Efficient Use of Computational Tools in Machine Design

Kyu-Jung Kim, Ph.D. & Amir Rezaei, Ph.D.
College of Engineering
California State Polytechnic University, Pomona, CA

Abstract

Machine design is a required course at junior year to learn essential skills for senior design projects. There is a great need for comprehensive and integrated software due to its complicate nature of the course materials. Such tools are expected to empower students to solve more challenging open-ended and/or integrated design problems, and to conduct design projects for a more rewarding experience in machine design. The Mechanical Design Toolbox has evolved over many years through continuous revision of the existing modules and addition of new modules for fully interactive computer-aided instruction of machine design lecture and lab classes at Cal Poly Pomona in an attempt to alleviate the burden of many trivial and time-consuming calculations but to solve complex open-ended computer assignment problems and term projects for improved understanding on machine design. A realistic design analysis and synthesis project is presented to demonstrate efficacy of the mechanical design toolbox in classroom and laboratory settings.

Introduction

Machine design is a required course for junior/senior level students in most mechanical engineering curricula nationwide. This advanced course is taken at the end of the mechanics course sequence consisting of statics, dynamics, and strength of materials. A typical machine design course deals with analysis of machine elements such as belts, shafts, columns, fasteners, gears, springs, and bearings for a variety of static as well as fatigue loads. The course is typically taught using traditional techniques such as the blackboard, overhead transparencies, etc.

In conventional machine design classes, students are given the dimensions and loading on a machine component and are asked to calculate physical quantities such as induced stresses, deformation, and fatigue life using theoretical and empirical equations, tables, and graphs. This is so-called design analysis. Though involving tedious hand calculations, design analysis is sequential and straightforward. On the other hand, design synthesis is real design process, which involves sizing a component under given design specifications. Design synthesis can be best learned through design projects. However, this often involves repetitive design analysis and/or solving implicit, nonlinear equations until a suitable or optimal solution is achieved. Furthermore, whereas no machine element is designed alone without considering functional interactions with other components; it is very hard to implement teaching integrated design of multiple machine elements as a whole in a typical classroom setting.

Machine Design Toolbox

The ready availability of powerful computers is helping shape new pedagogical trends in engineering courses, thus computer-aided machine design is a natural choice for adopting these new trends for improving teaching and learning of machine design in mechanical engineering curricula. Computational tools for machine design can help students alleviate the burden of many tedious and time-consuming activities such as performing repetitive calculations, back solving equations, solving lists, etc. but also to solve complex design synthesis problems and integrated design problems for improved understanding on machine design. Though some computational tools are currently available, but they are limited to mostly design analysis and/or are geared towards specific textbooks. There is a great need for comprehensive and integrated software tools for efficient machine design, which will provide educators with an opportunity to focus on teaching basic concepts and principles and their practical applications without being limited by the complexity and techniques of numerical computation. Such tools are expected to empower students to solve more challenging open-ended and/or integrated real-life design problems, and to subsequently conduct senior design projects for a more rewarding experience in machine design.

The Mechanical Design Toolbox (MDT) is a collection of individual design analysis and synthesis modules supported by a software architecture that allows them to be easily combined to accomplish an integrated design of multiple machine elements. The major advantages of using MDT in teaching and learning machine design are many folds. First of all, it eliminates tedious hand operations in solving design analysis and synthesis problems so that the design analysis and decision-making cycle becomes substantially shortened. With less computational burden, students can conduct various comparative design analyses or "design-sensitivity" studies. This can potentially lead to more problem-based learning and creative design experience. We also expect to replace or complement the traditional blackboard and note-taking paradigm into a multimedia interactive teaching and learning of machine design using MDT in a computer lab setting. The MDT is expected to have a major impact on student's retention of classroom materials. It has been observed by Kolb [1] that active experimentation leads to better than 90% retention of material compared to a 30% retention for reflective observations.

Programming Rationale for the MDT

The MDT has been developed using *de facto* numerical analysis software, MATLAB, by taking advantage of its user-friendly interactive graphic user interface (GUI) and multiple document interface capabilities. Development of the MDT using MATLAB was a meritorious choice for many reasons, since its versatile computational power, easy graphical user interface, and availability of numerous toolboxes have lead to its wide-use amongst universities and industry. The MATLAB GUI controls are very intuitive and provide an interactive learning environment using the web browser and they allow the user to immediately see the impact of changes in various analysis parameters. For efficient computer based instruction of the machine design course the MDT is designed to provide the following functionalities to the user.

