SHIGLEY'S MECHANICAL ENGINEERING DESIGN

ELEVENTH EDITION

solution manual

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Chapter 1

Problems **1-1** through **1-6** are for student research. No standard solutions are provided.

1-7 From Fig. 1-2, cost of grinding to ± 0.0005 in is 270%. Cost of turning to ± 0.003 in is 60%.

Relative cost of grinding vs. turning = 270/60 = 4.5 times *Ans.*

1-8 $C_A = C_B$,

$$10 + 0.8\,P = 60 + 0.8\,P - 0.005\,P^2$$

$$P^2 = 50/0.005 \quad \Rightarrow \quad P = 100 \text{ parts} \quad \textit{Ans.}$$

1-9 Max. load = 1.10 P
Min. area = $(0.95)^2 A$
Min. strength = 0.85 S
To offset the absolute uncertainties, the design factor, from Eq. (1-1) should be

$$n_d = \frac{1.10}{0.85(0.95)^2} = 1.43 \qquad \textit{Ans.}$$

1-10 **(a)** $X_1 + X_2$:

$$x_1 + x_2 = X_1 + e_1 + X_2 + e_2$$
$$\text{error } = e = (x_1 + x_2) - (X_1 + X_2)$$
$$= e_1 + e_2 \qquad \textit{Ans.}$$

(b) $X_1 - X_2$:

$$x_1 - x_2 = X_1 + e_1 - (X_2 + e_2)$$
$$e = (x_1 - x_2) - (X_1 - X_2) = e_1 - e_2 \qquad \textit{Ans.}$$

(c) $X_1 X_2$:

$$x_1 x_2 = (X_1 + e_1)(X_2 + e_2)$$
$$e = x_1 x_2 - X_1 X_2 = X_1 e_2 + X_2 e_1 + e_1 e_2$$
$$\approx X_1 e_2 + X_2 e_1 = X_1 X_2 \left(\frac{e_1}{X_1} + \frac{e_2}{X_2} \right) \qquad \textit{Ans.}$$

(d) X_1/X_2:

$$\frac{x_1}{x_2}=\frac{X_1+e_1}{X_2+e_2}=\frac{X_1}{X_2}\left(\frac{1+e_1/X_1}{1+e_2/X_2}\right)$$

$$\left(1+\frac{e_2}{X_2}\right)^{-1}\approx 1-\frac{e_2}{X_2}\quad\text{then}\quad\left(\frac{1+e_1/X_1}{1+e_2/X_2}\right)\approx\left(1+\frac{e_1}{X_1}\right)\left(1-\frac{e_2}{X_2}\right)\approx 1+\frac{e_1}{X_1}-\frac{e_2}{X_2}$$

$$\text{Thus,}\quad e=\frac{x_1}{x_2}-\frac{X_1}{X_2}\approx\frac{X_1}{X_2}\left(\frac{e_1}{X_1}-\frac{e_2}{X_2}\right)\qquad Ans.$$

1-11 **(a)** $x_1 = \sqrt{7} = 2.645\ 751\ 311\ 1$

$X_1 = 2.64$ (3 correct digits)

$x_2 = \sqrt{8} = 2.828\ 427\ 124\ 7$

$X_2 = 2.82$ (3 correct digits)

$x_1 + x_2 = 5.474\ 178\ 435\ 8$

$e_1 = x_1 - X_1 = 0.005\ 751\ 311\ 1$

$e_2 = x_2 - X_2 = 0.008\ 427\ 124\ 7$

$e = e_1 + e_2 = 0.014\ 178\ 435\ 8$

Sum $= x_1 + x_2 = X_1 + X_2 + e$

$= 2.64 + 2.82 + 0.014\ 178\ 435\ 8 = 5.474\ 178\ 435\ 8$ Checks

(b) $X_1 = 2.65$, $X_2 = 2.83$ (3 digit significant numbers)

