

FUN*da*MENTALS™ of Design

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FUN*da*MENTALS of Design

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ABOUT This Book

A college student challenged a senior citizen, saying it was impossible for their generation to understand his. "You grew up in a different world," the student said. "Today we have television, jet planes, space travel, nuclear energy, computers..." Taking advantage of a pause in the student's litany, the geezer said, "You're right. We didn't have those things when we were young; so we invented them! What are you doing for the next generation?"¹

This book is about helping people to learn how to create their own future! It does this by taking advantage of the fact that the reader's LEFT brain sees the LEFT side (FUN) of the book. The RIGHT brain sees the (MENTAL) side of the book. Its simply *FUNdaMENTAL!* This in itself is a key feature of this book: It seeks to train the brain to think by many a link. Creating things is NOT done by following a monotonous recipe... The ability to create can be learned by anyone who has a yearn to learn! But the eye must be quick to sort and pick! Embedded inside, many a hidden creative message may reside!

In fact, design is like a big box of LEGOS™ from which you want to pick pieces to build a toy spaceship: if you just pick from the top layer, you might not get a very interesting model. Turn over the box and scan through all the pieces! Better yet, if you either have the pieces organized into bins, or are aware of all the types that exist, you can select even faster! Whether it is the designer's desk, file cabinet, or the real world of resources available through catalogs and the internet, there is an element of randomness to the accessibility and presentation of information. This randomness, however, like nature itself, provides robustness to the system, for it ensures that different people will see different things and catalyze a team to develop new and innovative solutions to difficult problems. Contrast this to a team of clones all looking through the same catalogs in the same order...

Successful practising design engineers take advantage of this by wearing two hats: they are passionately wild & crazy, and they are coldly calculating & logical. They have no fear to think of wild and crazy things while randomly sifting and searching through resources. Accordingly, this book is organized in a similar way:

- The material is presented in a coarse-to-fine manner, with chapters, sections, and subsections, just like any other engineering textbook. In addition, dozens of spreadsheets are provided for making design calculations. *Hence this book can be effectively used for an introductory course, or an advanced course, because each time it is read, a new layer of depth will reveal itself.*
- Each topic is discussed on two pages, and if more space is needed, that defines the need for a finer level of granularity, and hence another set of two pages...
- Each set of two pages has one page of fine detail text, such as may be found in a conventional engineering science textbook, where the discussion focusses on the topic and addresses it in a systematic manner...
- The second page of the set presents visual information corresponding to the text NOT in a systematic numbered figure manner, but as a collage of images that represent a box of parts that has been spread across the floor (or information on the internet)! When reading the text, specific figures are rarely referenced. The intent is to get the reader to create a picture in their mind, to scan the picture page and find the image that fits the description. By working to find the image, and seeing others along the way, the images become better packed into the reader's neurons. Like life, full color is used, and the intent is to excite and entice the reader's eyes and brain to scan and search and try to create patterns and relations amongst the images, and then to connect them to the detailed text... Different people will see different things and make different connections, and hence begins the formation of a robust design team.
- The second page also often has some text, which is representative of what a student may have otherwise highlighted on the first page, if the reader was using a classical textbook.

How should the student use this book in a design class? When most people get a magazine, they first flip through and look at the pictures. Then they go back and read the articles of interest, and eventually they get around to reading the rest of it. Every time they pick it up, the images are seen again... Given that the best way to learn something is to see it/use it multiple times, the structure of this book, and modes in which it may be used in a class takes advantage of this:

1. An anonymous story received by many via email

Detail Read Side: Read in detail when a topic really interests you, or when you need to know the detail.

Fast Scan Side: First look through the whole chapter reading this side only.

Contact Bearings: Flexural

Flexural bearings rely on elastic deformation to attain smooth motion. Since there are millions of planes of atoms in a typical flexural bearing, an averaging effect is produced that allows flexural bearings to achieve atomically smooth motion. For example, flexural bearings allow the tip of a scanning tunneling microscope to scan an object with subatomic resolution. There are two types of flexures, monolithic and clamped.