- Interactive design: The MDT enables the user to select various input parameters by simply entering information interactively into the text boxes or making selections from the popup menu. Efficient GUI design [2] will eliminate the direct use of lookup tables and graphs.

- Design analysis & synthesis: Design analysis is readily conducted by prescribing the input parameters. If the input parameters are unknown while the output requirements are prescribed, repetitive design simulations enable the user to synthesize the appropriate input parameters that satisfy the given output requirements.

- Design consistency: The input parameters and the corresponding results will all be displayed in the MATLAB GUI. The consistency of the input parameters can be confirmed visually. All the intermediate results are also displayed in graphic and numeric format. A consistent unit system is used.

- Design simplicity: All the tedious design calculations are done by the program so that the user only needs to check the validity of the input parameters and the corresponding results. The MATLAB GUI containing the entire input and output parameters can also be saved to a file or printed for documentation. Furthermore, any nonlinear and iterative design calculations can be done in less than a second.

Graphic User Interface Design

An individual MDT design analysis/ synthesis module typically consists of GUIs and corresponding GUI control programs for each analysis module, and numerical analysis routines. The GUIs are designed to accept input parameters using textboxes, menus, lists, checkboxes, and dialogs, to receive user commands via pushbuttons and menus, and to display intermediate results and answers in separate graphic windows and textboxes. The GUI control program checks the validity of the input parameters and converts them into internal parameters for subsequent engineering calculation in the numerical analysis routines. The MDT contains 18 GUIs, corresponding 18 control programs, and a large number of numerical analysis routines. Substantial programming efforts have been devoted to design intuitive GUI, since well-design GUIs can foster faster learning, immediate feedback, faster use and problem solving [4]. The following example illustrates common GUI design in the MDT (Fig. 1). The Main Control Interface is a gateway to use various analysis tools and to prescribe the unit system for each analysis. Each main menu in the MCI indicates an analysis category, while a user can run an individual analysis tool directly from a submenu (Fig. 1).

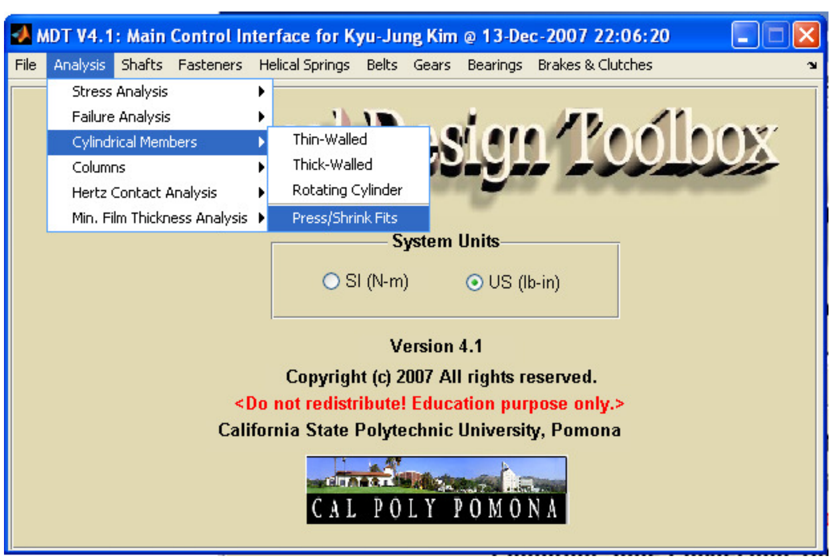


Figure 1. Main Control Interface of MDT

The following is a summary of all the analysis tools in each main menu.