$e_1 = x_1 - X_1 = -0.004\ 248\ 688\ 9$

$e_2 = x_2 - X_2 = -0.001\ 572\ 875\ 3$

$e = e_1 + e_2 = -0.005\ 821\ 564\ 2$

Sum $= x_1 + x_2 = X_1 + X_2 + e$

$= 2.65 + 2.83 - 0.001\ 572\ 875\ 3 = 5.474\ 178\ 435\ 8$ Checks

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1-12 $$\sigma=\frac{S}{n_d}\quad\Rightarrow\quad\frac{32(1000)}{\pi d^3}=\frac{25(10^3)}{2.5}\quad\Rightarrow\quad d=1.006\ \text{in}\qquad Ans.$$

Table A-17: $d = 1\frac{1}{4}$ in *Ans.*

Factor of safety: $$n=\frac{S}{\sigma}=\frac{25(10^3)}{\dfrac{32(1000)}{\pi(1.25)^3}}=4.79\qquad Ans.$$

1-13 (**a**)

x	f	fx	fx^2
60	2	120	7200
70	1	70	4900
80	3	240	19200
90	5	450	40500
100	8	800	80000
110	12	1320	145200
120	6	720	86400
130	10	1300	169000
140	8	1120	156800
150	5	750	112500
160	2	320	51200
170	3	510	86700
180	2	360	64800
190	1	190	36100
200	0	0	0
210	1	210	44100
Σ	69	8480	1 104 600

Eq. (1-6) $\quad \bar{x} = \dfrac{1}{N}\sum_{i=1}^{k} f_i x_i = \dfrac{8480}{69} = 122.9 \text{ kcycles}$

Eq. (1-7)

$$s_x = \sqrt{\frac{\sum_{i=1}^{k} f_i x_i^2 - N\bar{x}^2}{N-1}} = \left[\frac{1\,104\,600 - 69(122.9)^2}{69-1}\right]^{1/2} = 30.3 \text{ kcycles} \quad \textit{Ans.}$$

(**b**) Eq. (1-5) $\quad z_{115} = \dfrac{x-\mu_x}{\hat{\sigma}_x} = \dfrac{x_{115}-\bar{x}}{s_x} = \dfrac{115-122.9}{30.3} = -0.2607$

Interpolating from Table (A-10)

0.2600	0.3974
0.2607	x
0.2700	0.3936

$\Rightarrow \quad x = 0.3971$

$N\Phi(-0.2607) = 69\,(0.3971) = 27.4 \approx 27 \quad$ *Ans.*

From the data, the number of instances less than 115 kcycles is

2 + 1 + 3 + 5 + 8 + 12 = 31 (the data is not perfectly normal)

1-14

x	f	$f\,x$	$f\,x^2$
174	6	1044	181656
182	9	1638	298116
190	44	8360	1588400
198	67	13266	2626668
206	53	10918	2249108
214	12	2568	549552
222	6	1332	295704
Σ	197	39126	7789204

Eq. (1-6) $$\bar{x} = \frac{1}{N}\sum_{i=1}^{k} f_i x_i = \frac{39\,126}{197} = 198.61 \text{ kpsi}$$

Eq. (1-7) $$s_x = \sqrt{\frac{\sum_{i=1}^{k} f_i x_i^2 - N\bar{x}^2}{N-1}} = \left[\frac{7\ 789\ 204 - 197(198.61)^2}{197-1}\right]^{1/2} = 9.68 \text{ kpsi} \quad \textit{Ans.}$$

1-15 $\bar{L} = 122.9$ kcycles and $s_L = 30.3$ kcycles

Eq. (1-5) $$z_{10} = \frac{x-\mu_x}{\hat{\sigma}} = \frac{x_{10}-\bar{L}}{s_L} = \frac{x_{10}-122.9}{30.3}$$

Thus, $x_{10} = 122.9 + 30.3\, z_{10} = L_{10}$

From Table A-10, for 10 percent failure, $z_{10} = -1.282$. Thus,

$$L_{10} = 122.9 + 30.3(-1.282) = 84.1 \text{ kcycles} \quad \textit{Ans.}$$

1-16

x	f	fx	fx^2
93	19	1767	164331
95	25	2375	225625
97	38	3686	357542
99	17	1683	166617
101	12	1212	122412
103	10	1030	106090
105	5	525	55125
107	4	428	45796
109	4	436	47524
111	2	222	24642
Σ	136	13364	1315704

