钱学森 力学手稿

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出版前言

2011年12月11日是西安交通大学杰出校友钱学森先生的百年诞辰。为缅怀钱学森学长，学习他的科学思想和卓越风范，展示其丰功伟绩和人格魅力，西安交通大学举办了“纪念钱学森诞辰100周年”系列活动：作为制片方之一，参与西部电影集团摄制传记故事片《钱学森》；与中央电视台合作，出品纪录片《实验班的故事——沿着钱学森走过的路》；扩建钱学森生平业绩展馆，向校内外开放；举办钱学森科学与教育思想研讨会；出版发行《钱学森力学手稿》、《钱学森年谱（初编）》、《钱学森第六次产业革命思想探微丛书》等。

钱学森先生在美国深造和工作期间留下大量珍贵手稿，这些手稿真实展示了钱学森先生博大精深的学识、开拓求实的精神和严谨奋进的作风，是钱老勇攀科学高峰和严谨治学的集中体现。这里，我们将部分原稿整理汇集成册，出版《钱学森力学手稿》，作为钱老百年诞辰的献礼。

《钱学森力学手稿》共10卷，包含两部分内容。第一部分是草稿，包括扁壳、球壳和圆柱壳屈曲分析的公式推导和数值演算。在研究圆柱壳轴压屈曲问题时，为了求得圆柱壳体的临界压力，在有关的五百多页草稿中，对多达二十多种可能的屈曲模

态逐一进行公式推演和数值计算，最终才找到满意的并在论文中采用的屈曲模态。仔细观察草稿中的数据列表，每个数字有效位数都长达八位，在手摇机械式计算机作为主要计算工具的年代，这串串数字凝聚着多少现今难以想象的艰辛劳动。

第二部分是手稿，以航空航天工程为核心，涵盖空气动力学、固体力学、火箭技术、工程控制论和物理力学等领域的部分学术论文手稿、打印稿和讲义。

《钱学森力学手稿》是在西安交通大学校领导的大力支持下，由西安交通大学航天航空学院沈亚鹏教授整理完成。图书出版过程中得到了西安交通大学党委宣传部、校友关系发展部、图书馆、航天航空学院等的积极协助，在此深表感谢。

Preliminary Calculation of Circular Cylinder (V)

$$\frac{w}{R} = \left(f_0 + \frac{1}{4}f_1\right) + \frac{1}{2}f_1\left[\cos\frac{mx}{R}\cos\frac{my}{R} + \frac{1}{4}\cos\frac{2mx}{R} + \frac{1}{4}\cos\frac{2my}{R}\right]$$

$$+ \frac{1}{4}f_2\left[\cos\frac{2mx}{R} + \cos\frac{2my}{R}\right]$$

$$\frac{w}{R} = \left(f_0+\frac{1}{4}f_1\right) + \frac{1}{2}f_1\cos\frac{mx}{R}\cos\frac{my}{R} + \frac{1}{4}\left(\frac{1}{2}f_1+f_2\right)\cos\frac{2mx}{R} + \frac{1}{4}\left(\frac{1}{2}f_1+f_2\right)\cos\frac{2my}{R}$$

$$\frac{\partial w}{\partial y} = -m\left[\frac{1}{2}f_1\cos\frac{mx}{R}\sin\frac{my}{2} + \frac{1}{2}\left(\frac{1}{2}f_1+f_2\right)\sin\frac{2my}{R}\right]$$

$$\frac{1}{R}\frac{\partial^2 w}{\partial x^2} = -\left(\frac{m}{R}\right)^2\left[\frac{1}{2}f_1\cos\frac{mx}{R}\cos\frac{my}{R} + \left(\frac{1}{2}f_1+f_2\right)\cos\frac{2mx}{R}\right]$$

$$\frac{1}{R}\frac{\partial^2 w}{\partial y^2} = -\left(\frac{m}{R}\right)^2\left[\frac{1}{2}f_1\cos\frac{mx}{R}\cos\frac{my}{R} + \left(\frac{1}{2}f_1+f_2\right)\cos\frac{2my}{R}\right]$$

