# GEORGIA INSTITUTE OF TECHNOLOGY

The George W. Woodruff
School of Mechanical Engineering

## Ph.D. Qualifiers Exam - Fall Semester 2005

## DESIGN

EXAM AREA

Assigned Number (DO NOT SIGN YOUR NAME)

✷ Please sign your **name** on the back of this page —

## QUESTION 1 – METHOD & REALIZABILITY

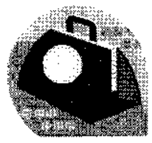
### Background

Hurricanes Katrina and Rita recently wrecked havoc along the gulf coast. Undoubtedly, you are aware of the hardships faced by those affected by the storms. People who were not able to evacuate before the storms arrived endured days of rising floodwaters, no electricity, and limited food and water. Many evacuees encountered terrible traffic jams, empty gas stations and crowded cities on their way out of town. Wouldn't it be nice if every family had a "hurricane survival kit for the family"?

### Task

Assume that you are in charge of the design team responsible for developing a hurricane survival kit. Speculate about the events faced by a family of four with two four legged pets once the notice to evacuate has been given. Some of these events include:

- the loss of the means to receive public service announcements;
- the loss of a means to communicate with the people in charge of the evacuation process;
- the inability to get information on travel conditions so that you can plan your departure;
- the potential loss of contact and separation from immediate family members;
- the need to relocate pets;
- the need to take valuable information from your home computer with you;
- the need to take care of minor hurt and /or sickness;
- the necessities to survive for 48 hours before help arrives;
- the need for a human-operated system to ensure that the survival kit has sufficient power to function;
- etc., etc., etc.



Continue the process of speculation and add to the events above. Then, start the process of designing your "hurricane survival kit for the family" using a systematic approach. Please ensure that the method you use is clearly enunciated.

### Deliverables

*Method*

1. *Clarify the Task:* State the overall function of your system in solution neutral terms. What are the most important drivers/design criteria? Define a design requirements list.

2. *Conceptual Design:* State and implement the steps (including functional diagrams/decomposition) for transforming the overall function that you have identified into at least three alternative design solutions. Ensure that you have identified the important sub functions. Sketch and describe the workings of these alternatives.

3. *Selection:* Suggest a structured approach to select one of the alternatives for further development.

*Realizability*

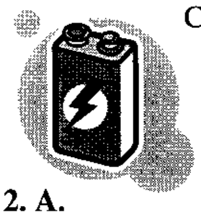
4. *Embodiment:* Further develop the alternative that you have selected.

5. *Costing:* How would you estimate the cost of your design? You may critically evaluate the design in terms of manufacturability, initial cost, maintenance cost, reliability, manipulation performance, and other criteria that you feel are important to consider in this phase of design.

6. *Pricing:* Based on the preceding analysis, how would you estimate the market size for such a system and set the price for selling such a system? Be brief.

## QUESTION 2 A - COMPONENT DESIGN ANALYSIS

**Background**



Clearly, the "hurricane survival kit for the family" needs power. Assume that one means of generating power is a hand-cranked generator. This generator necessitates the design of a helical extension spring the problem statement for which follows.

**2. A.** **Statement:** Design a helical extension spring for dynamic load over a given deflection. The spring must give a minimum force of 50 lb and a maximum force of 85 lb over a dynamic deflection of 0.5 in. An infinite life is desired. Use ASTM A228 music wire for the spring material. The spring is unpeened.

**Given:**

| | |
|---|---|
| Wire diameter, | $d = 0.177\ in.$ |
| Spring index, | $C = 9$ |
| Initial coil stresses for C=9, | $\tau_{i1} = 9774\ psi$ (lower bound of preferred range) |
| | $\tau_{i2} = 16699\ psi$ (upper bound of preferred range) |
| Direct shear factor, | $K_s = 1.06$ |
| Alternating force, | $F_a = 17.5\ lb.$ |
| Mean force, | $F_m = 67.5\ lb.$ |
| Wahl factor, | $K_w = 1.16$ |
| Torsional yield strength, | $S_{ys} = 0.45\ S_{ut}$ |
| Wire endurance limit, | $S_{ew} = 45000\ psi$ |
| Stress concentration factor, | $K_b = 1.09$ |
| Endurance strength, | $S_e = 38925\ psi$ |

