機械設計問題詳解

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前　言

研習理工的同學，都有一種認識，那就是：一本書的習題往往是該書的精華所在，藉着習題的印證，才能對書中的原理原則澈底的吸收瞭解。

有鑒於此，晚園出版社特地聘請了許多在本科上具有相當研究與成就的人士，精心出版了一系列的題解叢書，為各該科目的研習，作一番介紹與鋪路的工作。

一個問題的解答方法，常因思惟的角度而異。晚園題解叢書，毫無疑問的都是經過一番精微的思考與分析而得。其目的在提供對各該科目研讀時的參考與比較；而對於一般的自修者，則有啓發與提示的作用。希望讀者能藉着這一系列題解叢書的幫助，而在本身的學問進程上有更上層樓的成就。

本書自出版以來，廣受歡迎。唯有若干錯誤之處，承蒙李廣齋先生予以訂正，特此致謝。

機械設計問題詳解

目　錄

第一章　設計概論

設計是一種籌劃、安排或依一定的計劃以期達到目的之工作。

一部機器是由若干個有足夠強度的機件組合而成，利用力的傳遞，和一定形態的運動程序而達到工作的目的。

在建立一種設計之前，應考慮下述問題：

1. 所用結構組織及機構。
2. 使用何種驅動方式，機械的、電氣的。
3. 使用何種材料。
4. 負荷情形，即力之分析。
5. 尺寸及容量之大小。
6. 尺寸、體積、重量製造、操作、可靠性、修理維護、造價等問題。
7. 使用者對設計物之反應。

一種設計物完成之前，在邏輯上必有可依照之程序，機械設計的程序概可分爲：

1. 列舉本機器應具備條件，作完整的說明。
2. 構造的安排——選擇可造成需要運動的機構。
3. 算出各機件所傳遞的功能及承受之負荷。
4. 選擇各機件使用之材料。
5. 由受力的大小及允許的變形，依照材料強度算出各機件的尺寸。
6. 根據過去的經驗及判斷，修改計算的尺寸及形狀，使合乎易於施工製造的要求。
7. 繪製各物件之詳細圖及組合圖之裝配圖。圖中並說明所用材料及施工方法。

第二章　材　　料

摘　要

各個機件所使用的材料，選擇適當與否，直接影響到構成機械的成本、壽命，以及其能否確定達到設計的目的。而材料的選擇主要的是強度的核算。對此，本章特從材料本身強度，以及幾種影響材料強度的加工法開始介紹。首先介紹材料的標準規範，賦予特定材料一簡易明瞭的名稱。然後表列各種常用材料的強度，包括有靜力強度及疲勞強度。機器上的各機件，當操作時如係屬於動態者，其承受之負荷，大都爲週而得始之動態應力，對此，就應考慮其疲勞強度。實際的疲勞限度可由表列之疲勞強度利用經驗式子或圖解法計算之。

本章除了介紹鐵、鋁等常用材料外，還介紹了部份特殊性質而必須使用之合金。

§ 有關實驗疲勞限度之計算

表 2-2 列有幾種常用之材料的彎曲疲勞限度 S_{ef} 。而一般材料的軸向完全相反的疲勞限度（ S_{ea} ）約爲 彎曲負荷者的 70 %， S_{es} 約爲 S_{ef} 之 55 % 。而此三種疲勞限度 S_{ea} ， S_{ef} 及 S_{es} 是以精光的表面試品，以適當的覆變次數，所受之週期性的完全相反應力，試驗室的環境亦無任何腐蝕性。但是實際上，機器的機件，不可能完全都是經過精光的加工，空氣也可能有腐蝕性，不若試驗室內之合於理想。又覆變應力也不可能是大小完全相等而方向相反者。再則所希望之使用壽命，也不一定是疲勞限度定義中所規定者。似此，則實際的疲勞限度受到如此衆多的因素之影響，其數值自然也隨之變化。變化的情形可用下式表示之：

$$S_e = \frac{S_{ea}\text{，}S_{ef}\text{ 或 }S_{es}}{f\,l\,p}$$

f：表面光度與工作環境參數，由圖 2-3 查得

l：壽命參數，$l \leq 1$

p：應力變化參數

有關 p 值，對鐵金屬合金之鍛造材料言

$$S_e = \frac{S_{ea}}{flp} \quad , \quad p = \frac{1 - 0.4\,(S_{min}/S_{max})}{1.4}$$