Eq. (1-6) $\bar{x} = \frac{1}{N}\sum_{i=1}^{k} f_i x_i = 13\,364 / 136 = 98.26471 = 98.26 \text{ kpsi}$

Eq. (1-7) $s_x = \sqrt{\frac{\sum_{i=1}^{k} f_i x_i^2 - N\bar{x}^2}{N-1}} = \left(\frac{1\,315\,704 - 136(98.26471)^2}{136-1}\right)^{1/2} = 4.30 \text{ kpsi}$

Note, for accuracy in the calculation given above, $\bar{x}$ needs to be of more significant figures than the rounded value.

For a normal distribution, from Eq. (1-5), and a yield strength exceeded by 99 percent (R = 0.99, p_f = 0.01),

$$z_{0.01} = \frac{x - \mu_x}{\hat{\sigma}_x} = \frac{x_{0.01} - \bar{x}}{s_x} = \frac{x_{0.01} - 98.26}{4.30}$$

Solving for the yield strength gives

$$x_{0.01} = 98.26 + 4.30\, z_{0.01}$$

From Table A-10, $z_{0.01} = -2.326$. Thus

$$x_{0.01} = 98.26 + 4.30(-2.326) = 88.3 \text{ kpsi} \quad \textit{Ans.}$$

1-17 Eq. (1-9): $R = \prod_{i=1}^{n} R_i = 0.98(0.96)0.94 = 0.88$

Overall reliability = 88 percent *Ans.*

1-18 Obtain the coefficients of variance for strength and stress

$$C_S = \frac{\hat{\sigma}_{S_{sy}}}{\bar{S}_{sy}} = \frac{23.5}{312} = 0.07532$$

$$C_\sigma = \frac{\hat{\sigma}_\tau}{\bar{\tau}} = \frac{\hat{\sigma}_T}{\bar{T}} = \frac{145}{1\,500} = 0.09667$$

For $R = 0.99$, from Table A-10, $z = -2.326$.

Eq. (1-12):

$$\bar{n} = \frac{1 + \sqrt{1 - \left(1 - z^2 C_S^2\right)\left(1 - z^2 C_\sigma^2\right)}}{1 - z^2 C_S^2}$$

$$= \frac{1 + \sqrt{1 - \left[1 - (-2.326)^2 (0.07532)^2\right]\left[1 - (-2.326)^2 (0.09667)^2\right]}}{1 - (-2.326)^2 (0.07532)^2} = 1.3229 = 1.32 \quad \textit{Ans.}$$

From the given equation for stress,

$$\tau_{\max} = \frac{S_{sy}}{\bar{n}} = \frac{16T}{\pi d^3}$$

Solving for d gives

$$d = \left(\frac{16 T \bar{n}}{\pi S_{sy}}\right)^{1/3} = \left[\frac{16(1500)1.3229}{\pi (312) 10^6}\right]^{1/3} = 0.0319 \text{ m} = 31.9 \text{ mm} \quad \textit{Ans.}$$

1-19 Obtain the coefficients of variance for stress and strength

$$C_\sigma = \frac{\hat{\sigma}_\sigma}{\mu_\sigma} = \frac{\hat{\sigma}_P}{\bar{P}} = \frac{5}{65} = 0.09231$$

$$C_S = \frac{\hat{\sigma}_S}{\mu_S} = \frac{\hat{\sigma}_{S_y}}{\bar{S}_y} = \frac{6.59}{95.5} = 0.06901$$

(a) $\bar{n} = 1.2$

Eq. (1-11): $z = -\dfrac{\bar{n}_d - 1}{\sqrt{\bar{n}_d^2 C_S^2 + C_\sigma^2}} = -\dfrac{1.2 - 1}{\sqrt{1.2^2\left(0.06901^2\right) + 0.09231^2}} = -1.6127$