**Tasks:**

(a) Find the initial coil-tension force, $F_i$. (1 pt.)
(b) Determine $\tau_m$ and $\tau_a$. (2 pts.)
(c) Determine the fully reversed endurance strength, $S_{es}$. (1 pt.)
(d) Calculate the fatigue safety factor for the coils in torsion, $N_{fs}$. (1 pt.)
(e) Determine $\sigma_a$, $\sigma_m$, and $\sigma_{min}$. (3 pts.)
(f) Find the fatigue safety factor for the hook in bending, $N_{fb}$. (1 pt.)
(g) Comment on the two safety factors you have obtained. (1 pt.)

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II B. 1.Explain the meaning of Lead (*L*) as it pertains to Screws and Fasteners (0.5 pt.)

2. Discuss the differences (two) between UN and UNR series. (0.5 pt.)

3. Give two reasons why fastener nuts are made of soft materials which are weaker than the screw materials? (0.5 pt.)

4. What happens to the inner diameter and the coil-body length of a torsion spring as you apply a load to it? Please explain. (0.5 pt.)

5. Explain what happens when the static load rating is exceeded. (0.5 pt.)

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6. Explain the meaning of $L_{10}$ life. (0.5 pt.)

7. How are flaking and spalding produced in rolling element bearings? (0.5 pt.)

8. What is a gearset? ( 0.5 pt. )

9. When is the angular velocity ratio ($m_V$) negative and when is it positive? ( 0.5 pt. )

10. What causes backlash, and how can you avoid backlash? ( 0.5 pt. )

The stresses $\sigma_a$ and $\sigma_m$ can replace $S_a$ and $S_m$ in Eqs. (7-34) to (7-36) if each strength is divided by a factor of safety $n$. When this is done, the Soderberg equation becomes

$$\frac{\sigma_a}{S_e}+\frac{\sigma_m}{S_{yt}}=\frac{1}{n}$$

The modified Goodman relation is

$$\frac{\sigma_a}{S_e}+\frac{\sigma_m}{S_{ut}}=\frac{1}{n}$$

and the Gerber equation is

$$\frac{n\sigma_a}{S_e}+\left(\frac{n\sigma_m}{S_{ut}}\right)^2=1$$

The critical deflection is given by the equation

$$y_{cr}=L_0C_1\left[1-\left(1-\frac{C_2}{\lambda_{\text{eff}}^2}\right)^{1/2}\right]$$

where $y_{cr}$ is the deflection corresponding to the onset of instability.

TABLE 10-2

Formulas for Compression-Spring Dimensions. ($N_a$ = Number of Active Coils)

| TERM | TYPE OF SPRING ENDS | | | |
|---|---|---|---|---|
| | PLAIN | PLAIN AND GROUND | SQUARED OR CLOSED | SQUARED AND GROUND |
| End coils, $N_e$ | 0 | 1 | 2 | 2 |
| Total coils, $N_t$ ≈ $N$ | $N_a$ | $N_a + 1$ | $N_a + 2$ | $N_a + 2$ |
| Free length, $L_0$ ≈ $L_f$ | $pN_a + d$ | $p(N_a + 1)$ | $pN_a + 3d$ | $pN_a + 2d$ |
| Solid length, $L_s$ | $d(N_t + 1)$ | $dN_t$ | $d(N_t + 1)$ | $dN_t$ |
| Pitch, $p$ | $(L_0 - d)/N_a$ | $L_0/(N_a + 1)$ | $(L_0 - 3d)/N_a$ | $(L_0 - 2d)/N_a$ |

*Source:* Associated Spring–Barnes Group, *Design Handbook*, Bristol, Conn., 1981, p. 32.