$$S_e = \frac{S_{es}}{flp} \quad , \quad p = \frac{2 - (S_{min}/S_{max})}{3}$$

$$S_e = \frac{S_{-e}}{flp} \quad , \quad p = \frac{1 - (S_{min}/S_{max})}{2}$$

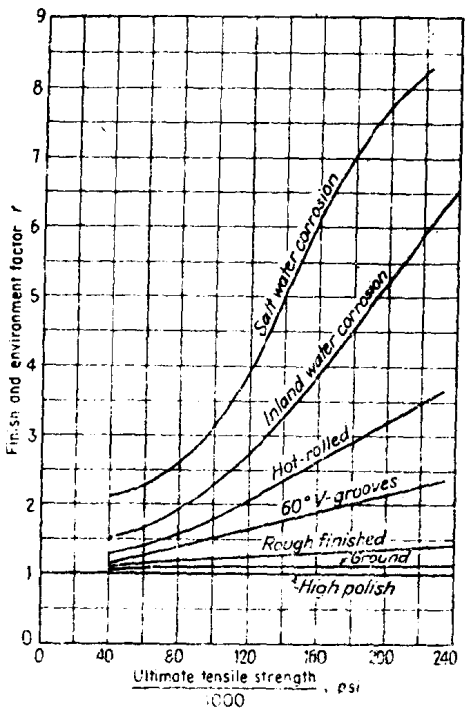

Fig. 2-3 Finish and environment factor f.

Table 2-2 Typical s_{ef} flexural endurance limits for fully reversed periodic loading of polished specimens of several commonly used materials*

Material	s_{ef}, psi
Aluminum:	
Cast alloys	6,000–11,000
Wrought alloys	8,000–18,000
Brass	7,000–20,000
Bronze:	
Phosphor	12,000
Tobin	21,000
Copper	12,000–17,000
Iron:	
Armco	24,000
Cast	6,000–18,000
Malleable	24,000
Magnesium alloys	7,000–17,000
Monel	20,000–50,000
Nitraloy	80,000
Steels:	
Cast	24,000–32,000
Plain carbon	25,000–75,000
6150 heat-treated	80,000

* L. S Marks, "Mechanical Engineer's Handbook," 5th ed., p. 403, McGraw-Hill Book Company, New York, 1951.

Table 2-5 **Properties of typical carbon steels**

Material	Ultimate strength		Yield stress		Flexural endurance limit s_{ef}, psi	Brinell hardness number BHN	Modulus of elasticity		Elongation in 2 in., %	Remarks and suggested uses
	Tension s_{tu}, psi	Shear s_{su}, psi	Tension and compression, s_{ty}, psi	Shear s_{sy}, psi			Tension and compression E, psi	Shear G, psi		
Wrought iron	48,000	50,000	27,000	30,000	25,000	100	28,000,000	11,200,000	30–40	
Cast steel:										
Soft	60,000	42,000	27,000	16,000	26,000	110	30,000,000	12,000,000	22	General-purpose castings
Medium	70,000	49,000	31,500	19,000	30,000	120	30,000,000	12,000,000	18	
Hard	80,000	56,000	36,000	21,000	34,000	130	30,000,000	12,000,000	15	
SAE 1025, annealed	67,000	41,000	34,000	20,000	29,000	120	30,000,000	12,000,000	26	Machinery and general-purpose steel
water-quenched	78,000	55,000	41,000	24,000	43,000	159	30,000,000	12,000,000	35	
	90,000	63,000	58,000	34,000	50,000	183			27	
SAE 1045, annealed	85,000	60,000	45,000	26,000	42,000	140	30,000,000	12,000,000	20	Large forgings, axles, shafts
water-quenched	95,000	67,000	60,000	35,000	53,000	197	30,000,000	12,000,000	28	
	120,000	84,000	90,000	52,000	67,000	248			15	
oil-quenched	96,000	67,000	62,000	35,000	53,000	192	30,000,000	12,000,000	22	
	115,000	80,000	80,000	45,000	65,000	235			16	
SAE 1095, annealed	110,000	75,000	55,000	33,000	52,000	200	30,000,000	12,000,000	20	Springs, cutting instruments
oil-quenched	130,000	85,000	66,000	39,000	68,000	300	30,000,000	11,500,000	16	
	188,000	120,000	130,000	75,000	100,000	380			10	

Upper figures: steel quenched and drawn to 1300°F.
Lower figures: steel quenched and drawn to 800°F.
Values for intermediate drawing temperatures may be approximated by direct interpolation.