$$\frac{1}{R}\frac{\partial^2 w}{\partial x\partial y} = +\left(\frac{m}{R}\right)^2\left[\frac{1}{2}f_1\sin\frac{mx}{R}\sin\frac{my}{R}\right]$$

$$\Delta\Delta F = E\left(\frac{m}{R}\right)^2\left[m^2\left\{-\frac{1}{8}f_1^2\left(\cos\frac{2mx}{R} + \cos\frac{2my}{R}\right) - \frac{1}{4}f_1\left(\frac{1}{2}f_1+f_2\right)\left(\cos\frac{mx}{R}+\cos\frac{3mx}{R}\right)\cos\frac{my}{R}\right.\right.$$

$$\left. - \frac{1}{4}f_1\left(\frac{1}{2}f_1+f_2\right)\cos\frac{mx}{R}\left(\cos\frac{my}{R} + \cos\frac{3my}{R}\right) - \left(\frac{1}{2}f_1+f_2\right)^2\cos\frac{2mx}{R}\cos\frac{2my}{R}\right\}$$

$$\left. + \frac{1}{2}f_1\cos\frac{mx}{R}\cos\frac{my}{R} + \left(\frac{1}{2}f_1+f_2\right)\cos\frac{2mx}{R}\right]$$

$$= E\left(\frac{m}{R}\right)^2\left[-\left\{\frac{1}{8}f_1^2m^2 - \left(g - \frac{1}{2}f_1\right)\right\}\cos\frac{2mx}{R} - \frac{1}{8}f_1^2m^2\cos\frac{2my}{R}\right.$$

$$- \left\{\frac{1}{2}f_1\left(g-\frac{1}{2}f_1\right)m^2 - \frac{1}{2}f_1\right\}\cos\frac{mx}{R}\cos\frac{my}{R} - \frac{1}{4}f_1\left(g-\frac{1}{2}f_1\right)m^2\cos\frac{3mx}{R}\cos\frac{my}{R}$$

$$\left. - \frac{1}{4}f_1\left(g-\frac{1}{2}f_1\right)m^2\cos\frac{mx}{R}\cos\frac{3my}{R} - \left(g-\frac{1}{2}f_1\right)^2m^2\cos\frac{2mx}{R}\cos\frac{2my}{R}\right]$$

$$F = E\left(\frac{R}{m}\right)^2\Big[-\frac{1}{16}\left\{\frac{1}{8}f_1^2 m^2-\left(g-\frac{1}{2}f_1\right)\right\}\cos\frac{2mx}{R}-\frac{1}{128}f_1^2 m^2\cos\frac{2my}{R}-\frac{1}{4}\left\{\frac{1}{2}f_1\left(g-\frac{1}{2}f_1\right)m^2-\frac{1}{2}f_1\right\}\cos\frac{mx}{R}\cos\frac{my}{R}$$

$$-\frac{1}{400}f_1\left(g-\frac{1}{2}f_1\right)m^2\cos\frac{3mx}{R}\cos\frac{my}{R}-\frac{1}{400}f_1\left(g-\frac{1}{2}f_1\right)m^2\cos\frac{mx}{R}\cos\frac{3my}{R}-\frac{1}{64}\left(g-\frac{1}{2}f_1\right)^2 m^2\cos\frac{2mx}{R}\cos\frac{2my}{R}\Big]$$

$$\sigma_x+\sigma_y = E\Big[\frac{1}{4}\left\{\frac{1}{8}f_1^2 m^2-\left(g-\frac{1}{2}f_1\right)\right\}\cos\frac{2mx}{R}+\frac{1}{32}f_1^2 m^2\cos\frac{2my}{R}+\frac{1}{2}\left\{\frac{1}{2}f_1\left(g-\frac{1}{2}f_1\right)m^2-\frac{1}{2}f_1\right\}\cos\frac{mx}{R}\cos\frac{my}{R}$$

$$+\frac{1}{40}f_1\left(g-\frac{1}{2}f_1\right)m^2\cos\frac{3mx}{R}\cos\frac{my}{R}+\frac{1}{40}f_1\left(g-\frac{1}{2}f_1\right)m^2\cos\frac{mx}{R}\cos\frac{3my}{R}+\frac{1}{8}\left(g-\frac{1}{2}f_1\right)^2 m^2\cos\frac{2mx}{R}\cos\frac{2my}{R}\Big]$$