TABLE 10-3

End-Condition Constants $\alpha$ for Helical Compression Springs*

| END CONDITION | CONSTANT $\alpha$ |
|---|---|
| Spring supported between flat parallel surfaces (fixed ends) | 0.5 |
| One end supported by flat surface perpendicular to spring axis (fixed); other end pivoted (hinged) | 0.707 |
| Both ends pivoted (hinged) | 1 |
| One end clamped; other end free | 2 |

*Ends supported by flat surfaces must be squared and ground.

quantity $\lambda_{\text{eff}}$ in Eq. (10-11) is the *effective slenderness ratio* and is given by the equation

$$\lambda_{\text{eff}}=\frac{\alpha L_0}{D} \tag{10-12}$$

$C_1$ and $C_2$ are the elastic constants and are defined by the equations

$$C_1=\frac{E}{2(E-G)} \tag{10-13}$$

$$C_2=\frac{2\pi^2(E-G)}{2G+E} \tag{10-14}$$

Equation (10-12) contains the *end-condition constant* $\alpha$. This depends upon how the ends of the spring are supported. Table 10-3 gives values of $\alpha$ for usual end conditions. Note how closely these resemble the end conditions for columns.

Absolute stability occurs when, in Eq. (10-11), the term $C_2/\lambda_{\text{eff}}^2$ is less than unity. This means that the condition for absolute stability is that

$$L_0<\frac{\pi D}{\alpha}\left[\frac{2(E-G)}{2G+E}\right]^{1/2} \tag{10-15}$$

For steels, this turns out to be

$$L_0<2.63\frac{D}{\alpha} \tag{10-16}$$

$$F_a = \frac{F_{max} - F_{min}}{2}$$

$$F_m = \frac{F_{max} + F_{min}}{2}$$

A **force ratio** $R_F$ can also be defined as:

$$R_F = \frac{F_{min}}{F_{max}}$$

**Table 13-5 Typical Properties of Spring Temper Alloy Strip**

Source: Reference 1

| Material | Sut MPa (ksi) | Rockwell Hardness | Elongation % | Bend Factor | E GPa (Mpsi) | Poisson's Ratio |
|---|---|---|---|---|---|---|
| Spring steel | 1 700 (246) | C50 | 2 | 5 | 207 (30) | 0.30 |
| Stainless 301 | 1 300 (189) | C40 | 8 | 3 | 193 (28) | 0.31 |
| Stainless 302 | 1 300 (189) | C40 | 5 | 4 | 193 (28) | 0.31 |
| Monel 400 | 690 (100) | B95 | 2 | 5 | 179 (26) | 0.32 |
| Monel K500 | 1 200 (174) | C34 | 40 | 5 | 17.9 (26) | 0.29 |
| Inconel 600 | 1 040 (151) | C30 | 2 | 2 | 214 (31) | 0.29 |
| Inconel X-750 | 1 050 (152) | C35 | 20 | 3 | 214 (31) | 0.29 |
| Beryllium copper | 1 300 (189) | C40 | 2 | 5 | 128 (18.5) | 0.33 |
| Ni-Span-C | 1 400 (203) | C42 | 6 | 2 | 186 (27) | – |
| Brass CA 260 | 620 (90) | B90 | 3 | 3 | 11 (16) | 0.33 |
| Phosphor bronze | 690 (100) | B90 | 3 | 2.5 | 103 (15 | 0.20 |
| 17-7PH RH950 | 1 450 (210) | C44 | 6 | flat | 203 (29.5) | 0.34 |
| 17-7PH Cond. C | 1 650 (239) | C46 | 1 | 2.5 | 203 (29.5) | 0.34 |

**Table 13-4 Coefficients and Exponents for Equation 13.3**

Source: Reference 1

| ASTM # | Material | Range mm | Range in | Exponent $b$ | Coefficient $A$ MPa | Coefficient $A$ psi | Correlation Factor |
|---|---|---|---|---|---|---|---|
| A227 | Cold drawn | 0.5–16 | 0.020–0.625 | –0.182 2 | 1 753.3 | 141 040 | 0.998 |
| A228 | Music wire | 0.3–6 | 0.010–0.250 | –0.1625 | 2 153.5 | 184 649 | 0.9997 |
| A229 | Oil tempered | 0.5–16 | 0.020–0.625 | –0.183 3 | 1 831.2 | 146 780 | 0.999 |
| A232 | Chrome-v. | 0.5–12 | 0.020–0.500 | –0.145 3 | 1 909.9 | 173 128 | 0.998 |
| A401 | Chrome-s. | 0.8–11 | 0.031–0.437 | –0.093 4 | 2 059.2 | 220 779 | 0.991 |