Table 2-6 **Properties of typical alloy steels (*Continued*)**

Material	Ultimate strength		Yield stress		Flexural endurance limit $s_{e'}$, psi	Brinell hardness number BHN	Modulus of elasticity		Elongation in 2 in., %	Remarks and suggested uses
	Tension s_{tu}, psi	Shear s_{su}, psi	Tension s_{ty}, psi	Shear s_{sy}, psi			Tension and compression E, psi	Shear G, psi		
Chromium-molybdenum:										
SAE 4140, oil-quenched	120,000	90,000	100,000	55,000	60,000	240	30,000,000	12,000,000	25	
	190,000	150,000	165,000	91,000	95,000	380			12	
Chromium-vanadium:										
SAE 6145, oil-quenched	105,000	75,000	98,000	54,000	94,000	220	30,000,000	12,000,000	25	
	230,000	180,000	210,000	115,000	105,000	425			12	
Silicon-manganese:										
SAE 9260, oil-quenched	158,000	120,000	100,000	60,000	62,000	240	30,000,000	12,000,000	16	Springs, gears
Stainless steel, 0.12 C, 18.0 Cr, 8.0 Ni	90,000	60,000	35,000	20,000	40,000	135	30,000,000	12,000,000	60	Hot-rolled
	200,000	150,000	175,000	100,000	90,000	380			5	Cold-worked

The endurance limit for reversed shear may be taken as 55 per cent of the endurance limit in reversed bending.
Tabulated values are minimum values to be expected with round bars up to 1½ in. diameter. Smaller sections and careful heat treatment will show higher values.
Upper figures: steel quenched and drawn to 1300°F.
Lower figures: steel quenched and drawn to 800°F.

Table 2-8 **Properties of typical copper-zinc alloys (brasses)**

Material	Ultimate tensile strength s_{tu}, psi	Tensile yield stress s_{ty}, psi	Flexural endurance limit $s_{e'}$, psi	Brinell hardness BHN	Modulus of elasticity in tension and compression E, psi	Elongation in 2 in, %	Remarks and suggested uses
Commercial bronze							90 Cu, 10 Zn
Rolled, hard	65,000	63,000	18,000	107	15,000,000	18	Sheet rod, wire, tubes, hardware, screws, rivets
Rolled, soft	35,000	11,000	12,000	52	15,000,000	56	
Forged, cold	40,000–65,000	25,000–61,000	12,000–16,000	62–102	15,000,000	55–20	
Red brass							85 Cu, 15 Zn
Rolled, hard	75,000	72,000	20,000	126	15,000,000	18	Sheet, wire, shapes, tubes, radiators, plumbing
Rolled, soft	37,000	14,000	14,000	54	15,000,000	55	
Forged, cold	42,000–62,000	22,000–54,000	14,000–18,000	63–120	15,000,000	47–20	
Low brass							80 Cu, 20 Zn
Rolled, hard	75,000	59,000	22,000	130	15,000,000	18	Drawn, stamped, bellows, flexible hose
Rolled, soft	44,000	12,000	15,000	56	15,000,000	65	
Forged, cold	47,000–80,000	20,000–65,000		63–133	15,000,000	30–15	
Spring brass							75 Cu, 25 Zn
Hard	84,000	64,000	21,000	107*	14,000,000	5	
Soft	45,000	17,000	17,000	57*	18,000,000	58	
Cartridge brass							70 Cu, 30 Zn
Rolled, hard	100,000	75,000	22,000	154	15,000,000	14	
Rolled, soft	48,000	30,000	17,000	70	15,000,000	55	
Deep-drawing brass							68 Cu, 32 Zn
Strip, hard	85,000	79,000	21,000	166*	15,000,000	3	
Strip, soft	45,000	11,000	17,000	13*	15,000,000	55	
Muntz metal							60 Cu, 40 Zn
Rolled, hard	80,000	66,000	25,000	151	15,000,000	20	Heat-exchanger tubes
Rolled, soft	52,000	22,000	21,000	82	15,000,000	48	
Tobin bronze							60 Cu, 39.25 Zn, 0.75 Sn
Hard	63,000	35,000	21,000	165	15,000,000	35	Marine parts and trim
Soft	56,000	22,000		90	15,000,000	45	
Manganese bronze							58 Cu, 40 Zn
Hard	75,000	45,000	20,000	110	15,000,000	20	Cast, rolled, drawn, propellers, bearings
Soft	60,000	30,000	16,000	90	15,000,000	30	

* Rockwell hardness, F scale.