- Analysis
  - Stress Analysis
    - SFD & BMD/ Deflection
    - Mohr's Circle Diagram
    - Curved Beam Bending
  - Failure Analysis
    - Stress Concentration
      - Static
      - Fatigue
    - Static Failure
    - Fatigue Failure
      - S-N Diagram
      - Cumulative Fatigue
      - Fluctuating Fatigue Stress
      - Modified Goodman Diagram
  - Cylindrical Members
    - Thin-Walled
    - Thick-Walled
    - Rotating Cylinder
    - Press/ Shrink Fits
  - Columns
    - Concentric
    - Eccentric
  - Hertz Contact Analysis
    - Elliptical Contact
    - Rectangular Contact
  - Min. Film Thickness Analysis
    - Elliptical Contact
    - Rectangular Contact
    - Gear Contact

- Shafts
  - Geometric Constraints
  - Static Strength Constraints
  - Fatigue Strength Constraints
  - Critical Speeds

- Fasteners
  - Power Screws
  - Tension Joints
    - Static
    - Fatigue
  - Shear Joints
  - Welded Joints

- Helical Springs
  - Compression Springs
    - Spring Kinematics
    - Static Design
    - Fatigue Design
  - Extension Springs
    - Static Design
    - Fatigue Design
  - Torsion Springs
    - Static Design
    - Fatigue Design

- Belts
  - Flat Belts
  - Flat Metal Belts
  - V-Belts
  - Roller Chains
- Gears
  - Spur Gears
    - Gear Kinematics
    - Center Distance Adjustment
    - Gear Stubbing
    - AGMA Allowable Bending Strength
    - AGMA Allowable Compressive Strength
    - AGMA Tooth Bending Stress
    - AGMA Tooth Compressive Stress
  - Gear Trains
    - Non-reverted Compound Two-Stage
    - Non-reverted Compound Three-Stage
    - Reverted Compound Two-Stage
    - Planetary/ Epicyclic Gear Train
  - Helical Gears
    - Gear Kinematics
    - AGMA Allowable Bending Strength
    - AGMA Allowable Compressive Strength
    - AGMA Tooth Bending Stress
    - AGMA Tooth Compressive Stress
  - Bevel Gears
    - Gear Kinematics
  - Worm Gears
    - Gear Kinematics
- Bearings
  - Thrust Slider Bearings
  - Journal Slider Bearings
  - Rolling Element Bearing Life
- Brakes & Clutches
  - Rim Brake/ Clutch
  - Band Brake/ Clutch
  - Axial Clutch
  - Annular Disk Brake
  - Circular Disk Brake
  - Annular Disk Brake
  - Thermal Analysis

Every analysis tool in the MDT has separate GUI's for interactive input and/or output display as shown in Fig. 2.