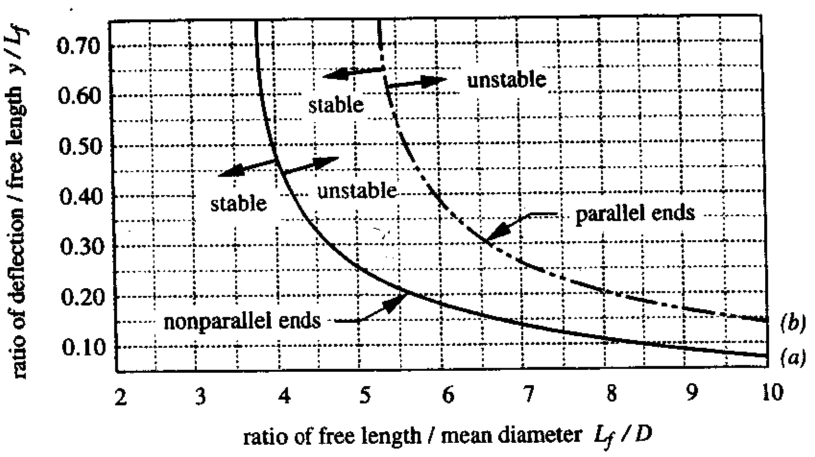

**FIGURE 13-14**

Critical Buckling Condition Curves Adapted from Reference 1

**Table 13-6 Maximum Torsional Yield Strength $S_{ys}$ for Helical Compression Springs in Static Applications**

Bending or Buckling Stresses Not Included. Source: Adapted from Ref. 1

| Material | Maximum Percent of Ultimate Tensile Strength: Before Set Removed (Use Eq. 13.9b) | Maximum Percent of Ultimate Tensile Strength: After Set Removed (Use Eq. 13.8b) |
|---|---|---|
| Cold-drawn carbon steel (e.g., A227, A228) | 45% | 60–70% |
| Hardened and tempered carbon and low-alloy steel (e.g., A229, A230, A232, A401) | 50 | 65–75 |
| Austenitic stainless steel (e.g., A313) | 35 | 55–65 |
| Nonferrous alloys (e.g., B134, B159, B197) | 35 | 55–65 |

Substituting equations 13.7 (p. 810) and 13.11*a* into 13.11*b* gives

$$f_n = \frac{2}{\pi N_a} \frac{d}{D^2} \sqrt{\frac{Gg}{32\gamma}} \text{ Hz} \tag{13.11c}$$

for the natural frequency of a fixed-fixed helical coil spring. If one end of the spring is fixed and the other free, it acts like a fixed-fixed spring of twice its length. Its natural frequency can be found by using a number for $N_a$ in equation 13.11*c* that is twice the actual number of active coils present in the fixed-free spring.

**Stress in Helical Torsion Spring at Inside Diameter (Section 13.8):**

$$K_{b_i} = \frac{4C^2 - C - 1}{4C(C-1)} \qquad (13.31a)$$

$$\sigma_{i_{max}} = K_{b_i}\frac{M_{max}c}{I} = K_{b_i}\frac{M_{max}(d/2)}{\pi d^4/64} = K_{b_i}\frac{32M_{max}}{\pi d^3} \qquad (13.32a)$$

**Stress in Helical Torsion Spring at Outside Diameter (Section 13.8):**

$$K_{b_o} = \frac{4C^2 + C - 1}{4C(C+1)} \qquad (13.31b)$$

$$\sigma_{o_{min}} = K_{b_o}\frac{32M_{min}}{\pi d^3}; \qquad \sigma_{o_{max}} = K_{b_o}\frac{32M_{max}}{\pi d^3} \qquad (13.32b)$$

$$\sigma_{o_{mean}} = \frac{\sigma_{o_{max}} + \sigma_{o_{min}}}{2}; \qquad \sigma_{o_{alt}} = \frac{\sigma_{o_{max}} - \sigma_{o_{min}}}{2} \qquad (13.32c)$$