Table 2-12 **Typical properties of aluminum alloys**

Material, Aluminum Association Code No. (AA No.)	Material, Aluminum Company of America Code No. (ALCOA No.)	Ultimate strength		Yield strength		Flexural endurance limit, s_e, psi	Brinell hardness, 500 kg on 10-mm ball	Elongation in 2 in., %	Remarks and suggested uses
		Tension s_u, psi	Shear s_{su}, psi	Tension s_{yt}, psi	Compression s_{yc}, psi				
	Sand-casting alloys:								
	43	19,000	14,000	9,000	9,000	6,500	40	6	High ductility and shock-resistance
	112	23,000	20,000	14,000	17,000	9,000	70	1.5	Easy machining, general-purpose castings
	122-T2	25,000	21,000	20,000	20,000	9,500	75	1	Pump cylinders and parts requiring good wear resistance
	122-T61	36,000	29,000	30,000	43,000	.....	100	1	
	142-T2	27,000	21,000	18,000	18,000	6,500	75	1	Air-cooled engine heads and parts requiring good mechanical properties up to 600°F
	142-T61	37,000	32,000	32,000	47,000	8,000	100	0.5	
	195-T4	31,000	24,000	16,000	16,000	6,000	65	8.5	Heat-treated castings
	212	22,000	20,000	14,000	14,000	8,000	65	2	Good casting qualities, general-purpose castings
	Permanent mold castings:								
	B-113	29,000	23,000	19,000	19,000	.....	70	1.5	General-purpose castings
	A-132-T4	38,000	29,000	30,000	30,000	.....	100	1.5	Gas-engine pistons; has lowest coefficient of expansion of the aluminum alloys
	Wrought alloys:								
1100	2 SO	13,000	9,500	5,000	.....	5,000	23	45	Low-cost, easily fabricated alloys; most common nonstructural alloy; used for cooking utensils and chemical equipment
3003	3 SO	16,000	11,000	6,000	.....	7,000	28	40	
	3 SH	29,000	16,000	25,000	.....	10,000	55	10	
2014	14 ST	65,000	45,000	58,000	.....	16,000	120	10	Best mechanical properties of the forging alloys
2017	17 SO	26,000	18,000	10,000	.....	11,000	45	22	Corrosion-resisting forgings; most popular heat-treatable alloy used for structural shapes
	17 ST	62,000	36,000	42,000	.....	15,000	100	22	
2024	24 SO	26,000	18,000	10,000	.....	12,000	42	22	Aeronautic structural shapes
	24 SRT	70,000	42,000	55,000	.....	.....	116		
2025	25 ST	55,000	35,000	30,000	.....	15,000	100	16	Easy forging alloy
3032	32 ST	52,000	38,000	30,000	.....	14,000	115	5	High strength at elevated temperatures
5052	52 SO	29,000	18,000	14,000	.....	17,000	45	30	Higher-strength, general-purpose alloy
	52 SH	41,000	24,000	36,000	.....	20,500	85	8	
6053	53 ST	36,000	24,000	30,000	.....	11,000	85	16	Forgings for severe corrosion resistance, as in dairies and breweries

Modulus of elasticity in tension, 10,300,000 psi, in shear 3,850,000 psi.
Yield stress taken at 0.2 per cent permanent deformation.
Endurance limit is based on 500,000,000 cycles of reversed stress.
Bearing strength is 1.8 times the tensile strength.

Table 2-4 **Properties of typical cast irons**

Material	Ultimate strength		Flexural endurance limit s_{ef}, psi	Brinell hardness number BHN	Modulus of elasticity		Tensile elongation in 2 in., %	Remarks and suggested uses
	Tension s_{tu}, psi	Compression s_{cu}, psi			Tension and compression. E, psi	Shear G, psi		
Gray:								
Ordinary	18,000	80,000	9,000	100–150	10–12,000,000	4,000,000	0–1	General industrial castings
Good	24,000	100,000	12,000	100–150	12,000,000	4,800,000	0–1	Pump cylinders, etc.
	16,000							
High-grade	30,000	120,000	15,000	100–150	14,000,000	5,600,000	0–1	Important castings
Malleable, SAE 32510	50,000	120,000	25,000	100–145	23,000,000	9,200,000	10	Substitute for unimportant forgings
Nickel alloys:								
Ni–0.75, C–3.40, Si–1.75, Mn–0.55	32,000	120,000	16,000	200	15,000,000	6,000,000	1–2	Light machine frames
	24,000			175				
Ni–2.00, C–3.00, Si–1.10, Mn–0.80	40,000	155,000	20,000	220	20,000,000	8,000,000	1–2	Heavy diesel cylinders, pump, and valve bodies
	31,000			200				
Nickel-chromium alloys:								
Ni–0.75, Cr–0.30, C–3.40, Si–1.90, Mn–0.65	32,000	125,000	16,000	200	15,000,000	6,000,000	1–2	Light machine-tool table light engine cylinders
Ni–2.75, Cr–0.80, C–3.00, Si–1.25, Mn–0.60	45,000	160,000	22,000	300	20,000,000	8,000,000	1–2	Heavy forming dies