$$\lambda+4\frac{\sigma}{E}-\frac{1}{2}m^2\left[\frac{1}{16}f_1^2+\frac{1}{8}\left(g-\frac{1}{2}f_1\right)^2\right]+\left(\delta_0+\frac{1}{4}f_1\right)=0$$

$$\boxed{K=-4\left(\frac{\sigma}{E}\right)^2-m^2\frac{\sigma}{E}\left[\frac{1}{4}f_1^2+\frac{1}{2}\left(g-\frac{1}{2}f_1\right)^2\right]}$$

$$P_1=\frac{1}{8}\left\{\frac{1}{8}f_1^2 m^2-\left(g-\frac{1}{2}f_1\right)\right\}^2+\frac{1}{512}f_1^4 m^4+\frac{1}{16}\left\{f_1\left(g-\frac{1}{2}f_1\right)m^2-f_1\right\}^2+\frac{1}{800}f_1^2 m^4\left(g-\frac{1}{2}f_1\right)^2$$

$$+\frac{1}{64}m^4\left(g-\frac{1}{2}f_1\right)^4$$

$$\wp_1 = \frac{1}{8}\Big\{ \frac{1}{64} f_1^4 m^4 - \frac{1}{4} f_1^2 m^2 \left(g - \frac{1}{2} f_1\right) + \left(g - \frac{1}{2} f_1\right)^2 + \frac{1}{64} f_1^4 m^4 + \frac{1}{2} f_1^2 m^4 \left(g - \frac{1}{2} f_1\right)^2 - f_1^2 m^2 \left(g - \frac{1}{2} f_1\right)$$

$$+ \frac{1}{2} f_1^2 + \frac{1}{100} f_1^2 m^4 \left(g^2 - g f_1 + \frac{1}{4} f_1^2\right) + \frac{1}{8} m^4 \left(g^4 - 2 g^3 f_1 + \frac{3}{2} g^2 f_1^2 - \frac{1}{2} g f_1^3 + \frac{1}{16} f_1^4\right)\Big\}$$

$$= \frac{1}{8}\Big\{ \cancel{\frac{1}{64} f_1^4 m^4} - \cancel{\frac{1}{4} f_1^2 g m^2} + \cancel{\frac{1}{8} f_1^3 m^2} + g^2 - g f_1 + \frac{1}{4} f_1^2 + \cancel{\frac{1}{64} f_1^4 m^4} + \cancel{\frac{1}{2} f_1^2 g^2 m^4} - \cancel{\frac{1}{2} f_1^3 g m^4}$$

$$+ \cancel{\frac{1}{8} f_1^4 m^4} - \cancel{f_1^2 g m^2} + \cancel{\frac{1}{2} f_1^3 m^2} + \frac{1}{2} f_1^2 + \cancel{\frac{1}{100} f_1^2 g^2 m^4} - \cancel{\frac{1}{100} f_1^3 g m^4} + \cancel{\frac{1}{400} f_1^4 m^4}$$

$$+ \cancel{\frac{1}{8} g^4 m^4} - \cancel{\frac{1}{4} f_1 g^3 m^4} + \cancel{\frac{3}{16} f_1^2 g^2 m^4} - \cancel{\frac{1}{16} f_1^3 g m^4} + \cancel{\frac{1}{128} f_1^4 m^4}\Big\}$$

$$= \frac{1}{8}\Big[m^4 \Big\{ \left(\frac{1}{64} + \frac{1}{64} + \frac{1}{8} + \frac{1}{128} + \frac{1}{400}\right) f_1^4 + \left(-\frac{1}{2} - \frac{1}{100} - \frac{1}{16}\right) f_1^3 g + \left(\frac{1}{2} + \frac{1}{100} + \frac{3}{16}\right) f_1^2 g^2 - \frac{1}{4} f_1 g^3 + \frac{1}{8} g^4 \Big\}$$

$$- m^2 \Big\{ \left(-\frac{1}{8} - \frac{1}{2}\right) f_1^3 + \left(\frac{1}{4} + 1\right) f_1^2 g \Big\} + \Big\{ \frac{3}{4} f_1^2 - g f_1 + g^2 \Big\}\Big]$$