Interpolating Table A-10,

1.61	0.0537		
1.6127	Φ	$\Rightarrow$	$\Phi = 0.0534$
1.62	0.0526		

$R = 1 - 0.0534 = 0.9466$ *Ans.*

$$\bar{n} = \frac{\bar{S}_y}{\bar{\sigma}} = \frac{\bar{S}_y}{\bar{P} / (\pi d^2 / 4)} = \frac{\pi d^2 \bar{S}_y}{4\bar{P}} \Rightarrow d = \sqrt{\frac{4\bar{P}\bar{n}}{\pi \bar{S}_y}} = \sqrt{\frac{4(65)1.2}{\pi(95.5)}} = 1.020 \text{ in} \quad \textit{Ans.}$$

(b) $\bar{n} = 1.5$

$$z = -\frac{1.5 - 1}{\sqrt{1.5^2\left(0.06901^2\right) + 0.09231^2}} = -3.605$$

3.6	0.000159		
3.605	Φ	$\Rightarrow$	$\Phi = 0.00015645$
3.7	0.000108		

$R = 1 - 0.00015645 = 0.9998$ *Ans.*

$$d = \sqrt{\frac{4\bar{P}\bar{n}}{\pi \bar{S}_y}} = \sqrt{\frac{4(65)1.5}{\pi(95.5)}} = 1.140 \text{ in} \quad \textit{Ans.}$$

1-20 $\mu_{\sigma_{\max}} = \bar{\sigma}_{\max} = \bar{\sigma}_a + \bar{\sigma}_b = 90 + 383 = 473 \text{ MPa}$

From footnote 9 of text,

$$\hat{\sigma}_{\sigma_{\max}} = \left(\hat{\sigma}_{\sigma_a}^2 + \hat{\sigma}_{\sigma_b}^2\right)^{1/2} = (8.4^2 + 22.3^2)^{1/2} = 23.83 \text{ MPa}$$

$$C_{\sigma_{\max}} = \frac{\hat{\sigma}_{\sigma_{\max}}}{\mu_{\sigma_{\max}}} = \frac{\hat{\sigma}_{\sigma_{\max}}}{\bar{\sigma}_{\max}} = \frac{23.83}{473} = 0.0504$$

$$C_{S_y} = \frac{\hat{\sigma}_{S_y}}{\mu_{S_y}} = \frac{\hat{\sigma}_{S_y}}{\bar{S}_y} = \frac{42.7}{553} = 0.0772$$

$$\bar{n} = \frac{\bar{S}_y}{\bar{\sigma}_{max}} = \frac{553}{473} = 1.169 = 1.17 \quad \textit{Ans.}$$

Eq. (1-11): $$z = -\frac{\bar{n}_d - 1}{\sqrt{\bar{n}_d^2 C_S^2 + C_\sigma^2}} = -\frac{1.169 - 1}{\sqrt{1.169^2\left(0.0772^2\right) + 0.0504^2}} = -1.635$$

From Table A-10, $\Phi(-1.635) = 0.05105$

$$R = 1 - 0.05105 = 0.94895 = 94.9 \text{ percent} \quad \textit{Ans.}$$

1-21 $a = 1.500 \pm 0.001$ in
$b = 2.000 \pm 0.003$ in
$c = 3.000 \pm 0.004$ in
$d = 6.520 \pm 0.010$ in

(**a**) $$\bar{w} = \bar{d} - \bar{a} - \bar{b} - \bar{c} = 6.520 - 1.5 - 2 - 3 = 0.020 \text{ in}$$

$$t_w = \sum t_{all} = 0.001 + 0.003 + 0.004 + 0.010 = 0.018$$

$w = 0.020 \pm 0.018$ in *Ans.*

(**b**) From part (a), $w_{min} = 0.002$ in. Thus, must add 0.008 in to $\bar{d}$. Therefore,

$$\bar{d} = 6.520 + 0.008 = 6.528 \text{ in} \quad \textit{Ans.}$$

1-22 $V = xyz$, and $x = a \pm \Delta a$, $y = b \pm \Delta b$, $z = c \pm \Delta c$,

$$\bar{V} = abc$$

$$V = (a \pm \Delta a)(b \pm \Delta b)(c \pm \Delta c)$$
$$= abc \pm bc\Delta a \pm ac\Delta b \pm ab\Delta c \pm a\Delta b\Delta c \pm b\Delta c\Delta a \pm c\Delta a\Delta b \pm \Delta a\Delta b\Delta c$$

