mechanical engineer learns in school, but finds escapes exponentially if not used regularly. Here, four chapters provide every important calculation practicing engineers should need, and they are introduced in a manner that can be understood and used with confidence.

1.3 SOME OPPORTUNITIES TO DISCOVER

As mentioned earlier, this Third Edition of the *Standard Handbook of Machine Design* has been organized differently as compared to the two previous editions. In addition to grouping the chapters into nine sections, almost a dozen of the 50 chapters in the Second Edition, which contained a variety of information ancillary to the machine design process, have been removed. Therefore, the scope of this edition of the Handbook is focused on the more traditional machine design topics.

For those familiar with the previous editions, one chapter that was in the First Edition but not in the Second, "Pressure Cylinders," has been included in the Third. This additional chapter is located in Part 9, completing the information important relative to stress and deformation analysis. Also, one of the chapters in the two previous editions, "Sections and Shapes—Tabular Data," is now Appendix A.

Discovering opportunities to improve or evolve your designs successfully is one of the primary ways we expect you to use this Handbook. Each chapter has considerable design information and the format used is unique. What follows is a discussion of just some of the helpful information you will find in each chapter.

Part 1: *Machine Elements in Motion*

Chapter 2 in this section is undoubtedly one of the most distinctive chapters you will find anywhere. There is page after page of diagrams of every conceivable mechanism and machine device. There are snap-action mechanisms, linear actuators, fine adjustment devices, clamping and locating mechanisms, escapements and indexing mechanisms, oscillating mechanisms, ratchets and latches, reciprocating and reversing mechanisms, and couplings (see the commercial designs in Chap. 16) and connectors, including slider connectors.

There are devices that stop, pause, and hesitate motion, and devices that transport motion between machine elements. There are two pages of loading and unloading mechanisms, many that are commonly used for construction and earth-moving equipment, as well as bulk-handling railcars. You will find path generators, function generators, and even mechanical computing mechanisms, still finding a place in this electronic age. There are speed-changing mechanisms and multidegree mechanisms that form the basis of many robotic-type machines. I hope you enjoy as much as I do just flipping pages in this one-of-a-kind catalog of mechanical devices.

If a particular linkage catches your eye in Chap. 2, then the information contained in Chap. 3 takes you many steps further, providing all the geometry of motion diagrams, or kinematics, you will need. Details of the famous slider-crank and four-bar linkages are provided. The material in this chapter might seem intimidating graphically, but without it, the preciseness of the motion you most likely need will be difficult to achieve any other way.

If your machine requires a cam to achieve its design requirements, then Chap. 4 contains everything about this particular device. From simplified schematics to the complexity of cam trigonometry, everything a designer will need is here in these pages. There is even a computer program flowchart to help you develop a comprehensive analysis of your design, whether you use a programming code like FORTRAN or a personal computer spreadsheet.

The last chapter in this section, "Gear Trains," presents all the relative speed calculations for the two most common arrangements of gears: spur and planetary. Also, the speed calculations for differential gear trains are presented. Once these calculations are made, then the detailed specifications can be made using the information in Part 3.

Part 2: *Machine Elements That Absorb and Store Energy*

Personally, I have consulted Chap. 6, "Springs," as much as any other chapter in the Handbook. It contains information on every kind of spring, from the commonly used helical spring, with all its variations, to the unique Belleville spring washer. Elliptical and even torsion bar springs are covered. In fact, basically everything I know about springs is in this chapter, one of the longest in the Handbook.

Flywheels are an important machine element in devices such as automobile engines and punch presses. They act like an accumulator tank in an air compressor system, thus evening out the fluctuations in rotational motion. Careful sizing is necessary to make sure that just the right amount of inertia is provided. Too much can cause the system to be have too long a recovery period or too little inertia, causing the system to loose too much energy between loading cycles. For high-speed flywheels or machine elements like compressor blades, consideration of the inertial stresses developed can be important.

The late John Muir, in his book *How to Keep Your Volkswagen Alive,* said, "Brakes perform a negative function, applying negative acceleration to stop the car, remaining inert when not being used." Brakes may have a negative function; however, their design can be critical to a successful product. Chapter 8 covers all aspects of brakes and all aspects of what might be the opposite of brakes—clutches. Clutches are designed to transfer power evenly and gradually between two shafts rotating at different speeds, even when one shaft is at rest. There has been a great deal of ingenuity in the design of brakes and clutches, accounting for many patents and commercial products. Centrifugal, cone, and disk-type clutches and brakes are two such commercial success stories. Both brakes and clutches produce significant temperature gradients in service. The design considerations associated with temperature variations are covered in this important chapter, including information on selecting the right clutch or brake materials for your specific application.