$$\boxed{\begin{aligned} \wp_1 = \frac{1}{8}\Big[& m^4 \Big\{ \frac{533}{3200} f_1^4 - \frac{229}{400} f_1^3 g + \frac{279}{400} f_1^2 g^2 - \frac{1}{4} f_1 g^3 + \frac{1}{8} g^4 \Big\} \\ & + m^2 \Big\{ \frac{5}{8} f_1^3 - \frac{5}{4} f_1^2 g \Big\} + \Big\{ \frac{3}{4} f_1^2 - g f_1 + g^2 \Big\}\Big] \end{aligned}}$$

$$\beta_2 = \frac{1}{12(1-\nu^2)}\left(\frac{t}{R}\right)^2 m^4\left[f_1^2 + 4\left(g - \frac{1}{2}f_1\right)^2\right] = \frac{1}{12(1-\nu^2)}\left(\frac{t}{R}\right)^2 m^4\left[2f_1^2 + 4g^2 - 4f_1 g\right]$$

$$\beta_2 = \frac{1}{6(1-\nu^2)}\left(\frac{t}{R}\right)^2 m^4\left[f_1^2 - 2f_1 g + 2g^2\right]$$

$$\eta = \left(\frac{f}{t}\right) = \frac{g}{\left(\frac{t}{R}\right)}$$

$$\rho = \frac{f_1}{g}$$

$$K = -4\left(\frac{\sigma}{E}\right)^2 - m^2\frac{\sigma}{E}\left[\frac{3}{8}f_1^2 - \frac{1}{2}gf_1 + \frac{1}{2}g^2\right]$$

$$\frac{\sigma R}{Et}\gamma\left(\frac{3}{4}\rho - \frac{1}{2}\right) = \frac{1}{8}\left[(\gamma\eta)^2\left(\frac{533}{800}\rho^3 - \frac{687}{400}\rho^2 + \frac{279}{200}\rho - \frac{1}{4}\right) + (\gamma\eta)\left(\frac{15}{8}\rho^2 - \frac{5}{2}\rho\right)\right.$$
$$\left. + \left(\frac{3}{2}\rho - 1\right)\right] + \frac{1}{3(1-\nu^2)}\gamma^2(\rho - 1)$$

$$\frac{\sigma R}{Et}\gamma\left(\frac{1}{2}\rho - 1\right) = \frac{1}{8}\left[(\gamma\eta)^2\left(\frac{229}{400}\rho^3 - \frac{279}{200}\rho^2 + \frac{3}{4}\rho - \frac{1}{2}\right) + (\gamma\eta)\left(\frac{5}{4}\rho^2\right) + (\rho - 2)\right]$$
$$+ \frac{1}{3(1-\nu^2)}\gamma^2(\rho - 2)$$

$\frac{10}{16}$ $\frac{10}{8}$ $\frac{2}{4}$

$$\frac{\sigma R}{Et}\gamma(3\rho-2) = (\gamma\eta)^2\left(\frac{533}{1600}\rho^3 - \frac{687}{800}\rho^2 + \frac{279}{400}\rho - \frac{1}{8}\right) + (\gamma\eta)\left(\frac{15}{16}\rho^2 - \frac{5}{4}\rho\right) + \left(\frac{3}{4}\rho - \frac{1}{2}\right) + \frac{2}{3(1-\nu^2)}\gamma^2(2\rho-2)$$

$$\frac{\sigma R}{Et}\gamma(\rho-2) = (\gamma\eta)^2\left(\frac{229}{1600}\rho^3 - \frac{279}{800}\rho^2 + \frac{75}{400}\rho - \frac{1}{8}\right) + (\gamma\eta)\left(\frac{5}{16}\rho^2 + 0\right) + \left(\frac{1}{4}\rho - \frac{1}{2}\right) + \frac{2}{3(1-\nu^2)}\gamma^2(\rho-2)$$