The higher order terms in Δ are negligible. Thus,

$$\Delta V \approx bc\Delta a + ac\Delta b + ab\Delta c$$

and, $$\frac{\Delta V}{\bar{V}} \approx \frac{bc\Delta a + ac\Delta b + ab\Delta c}{abc} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c} = \frac{\Delta a}{\bar{a}} + \frac{\Delta b}{\bar{b}} + \frac{\Delta c}{\bar{c}} \quad \textit{Ans.}$$

For the numerical values given, $\bar{V} = 1.500(1.875)3.000 = 8.4375 \text{ in}^3$

$$\frac{\Delta V}{\bar{V}} \approx \frac{0.002}{1.500} + \frac{0.003}{1.875} + \frac{0.004}{3.000} = 0.004267 \quad \Rightarrow \quad \Delta V \approx 0.004267(8.4375) = 0.0360 \text{ in}^3$$

$V = 8.4375 \pm 0.0360 \text{ in}^3$ *Ans.*

This answer yields $V \approx \begin{matrix} 8.4735 \\ 8.4015 \end{matrix}$ in, whereas, exact is $V = \begin{matrix} 8.473551.. \\ 8.401551.. \end{matrix}$ in

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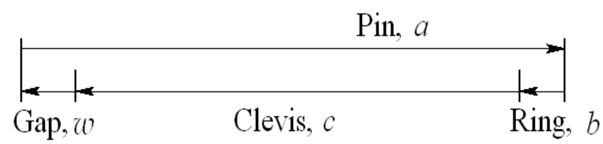
1-23



$w_{max} = 0.05$ in, $w_{min} = 0.004$ in

$$\bar{w} = \frac{0.05 + 0.004}{2} = 0.027 \text{ in}$$

Thus, $\Delta w = 0.05 - 0.027 = 0.023$ in, and then, $w = 0.027 \pm 0.023$ in.

$$\bar{w} = \bar{a} - \bar{b} - \bar{c}$$

$$0.027 = \bar{a} - 0.042 - 1.5$$

$$\bar{a} = 1.569 \text{ in}$$

$$t_w = \sum t_{\text{all}} \quad \Rightarrow \quad 0.023 = t_a + 0.002 + 0.005 \quad \Rightarrow \quad t_a = 0.016 \text{ in}$$

Thus, $a = 1.569 \pm 0.016$ in *Ans.*

1-24 $$\bar{D}_o = \bar{D}_i + 2\bar{d} = 3.734 + 2(0.139) = 4.012 \text{ in}$$

$$t_{D_o} = \sum t_{\text{all}} = 0.028 + 2(0.004) = 0.036 \text{ in}$$

$D_o = 4.012 \pm 0.036$ in *Ans.*

1-25 From O-Rings, Inc. (oringsusa.com), $D_i = 9.19 \pm 0.13$ mm, $d = 2.62 \pm 0.08$ mm

$$\bar{D}_o = \bar{D}_i + 2\bar{d} = 9.19 + 2(2.62) = 14.43 \text{ mm}$$

$$t_{D_o} = \sum t_{\text{all}} = 0.13 + 2(0.08) = 0.29 \text{ mm}$$

$D_o = 14.43 \pm 0.29$ mm *Ans.*

1-26 From O-Rings, Inc. (oringsusa.com), D_i = 34.52 ± 0.30 mm, d = 3.53 ± 0.10 mm

$$\bar{D}_o = \bar{D}_i + 2\bar{d} = 34.52 + 2(3.53) = 41.58 \quad \text{mm}$$

$$t_{D_o} = \sum t_{\text{all}} = 0.30 + 2(0.10) = 0.50 \quad \text{mm}$$

D_o = 41.58 ± 0.50 mm *Ans.*

1-27 From O-Rings, Inc. (oringsusa.com), D_i = 5.237 ± 0.035 in, d = 0.103 ± 0.003 in