Flexural bearings' major drawback is their limited range of motion. For monolithic bearings, the ratio of range of motion to bearing size is on the order of 1/20. For flexural bearings made from high strength spring steel clamped in place, the ratio of range of motion to bearing size is on the order of 1/10. Unlike other bearings, flexural bearings are inherently preloaded and they generate a restoring force because they are essentially self-guided springs. Their applications range from silicon Micro Electro Mechanical Systems (MEMS), to fine instruments, to large trucks and trains where leaf springs also guide the motion of axles. They can also be used as "living hinges" in consumer products where plastics can endure very large deformations for the intended limited life of the product. In robot design contexts, they can be made from sheet metal and used to create small range of motion adjustment mechanisms, or as flexural Vees for kinematic couplings (see page 9-20).

Because flexural bearings are elastic elements, they are easily designed using the basic principles of strength of materials. Most flexures are used as either pivots, or as four-bar linkages. For a simple pivot as shown:

$$\alpha = \frac{3MR}{2Ew[y^3 - R^3]} \left[\frac{1}{\gamma} \left[\frac{1}{y^3 - R^3} \right] + \frac{2Ry}{\gamma} \left[\frac{\pi}{2} - \tan^{-1} \left(\frac{-R}{\sqrt{y^2 - R^2}} \right) \right] \right]$$

For a 4-bar flexure with blades of length L, thickness t, and width w, subject to a force F, each blade is subject to F/2, and the maximum bending moment in the blades will be FL/4. The first-order deflection δ of the platform in the desired motion direction, and the maximum stress will be:

$$\gamma = \frac{y}{2} + R \quad \delta = \frac{FL^3}{2Ewt^3} \quad \sigma = \frac{3FL}{2wt^2}$$

There are two parasitic error motions that occur with simple 4-bar flexures. The first parasitic error motion is the motion of the platform normal to the direction of motion. The second parasitic error motion is a pitching motion that occurs when the force is applied to the platform to just overcome the spring force of the blades. For small displacements δ, distance between flexure blades b, and force applied at a distance a, above the fixed end of the springs, the parasitic error motions are:

$$\delta_{\text{normal}} \approx \frac{\delta^2}{2L} \quad \delta_{\text{pitch}} \approx \left(\frac{6(L-2a)^2}{3Lb^2 - 2L^2 + 6a^2} \right) \delta$$

These problems can be overcome by twice applying reciprocity to flip the flexure twice, which results in a folded flexure design. Hence there are four sets of 4-bar flexures, and the travel (deflection) is δ_{folded flexure} = 2δ_{4-bar}.

Note the green flexure with the purple screws and the round holder located 2/3rds of the way back from the ends of cantilever beams. Recall that δ = FL³/3EI and the slope α = FL²/2EI. Here a sine error Lo is used to cancel deflection so the round holder (of a lens) undergoes pure rotation. Why are the purple screws threaded into thin cantilevers that push on thicker cantilevers? Can flexures act as transmission elements? What is the Transmission ratio? This clever device was created by Dr. Bill Plummer of Polaroid.

Flexures are easily designed and made. They can be made from baked-together components or cut from a plate using an abrasive waterjet. They can also be machined; however, the thin sections can be difficult to mill. For precision flexures, wire EDM can be used to cut them from hardened steel.

Identify small range of motion elements in your machine, such as triggers or alignment devices, where flexures could provide the desired motion without any parasitic friction forces. Play with the flexure design spreadsheets Flexures_4_bar.xls and Flexures_fourplus_pivot.xls.

Contact Bearings: Flexural

- Flexures use elastic deformation to provide the desired motion
- Linear and rotary motion flexures can be created
 - The challenge is to manage stress and constraints
- "Infinite-life": flexure will be 20x larger than the range of motion that it can provide (e.g., precision machines and instruments)
- "Shortlife": flexure can be much smaller than other bearings (e.g., "living hinges" for flip-top bottles and lids)

What is the thinness ratio?