Part 3: *Gearing*

One of the most fascinating sections in this Third Edition of the Handbook is Part 3, "Gearing." Most of us as mechanical engineers will never actually be involved in designing and manufacturing gear sets, even the simplest spur gear. However, it has always been comforting to know that this Handbook contained everything needed if we were ever put in the situation of having to design a set of gears. Chapter 9, "Spur Gears" is relatively short and straightforward, giving the impression that gears are not that complicated. Then, Chap. 10, "Helical Gears," makes the point, by the extent of the information provided, of just how complicated gear sets can be if they are to be done correctly. This is one of the longest chapters in the Handbook. Another equally long chapter, 11, covers "Bevel and Hypoid Gears." This has always been a special chapter, providing insight into one of the most magical machine elements in mechanical engineering. There are few vehicles on earth that do not have a differential, and every differential has either a bevel or hypoid gear set. All the geometry of motion is explained, with table after table and chart after chart of applicable formulas and performance data for all variations and design parameters.

I've already referred to the importance of the material in Chap. 12, "Worm Gearing," in my story about the remote positioning of an antenna feed horn project. As I said earlier, the information in this chapter was invaluable in helping me modify an existing design to satisfy the needs of a high-profile customer.

As I look back on the years I spent associated with large antenna systems, it seems as though every aspect of these systems had me searching the *Standard Handbook of Machine Design* for important information. Chapter 13, "Power Screws," was another of those chapters I became very familiar with, since the primary positioning of the antenna dish on the satellite was accomplished by heavy duty power screws driven by dc motors. This Handbook is where I obtained the information I needed.

Part 4: *Power Transmission*

This section contains four chapters directed at the requirements of transferring motion from one rotating axis to another, whether by the time-honored belt (Chap. 14) or chain (Chap. 15) configurations, or by the wide variety of couplings (Chap. 16) used to isolate and protect downstream machine elements. This seemed to be the best place to discuss the design of shafts (Chap. 17), from both a static and dynamic viewpoint. While new belt, chain, and coupling products are introduced every year, the basic design considerations remain the same. Speed ratio calculations; tension adjustment schemes; and materials, many of which are composite constructions, are universal to these machine elements. Serpentine-notched belts seek to combine the flexibility and low noise of traditional belt drives, while providing the positional accuracy to meet strict timing requirements such as in automotive applications. For large horsepower transfer, metal chain and sprocket drives, usually in multiple-strand configurations, seem the best approach—and what you need is provided in this Handbook.

Since lining up shafts exactly is difficult, if not impossible, the usual solution is a coupling between the shafts. This is another area of intense ingenuity and cleverness, with many of the successful products highlighted in this section. A complete discussion of universal joints and constant velocity joints is also included.

Part 5: *Bearings and Lubrication*

One of the great inventions of the twentieth century is the roller bearing—in particular, the tapered roller bearing. Roller bearings allow high speeds under relatively heavy loads not possible before their introduction. Every automobile on the road today has a plethora of roller-type bearings. Journal bearings, which were the primary bearing type before the roller bearing, are still an important mechanical design element. The main and rod bearings in an internal combustion engine are of the journal type. Chapter 19, "Journal Bearings," is one of the longest chapters in the Handbook, punctuating the amount of design information available. Its length also indicates the extent of the design considerations necessary for their successful use.

Bearings could not do their job without lubrication, and lubrication would be lost from most bearings without the proper seals. Traditional and nontraditional seal designs are presented in this section, including those operating in static conditions and those operating between rotating parts. Lubricants are another product in constant flux. This Third Edition presents the properties and uses of the more common and trusted oils, greases, and solid lubricants.

Part 6: *Fastening, Joining, and Connecting*

Chapter 22, "Bolted and Riveted Joints," covers the design of bolts and rivets used not only to hold parts together in an assembly but also as structural elements. Complex joints in tension and shear are presented, including the effect of gaskets in a structural joint. Calculations for the proper preload of a structural bolt are provided.

Chapters 23 and 24 cover every conceivable type of mechanical fastener. Chapter 23 presents design information for threaded fasteners while Chap. 24 presents design information for unthreaded fasteners.