$$\bar{D}_o = \bar{D}_i + 2\bar{d} = 5.237 + 2(0.103) = 5.443 \quad \text{in}$$

$$t_{D_o} = \sum t_{\text{all}} = 0.035 + 2(0.003) = 0.041 \quad \text{in}$$

D_o = 5.443 ± 0.041 in *Ans.*

1-28 From O-Rings, Inc. (oringsusa.com), D_i = 1.100 ± 0.012 in, d = 0.210 ± 0.005 in

$$\bar{D}_o = \bar{D}_i + 2\bar{d} = 1.100 + 2(0.210) = 1.520 \quad \text{in}$$

$$t_{D_o} = \sum t_{\text{all}} = 0.012 + 2(0.005) = 0.022 \quad \text{in}$$

D_o = 1.520 ± 0.022 in *Ans.*

1-29 From Table A-2,

(**a**) σ = 150/6.89 = 21.8 kpsi *Ans.*

(**b**) F = 2 /4.45 = 0.449 kip = 449 lbf *Ans.*

(**c**) M = 150/0.113 = 1330 lbf · in = 1.33 kip · in *Ans.*

(**d**) A = 1500/ 25.4^2 = 2.33 in^2 *Ans.*

(**e**) I = 750/2.54^4 = 18.0 in^4 *Ans.*

(**f**) E = 145/6.89 = 21.0 Mpsi *Ans.*

(**g**) v = 75/1.61 = 46.6 mi/h *Ans.*

(**h**) V = 1000/946 = 1.06 qt *Ans.*

1-30 From Table A-2,

(**a**) l = 5(0.305) = 1.53 m *Ans.*

(**b**) σ = 90(6.89) = 620 MPa *Ans.*

(**c**) p = 25(6.89) = 172 kPa *Ans.*

(**d**) Z =12(16.4) = 197 cm^3 *Ans.*

(**e**) w = 0.208(175) = 36.4 N/m *Ans.*

(**f**) δ = 0.001 89(25.4) = 0.048 0 mm *Ans.*

(**g**) v = 1 200(0.0051) = 6.12 m/s *Ans.*

(**h**) $\int$ = 0.002 15(1) = 0.002 15 mm/mm *Ans.*

(**i**) V = 1830(25.4^3) = 30.0 (10^6) mm^3 *Ans.*

1-31

(**a**) $\sigma = M/Z$ = 1770/0.934 = 1895 psi = 1.90 kpsi *Ans.*

(**b**) $\sigma = F/A$ = 9440/23.8 = 397 psi *Ans.*

(**c**) $y = Fl^3/3EI$ = 270(31.5)^3/[3(30)10^6(0.154)] = 0.609 in *Ans.*

(**d**) $\theta = Tl/GJ$ = 9 740(9.85)/[11.3(10^6)(π/32)1.00^4] = 8.648(10^{-2}) rad = 4.95° *Ans.*

1-32

(**a**) $\sigma = F/wt$ = 1000/[25(5)] = 8 MPa *Ans.*

(**b**) $I = bh^3/12$ = 10(25)^3/12 = 13.0(10^3) mm^4 *Ans.*

(**c**) $I = \pi d^4/64$ = π(25.4)^4/64 = 20.4(10^3) mm^4 *Ans.*

(**d**) $\tau = 16T/\pi d^3$ = 16(25)10^3/[π(12.7)^3] = 62.2 MPa *Ans.*

1-33

(**a**) $\tau = F/A = 2\,700/[\pi(0.750)^2/4] = 6110$ psi = 6.11 kpsi *Ans.*

(**b**) $\sigma = 32Fa/\pi d^3 = 32(180)31.5/[\pi(1.25)^3] = 29\,570$ psi = 29.6 kpsi *Ans.*

(**c**) $Z = \pi(d_o^4 - d_i^4)/(32\,d_o) = \pi(1.50^4 - 1.00^4)/[32(1.50)] = 0.266$ in^3 *Ans.*

(**d**) $k = (d^4 G)/(8D^3 N) = 0.062\,5^4(11.3)10^6/[8(0.760)^3\,32] = 1.53$ lbf/in *Ans.*