**Ultimate Tensile Strength of Steel Wire—See Table 13-4 for Constants (Section 13.4):**

$$S_{ut} \cong Ad^b \qquad (13.3)$$

**Ultimate Shear Strength of Wire (Section 13.4):**

$$S_{us} \cong 0.67S_{ut} \qquad (13.4)$$

**Torsional Endurance Limits for Spring-Steel Wire for Stress Ratio R = 0 (Section 13.4):**

$$\begin{aligned} S_{ew}' &\cong 45.0 \text{ kpsi } (310 \text{ MPa}) \quad \text{for unpeened springs} \\ S_{ew}' &\cong 67.5 \text{ kpsi } (465 \text{ MPa}) \quad \text{for peened springs} \end{aligned} \qquad (13.12)$$

**Torsional Endurance Limits for Spring-Steel Wire for Stress Ratio R = −1 (Section 13.4):**

$$S_{es} = 0.5\frac{S_{ew}S_{us}}{S_{us} - 0.5S_{ew}} \qquad (13.17b)$$

**Bending Endurance Limits for Spring-Steel Wire for Stress Ratio R = 0 (Section 13.4):**

$$S_{ew_b}' = \frac{S_{ew}'}{0.577} \qquad (13.33a)$$

**Bending Endurance Limits for Spring-Steel Wire for Stress Ratio R = −1 (Section 13.4):**

$$S_e = 0.5\frac{S_{ew_b}S_{ut}}{S_{ut} - 0.5S_{ew_b}} \qquad (13.34c)$$

**Static Safety Factor for Helical Compression or Extension Spring (Section 13.5):**

$$N_s = \frac{S_{ys}}{\tau} \qquad (13.14)$$

**Dynamic Safety Factor for Helical Compression or Extension Spring (Section 13.4):**

$$N_{f_s} = \frac{S_{es}(S_{us} - \tau_i)}{S_{es}(\tau_m - \tau_i) + S_{us}\tau_a} \qquad (13.17a)$$

**Dynamic Safety Factor for Helical Torsion Spring (Section 13.8):**

$$N_{f_b} = \frac{S_e\left(S_{ut} - \sigma_{o_{min}}\right)}{S_e\left(\sigma_{o_{mean}} - \sigma_{o_{min}}\right) + S_{ut}\sigma_{o_{alt}}} \qquad (13.34b)$$

$$N_y = \frac{S_y}{\sigma_{i_{max}}} \qquad (13.34a)$$

**Solve for $d$ using the static yield criterion.**

$$d := \left(\frac{32\cdot K_{bi}\cdot N_{yd}\cdot M}{\pi\cdot K_s\cdot A\cdot mm^3}\right)^{\frac{1}{3+b}}\cdot mm$$

**Table C-1** **Physical Properties of Some Engineering Materials**

Data from Various Sources.* These Properties are Essentially Similar for All Alloys of the Particular Material