$$0 = (\gamma\eta)^2\left(\frac{154}{1600}\rho^4 - \frac{150}{800}\rho^3 - \frac{54}{400}\rho^2 - \frac{25}{100}\rho\right) + (\gamma\eta)\left(\frac{5}{4}\rho^2 + 0\right) + (-\rho + 0) + \frac{2}{3(1-\nu^2)}\gamma^2(\rho^2 - 4\rho)$$

$$+ (\gamma\eta)^2\left(+\frac{304}{800}\rho^3 - \frac{408}{400}\rho^2 + \frac{102}{100}\rho\right) + (\gamma\eta)\left(\frac{5}{4}\rho^2 - \frac{5}{2}\rho\right) + (\rho) + \frac{2}{3(1-\nu^2)}\gamma^2(+4\rho)$$

$$0 = (\gamma\eta)^2\left(\frac{77}{800}\rho^3 + \frac{77}{400}\rho^2 - \frac{231}{200}\rho + \frac{77}{100}\right) + (\gamma\eta)\left(\frac{5}{2}\rho - \frac{5}{2}\right) + \frac{2}{3(1-\nu^2)}\gamma^2(\rho-2)$$

$$\boxed{\begin{aligned}&\left\{\frac{77}{800}(\gamma\eta)^2\right\}\rho^3 + \left\{\frac{77}{400}(\gamma\eta)^2\right\}\rho^2 + \left\{-\frac{231}{200}(\gamma\eta)^2 + \frac{5}{2}(\gamma\eta) + \frac{2}{3(1-\nu^2)}\gamma^2\right\}\rho \\ &\qquad + \left\{\frac{77}{100}(\gamma\eta)^2 - \frac{5}{2}(\gamma\eta) - \frac{4}{3(1-\nu^2)}\gamma^2\right\} = 0\end{aligned}}$$

$$\boxed{\gamma = 0.10, \quad \eta = 10, \ \xi = 10.5051 \ \gamma\eta = 1}$$

$\lambda = -0.0480814$

$$0.09625\rho^3 + 0.19250\rho^2 + 1.352326\rho - 1.744652 = 0$$

$$F(\rho) - \rho^3 + 2.00000\rho^2 + 14.05014\rho - 18.12625 = 0$$

$$F'(\rho) = 3\rho^2 + 4.00000\rho + 14.05014$$

$$F(1.05) = -0.010978 \qquad F'(1.05) = 21.558$$

$$\underline{0.00051}$$

$$F(1.05051) = 0$$

$$\rho^2 + 3.05051\rho + 17.2547 = 0$$ no here Real Root !!!

$$\boxed{\rho = 1.05051,} \quad \rho^2 = 1.10357, \quad \rho^3 = 1.15931$$

$$\boxed{\frac{\sigma R}{Et} = \frac{2}{3(1-\nu^2)}\gamma + \frac{1}{\gamma(\rho-2)}\left\{(\gamma\eta)^2(0.143125\rho^3 - 0.34875\rho^2 + 0.1875\rho - 0.1250) + (\gamma\eta)\,0.3125\rho^2\right\} + \frac{1}{4\gamma}}$$

For this particular case

$$\frac{\sigma R}{Et} = 0.07326 + 10\left\{\frac{0.143125\rho^3 - 0.03625\rho^2 + 0.1875\rho - 0.1250}{-0.94949} + 0.25\right\}$$

$$= 0.07326 + 0.41580 = \underline{\underline{0.4891}}$$

$$(\gamma\xi) = 1.05051$$

$$(\gamma\xi)^2 = 1.103571$$

$$\dot{\mathcal{E}} = 0.23919 + (10.5051)^2\Big[0.004310824(-\lambda)^4 - 0.008621148(-\lambda)^3$$

$$+ 0.056220149(-\lambda)^2 - 0.010873779(-\lambda) + 0.009121777\Big]$$

$$= \underline{1.2024} \qquad (0.9502350).$$

$$\Theta = + \quad 0.\underline{2653712}$$

Check !!!