Upper figures refer to arbitration test bars. Lower figures refer to the center of 4-in. round specimens.

Flexure: For cast irons in bending, the modulus of rupture may be taken as $1.75s_{tu}$ for circular sections, $1.50s_{tu}$ for rectangular sections, and $1.25s_{tu}$ for I and T sections.

Shear: The strength of cast iron in shear may be taken as $1.10s_{tu}$.

問題詳解

2—1 一 SAE 3240 油淬火勃氏硬度數 229 之鋼樑，承受覆變彎曲應力由一方向之 25,000psi 的拉應力，另至一方向 15,000psi 的壓應力。其表面情況爲粗加工者。求此鋼樑在此種負荷情況下之疲勞限定。

〔解〕 由表 2-6 可查 SAE3240 油淬火勃氏硬度 229 之材料，其

$S_{ef} = 84{,}000psi$ ， $S_{ult} = 110{,}000\ psi$

則實際疲勞限度爲

$$S_e = \frac{S_{ef}}{flp}$$

式中：f 可由圖 2-3 查得其值爲 1.25（表面爲粗加工者）

l 直接令爲 1（不考慮因希望的覆變次數較少而獲得之利益）

$$p = \frac{2 - \dfrac{S_{min}}{S_{max}}}{3}$$

因 $S_{min} = -15{,}000\ psi$ ， $S_{max} = 25{,}000\ psi$

$$p = \frac{2 - \left(\dfrac{-15{,}000}{25{,}000}\right)}{3} = 0.867$$

所以 $$S_e = \frac{84{,}000}{1.25 \times 1 \times 0.867} = 77508.7\,psi$$

2—2 一 SAE1095 退火之鋼軸，表面曾經磨床磨光，接受覆變的扭矩，產生由一個方向的 30,000psi 剪應力，至另一方

向 15,000psi 之剪應力。求此種負荷情況之疲勞限度。

〔解〕 由表 2-5 可查 $SAE1095$ 退火之材料，其

$$S_{sf} = 52{,}000psi \quad , \quad S_{ult} = 75{,}000psi$$

而由參考資料知 $S_{es} = 0.55\ S_{sf} = 28{,}660$

則實際疲勞限度爲

$$S_e = \frac{S_{es}}{flp}$$

式中：f 可由圖 2-3 查得其值爲 1.1（表面爲磨床磨光者）l 直接令爲 1

$$p = \frac{1 - (\frac{S_{min}}{S_{max}})}{2}$$

由題意知：$S_{max} = 30{,}000psi$，$S_{min} = -15{,}000psi$ } ——— (1)

$S_{max} = 15{,}000psi$，$S_{min} = -30{,}000psi$ } ——— (2)

由(1)得：

$$p = 1 - (-15{,}000/30{,}000)/2 = 0.75$$

所以 $S_e = \frac{28{,}600}{1.1 \times 1 \times 0.75} = 34{,}667\ psi$

由(2)得：

$$p = \frac{1 - (-30{,}000/15{,}000)}{2} = 1.5$$

所以 $S_e = \frac{28{,}600}{1.1 \times 1 \times 1.5} = 17{,}333\ psi$

討論：比較(1)和(2)可知取 $S_e = 34667\ psi$

2—3 一鋼製機器零件，負載軸向的複變應力，由 50,000psi 之拉應力至 30,000psi 之壓應力。鋼料之降伏拉力強度爲 100,000 psi 完全覆變之疲勞限度爲 70,000 psi，此應力強度已將表面加工影響考慮在內。若設計因數爲 1.3，求在此負荷情況之允許的工作應力。

〔解〕 由題意知材料之 $S_{ty} = 100{,}000$ psi