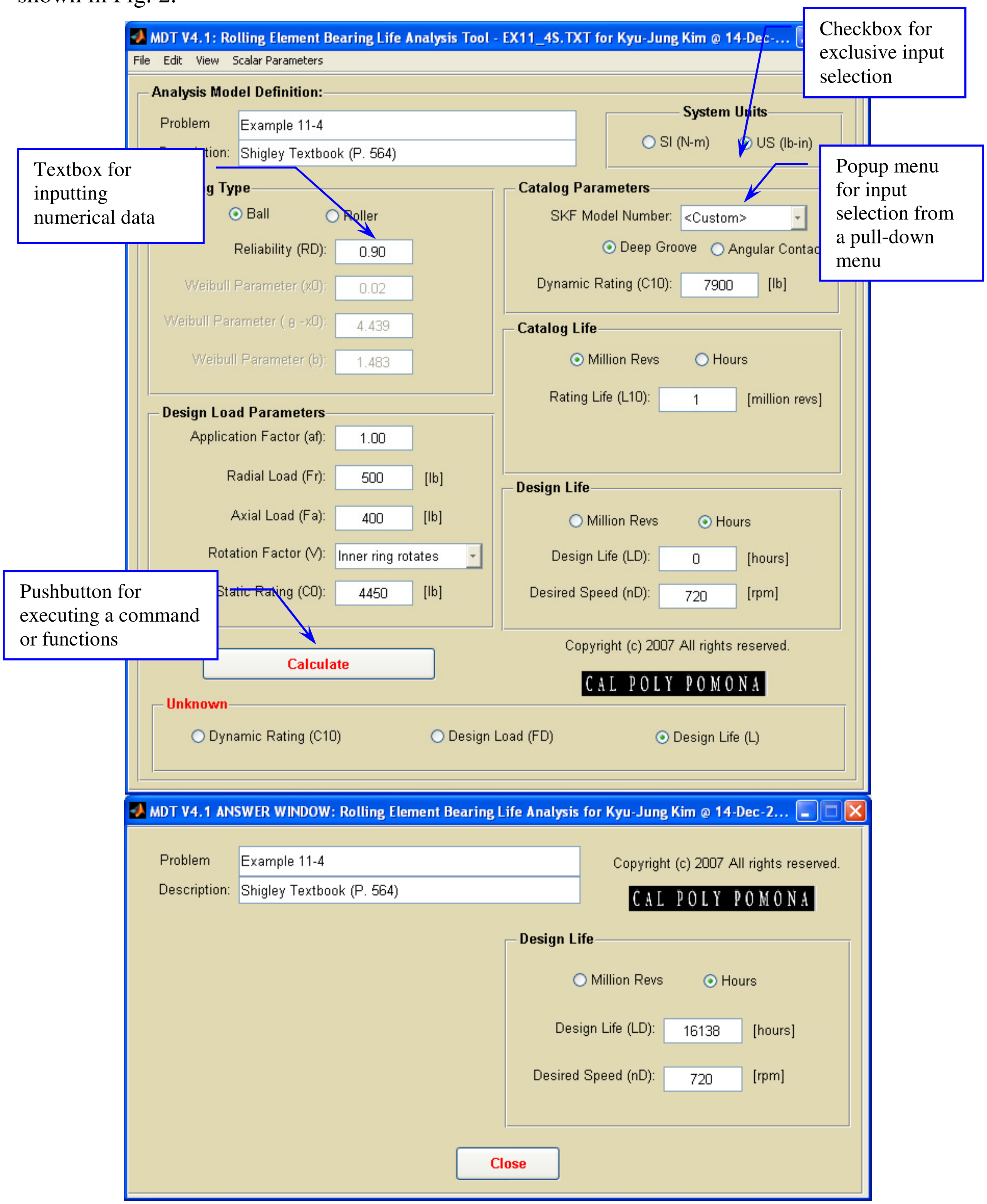


Figure 2. Input and output GUI's for rolling element bearing life analysis tool

Case Study [3]

Problem statement: Design a flat-belt drive to connect horizontal shafts on 16-ft centers. The velocity ration is to be 2.25:1. The angular speed of the small driving pulley is 860 rev/min, and the nominal power transmission is to be 60 hp under very light shock.

Textbook solution: Polyamide A-3 belt with 10 in. belt width. The results are shown in the Fig. 3.