$$\boxed{\frac{\sigma R}{Et} = \frac{2}{3(1-\nu^2)}\gamma\,\frac{2\rho-2}{3\rho-2} + \frac{1}{\gamma(3\rho-2)}\Big\{(\gamma\eta)^2(0.333125\rho^3 - 0.85875\rho^2 + 0.6975\rho - 0.125) + (\gamma\eta)(0.9375\rho^2 - 1.250\rho) + (0.25\rho - 0.5)\Big\}}$$

$$= \frac{0.2}{3(1-\nu^2)}\,\frac{0.10102}{1.15153} + \frac{10}{1.15153}\Big\{0.333125\rho^3 + 0.07875\rho^2 + 0.1975\rho - 0.625\Big\}$$

$$= \underline{\underline{0.48907}} \qquad O.K.$$

$\left(\frac{\varepsilon R}{t}\right) = 0.9748 \qquad \Phi = +0.124455$

$\eta = 10 \quad \boxed{\gamma = 0.144 \qquad \gamma\eta = 1.44} \quad \rho = 10.7961, \quad \lambda = 0.0737316$

$$0.199584\rho^3 + 0.399168\rho^2 + 1.220163\rho - 2.033710 = 0$$

$$F(\rho) = \rho^3 + 2.00000\rho^2 + 6.113631\rho - 10.18974 = 0$$

$$F'(\rho) = 3\rho^2 + 4.0000\rho + 6.113631$$

$F(1) = -1.07611 \qquad F'(1) = 13.113631$

$F(1.082) = +0.03338 \qquad F'(1.082) = 13.954$

$\frac{.00239}{1.07961}$

$F(1.07961) = +0.00006$, O.K.

$$\rho^2 + 3.07961\rho + 9.43841 = 0$$ No more real Root

$\gamma^2 = 0.020736$ $\qquad (\gamma\xi) = 1.5546384$

$$(\gamma\xi)^2 = 2.4169006$$

$$\xi = 0.0461446 + (10.7951)^2 \{ 0.009441018(-\lambda)^4 - 0.018882036(-\lambda)^3$$

$$+ 0.085829781(-\lambda)^2 - 0.015660708(-\lambda) + 0.006603078 \}$$

$$= \underline{0.7347181} \qquad (0.847512)$$

$$\Theta = -\ 0.1503705$$

$\rho = 1.07961, \quad \rho^2 = 1.16555, \quad \rho^3 = 1.25834$

$$\frac{\sigma R}{Et} = 0.105495 + 6.944444\left\{\frac{0.296784\rho^3 - 0.273168\rho^2 + 0.368800\rho - 0.2592}{-0.92039} + 0.25\right\}$$

$$= 0.105495 + 0.109257 = \underline{0.2148}$$

Check

$$\frac{\sigma R}{Et} = \frac{0.288}{2.73}\,\frac{0.15922}{1.23883} + \frac{6.94444}{1.23883}\left\{0.690768\rho^3 - 0.430704\rho^2 + 0.396336\rho - 0.7592\right\}$$

$$= 0.0135587 + 0.201254 = \underline{0.214813}$$

$\frac{\varepsilon R}{t} = 0.92999$ $\qquad \Phi = +0.167600$

$\boxed{\gamma = 0.144 \quad n = 15, \quad (n\gamma) = 2.16}$ $\xi = 17.0025,$

$0.449064\rho^3 + 0.898128\rho^2 + 0.0264230\rho - 1.837870 = 0$ $\qquad \lambda = \underline{0.1177768}$

$F(\rho) = \rho^3 + 2.000000\rho^2 + 0.0588402\rho - 4.092668 = 0$

$F'(\rho) = 3\rho^2 + 4.000\rho + 0.0588402$

$F(1.134) = +0.004243 \qquad F'(1.134) = 8.4527$

$$\frac{50}{1.13350}$$

$F(1.13350) = 0, \qquad \rho^2 + 3.13350\rho + 3.61066 = 0$ no more real root.

$\gamma^2 = 0.020736$, $(f\zeta) = 2.4483600$

$(f\zeta)^2 = 5.9944667$

$$\xi = 0.3350094 + (17.0025)^2 \{ 0.023415886(-\lambda)^4 - 0.046831771(-\lambda)^3$$

$$+ 0.113809542(-\lambda)^2 - 0.044754594(-\lambda) + 0.007769092 \}$$

$$(5.1061960)$$

$$= \underline{1.6932169}$$

$$\theta = -0.668432$$