Width w into page

Either the wonderfully designed top and flip-top cover (with flexural hinge), OR a happy space alien couplet!

Intermediate floating structures
Fixed to ground

Floating platform

Folded Flexure 10-14

Cross-section rendering through a CFlex flexural pivot bearing (see www.cflex.com. Special thanks to William R. Harbison of PageOne Web-Design for the rendering!)

Detailed text and analysis (for the fine points, stuff you really need to know if you are really going to create detailed designs).

Figures and "primary" points and info (stuff most likely to highlight, and to help pin the ideas in your brain so you know where to go to look for detail later if needed).

- At the start of a course, students are asked to flip through the entire book and just focus on the picture pages. This preloads the students' minds with essential information and plants markers so when they face a design challenge, an image should appear that will direct them to the location of more detailed information...
- Before each lecture, students are asked to more carefully look at the images on each page of the chapter covered by the lecture. If the student sees an interesting image, they are likely to read the detailed text. This reinforces the information markers.
- The instructor now does NOT have to put up overheads of the 2nd page, but instead can talk about how they use the material as a real designer.
- The instructor can instead give a lecture on a topic that uses information from the text as a supporting material, or the instructor could cover one of the topics in extra detail. If the class is working on a design problem, the instructor could go through in detail one aspect of the problem, so the class can see the instructor as a designer in action.
- After lecture, students can flip back through the text and read the detailed discussion pages to clarify issues or gain more in-depth knowledge.
- The student should keep a notebook for the course, which should address the thought exercises presented in red italics at the end of most pages.

There are several types of courses that can use this book:

- A project-based introduction to design course at the advanced high school or community college level can use this book, where the primary emphasis is on the image-filled pages. Selected detailed text pages would also be appropriate. The spreadsheet design tools can be used without having to worry about the details of the mathematics behind the formulas. For example, schools that have FIRST robot contest teams may want to give an introduction to design course, where the design topic is the previous year's contest. Students can use the book to help develop plans for a design to beat the previous year's winner. Then, when the new contest is announced, the students would be experienced and ready to begin development of the robot for the current year.
- A project-based introduction to design course at the university level can use this book, where it is expected that students will read the detailed first pages before lecture and study the detailed text pages before or after lecture. The spreadsheet design tools can be used as is, or with modification

by engineering students who should have the analytical skills required for their customizing. For example, schools that have a robot design competition, such as MIT's 2.007, can use this text in the same manner as 2.007.¹

- An advanced project-based course or a machine elements course at the university level can use this book. Students would be study image and detailed text pages before lecture, and then lectures could focus on the mechanics of machine elements and many of the subtle points that are associated with their optimization and use. Students may write their own design code for analysis or build from the spreadsheets. All the details in the book would be utilized in the completion of the design project.

An excellent and fun way to use this book in a none-project design course is to use it in a how-things-work course, or an introduction to technology course, where topics are assigned from the book, and then discussions and assignments are focussed on study of real-world objects with respect to how they work and can students identify elements of the book at use in the objects. From FUNdaMENTAL principles to machine elements, philosophy in reality is a fantastic learning mode.

Speaking of FUNdaMENTAL principles, hardware is constantly changing, but FUNdaMENTAL principles do not; hence above all else, the goal of this book is to help readers better understand how to design, with the understanding that success requires continual learning. Finally, writing this book has been a labor of love and passion, and it has also been just *plane* fun. Sprinkled throughout are various little mind puzzles, puns, and fun-connections that were placed strategically using random neural firing methods. Indeed, the reader may occasionally encounter some unconventional thoughts and references, or create their own, all lovingly associated with making machines better, because we are extremely super extra **♥Passionate♥**



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1. Indeed, this book was developed for MIT course 2.007, and with the availability of a standard kit of parts, it makes it easy for any school to run this type of course and contest: <http://pergatory.mit.edu/2.007>
 2. This is the reader's first notice: this book will try to get the reader to think about things from different perspectives, and to decode the true meaning of design life! After all, the QUESTION is does anyone really have a zip code of 0.02381 (see page 3-14)

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