If a connection must contain or keep out gases or liquids, then a gasket is usually specified. The types of gaskets typically available and their appropriate application criteria are provided in Chap. 25.

When disassembly is not required or when maximum strength is needed, then usually the only solution to connecting separate parts is a weld. All aspects of a welded connection are presented in Chap. 26. This chapter begins with the basic principles of the arc welding process, followed by the various commercial processes, including exhaustive information on the materials used in welding. This chapter also includes the information needed to design a welded joint to be as strong, or stronger, than the materials being welded together. Since failure of welded joints has had such a high impact on the safety of the public, many national codes and industry specifications have been established and must be met. These are covered in detail in Chap. 26.

As mentioned earlier, the ongoing effort in manufacturing to hold to a high standard of quality requires a thorough understanding of the factors in fits and tolerances. Chapter 27 presents the standards of fit universally accepted and the complications associated with a buildup of tolerances in an assembly.

Part 7: *Load Capability Considerations*

Chapter 28 covers static theories of failure, from the theories for ductile materials to brittle materials. Charts for determining stress concentration factors for various design geometries are provided. In contrast, Chap. 29 covers dynamic theories of failure, including the determination of endurance limits. For various design factors, such as surface roughness, size, loading, temperature, and a host of miscellaneous factors, the Marin equation is used to modify the endurance limit determined from experiment. Alternating and fluctuating loading are considered, including combined loading considerations.

Machine elements in compression must be analyzed to protect against buckling or sudden collapse. Chapter 30 covers all aspects of compression loading of beams and columns, from Euler's formulas to complex beam–column analysis.

Chapter 31 covers mechanical vibration, from the forced vibration of damped single-degree-of-freedom systems to multi-degree-of-freedom systems. Torsional vibration and vibration isolation are presented.

Part 8: *Performance of Engineering Materials*

This section contains four chapters focused on the decisions associated with the selection of materials for the critical parts in a design. Chapter 32 is a summary of the science of material behavior, including the procedures used to determine various material properties. It is one of the longer chapters in the Handbook. Chapter 33 focuses on the properties and engineering considerations of the most common material in machines—steel. Whatever manufacturing is process used, everything needed in designing with steel is provided.

Once in service, machine elements are subject to constant wear and the adverse effects of corrosion. Chapters 34 and 35, respectively, cover the important aspects of wear and corrosion. It would seem a shame to spend so much time on the other aspects of design only to be blindsided by these two factors. Corrosion, especially galvanic, is insidious and only careful selection of mating materials will avoid disaster. Chapter 35 contains a listing from "A" for *acetone* to "W" for *water* relative to their adverse reaction to other chemicals.

Part 9: *Classical Stress and Deformation Analysis*

This last section in the Third Edition provides the mechanical design engineer with the fundamental formulas for stress (Chap. 36) and deflection of beams (Chap. 37). This section also includes the stress and deformation of special geometries, such as curved beams and rings (Chap. 38), and the stress and deformation of pressurized cylinders (Chap. 39), which are developed as a result of internal pressure or from the effects of a press or shrink fit.

Appendix

As indicated earlier, one of the chapters included in the First and Second Editions, "Sections and Shapes—Tabular Data," has been provided in this Third Edition as an Appendix. Here are found the properties of common cross-sectional areas used in various mechanical elements, particularly beams, and the properties of standard structural shapes, such as rectangular tubing, channels, angles, and variations on the I-beam.

1.4 FINAL THOUGHTS

The process of creating or improving a mechanical system is an adventure. Like all adventures, machine design has its complications and logistics. When we are successful meeting these difficult challenges, the pride and feeling of accomplishment are so exhilarating they might be compared to how Sir Edmund Hillary must have felt after his successful assault on Everest. Or how Sir Henry Royce, of the famous motorcar company Rolls-Royce, felt when he was knighted. While knighthood might not be one of our rewards for success, the recognition we receive is no less significant in our careers as design engineers—bringing admiration and respect from our peers and considerable personal satisfaction and enjoyment.

Adventures also have their heroes. In the field of machine design, no two individuals stand out more than Joseph Shigley and Charles Mischke. Their professional partnership has been synonymous with machine design for 20 years, and Joseph Shigley has been a household word in mechanical engineering for over 40 years. We hope the wealth of information contained in this Third Edition of the *Standard Handbook of Machine Design,* and the way in which it is presented, will provide the necessary resources for your design projects.