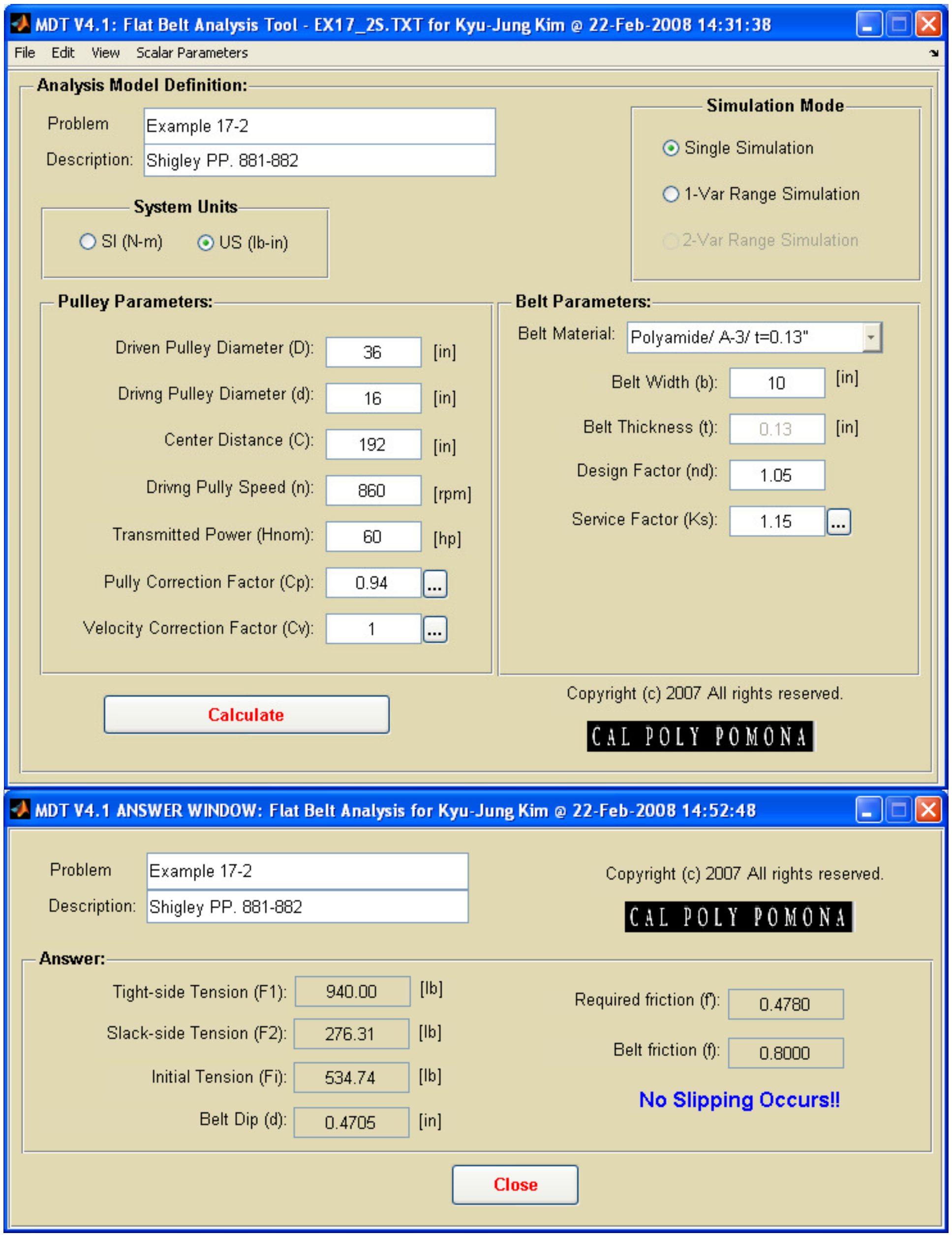
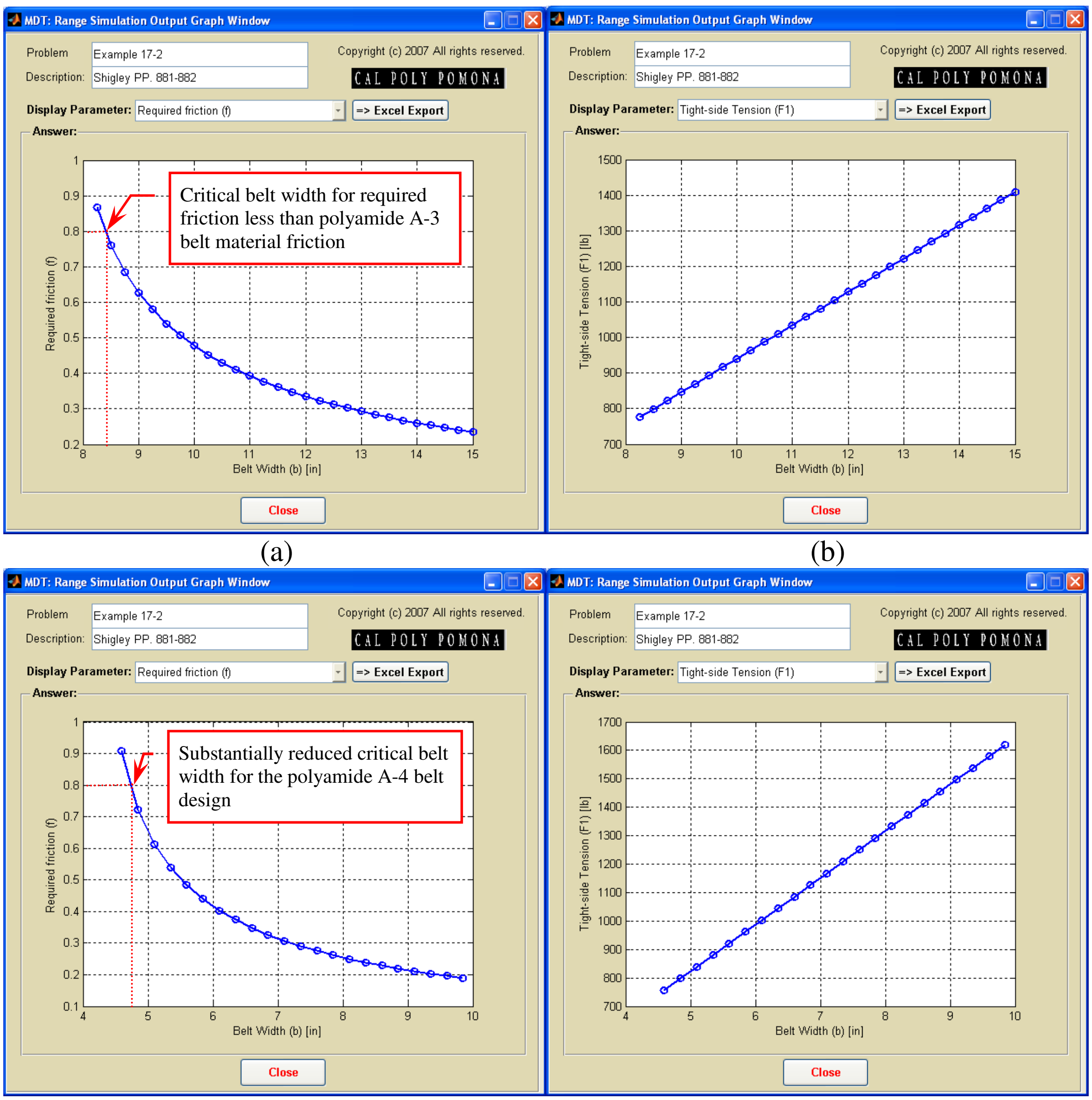