| Material | Modulus of Elasticity $E$ | | Modulus of Rigidity $G$ | | Poisson's Ratio $\nu$ | Weight Density $\gamma$ | Mass Density $\rho$ | Specific Gravity |
|---|---|---|---|---|---|---|---|---|
| | Mpsi | GPa | Mpsi | GPa | | lb/in$^3$ | Mg/m$^3$ | |
| Aluminum Alloys | 10.4 | 71.7 | 3.9 | 26.8 | 0.34 | 0.10 | 2.8 | 2.8 |
| Beryllium Copper | 18.5 | 127.6 | 7.2 | 49.4 | 0.29 | 0.30 | 8.3 | 8.3 |
| Brass, Bronze | 16.0 | 110.3 | 6.0 | 41.5 | 0.33 | 0.31 | 8.6 | 8.6 |
| Copper | 17.5 | 120.7 | 6.5 | 44.7 | 0.35 | 0.32 | 8.9 | 8.9 |
| Iron, Cast, Gray | 15.0 | 103.4 | 5.9 | 40.4 | 0.28 | 0.26 | 7.2 | 7.2 |
| Iron, Cast, Ductile | 24.5 | 168.9 | 9.4 | 65.0 | 0.30 | 0.25 | 6.9 | 6.9 |
| Iron, Cast, Malleable | 25.0 | 172.4 | 9.6 | 66.3 | 0.30 | 0.26 | 7.3 | 7.3 |
| Magnesium Alloys | 6.5 | 44.8 | 2.4 | 16.8 | 0.33 | 0.07 | 1.8 | 1.8 |
| Nickel Alloys | 30.0 | 206.8 | 11.5 | 79.6 | 0.30 | 0.30 | 8.3 | 8.3 |
| Steel, Carbon | 30.0 | 206.8 | 11.7 | 80.8 | 0.28 | 0.28 | 7.8 | 7.8 |
| Steel, Alloys | 30.0 | 206.8 | 11.7 | 80.8 | 0.28 | 0.28 | 7.8 | 7.8 |
| Steel, Stainless | 27.5 | 189.6 | 10.7 | 74.1 | 0.28 | 0.28 | 7.8 | 7.8 |
| Titanium Alloys | 16.5 | 113.8 | 6.2 | 42.4 | 0.34 | 0.16 | 4.4 | 4.4 |
| Zinc Alloys | 12.0 | 82.7 | 4.5 | 31.1 | 0.33 | 0.24 | 6.6 | 6.6 |

* *Properties of Some Metals and Alloys,* International Nickel Co., Inc., N.Y.; *Metals Handbook,* American Society for Metals, Materials Park, Ohio.

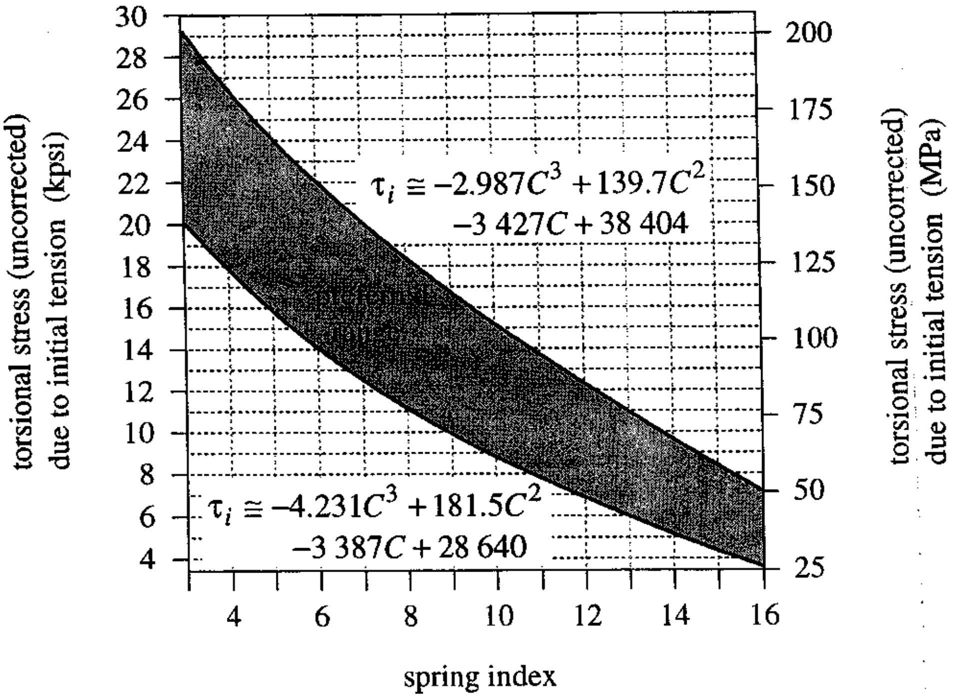

**FIGURE 13-22**

Preferred Range of Initial Stress in Extension Springs as a Function of Spring Index