Figure 3. Solution of Example 17-2 from Shigley's Textbook [3].

Design Sensitivity Study: The textbook provides little understanding on the underlying principles of mechanical functions of a flat-belt drive. Subsequent design sensitivity study will reveal interaction between various design parameters. For example, the belt type and width will be the ultimate design selection parameters from vendor catalogs. For the selected polyamide A-3 belt, the 10" belt width can not be justified unless the following design sensitivity results (Fig. 4a). It shows that as long as the belt width is wider than 8.4 in., the belt drive should function well. The increased belt width requires less friction at the cost of increase tight-side tension (Fig. 4b), that such insight can not readily be obtained from the governing mathematical equations. Though not stated in the original problem statement, 10" belt width is not practical for space limitations of common belt drive design so that further design study is essential. With a thicker belt material, polyamide A-4 the critical belt width is substantially reduced to 4.7 in. (Fig. 4c), while a tight-side tension has a similar magnitude and trends.



(a) (b)

(c) (d)

Figure 4. Design sensitivity studies of Example 17-2 from Shigley's Textbook [3]. (a) required friction and (b) tight-side tension of the polyamide A-3 belt design with various belt widths, while (c) and (d) are same graphs for the polyamide A-4 belt design.

Future Study

It is expected that the MDT should help students to gain deeper understanding on how a mechanical system works and thus to develop improved engineering intuition for machine design. More analysis tools will be developed to cover more machine components. Further integrated simulation capabilities for simulation of a whole machine will be an ultimate goal. Quantitative efficacy assessment study of the classroom use of the MDT will be done in the near future.

References

[1] Kolb, D.A., Experiential Learning: Experience as the Source of Learning and Development, Prentice Hall, NJ, 1984.

[2] Galitz, W. O., The Essential Guide to User Interface Design: An Introduction to GUI Design Principles and Techniques. Second Edition, John Wiley & Sons, NY, 2002.

[3] Budynas, R.G., and Nisbett, J.K., Shigley's Mechanical Engineering Design. Prentice-Hall, NJ, pp. 873-4, 2008.

Author Information

KYU-JUNG KIM, Ph.D., is an Associate Professor of Mechanical Engineering at the California State Polytechnic University, Pomona.
AMIR REZAEI, Ph.D., is also an Associate Professor of Mechanical Engineering at the California State Polytechnic University, Pomona.