时代教育·国外高校优秀教材精选

Mc Graw Hill Education

（英文版·原书第5版）

测量系统应用与设计 下册

Measurement Systems Application and Design

（美）欧内斯特 O.德贝林
（Ernest O.Doebelin） 著

机械工业出版社
CHINA MACHINE PRESS

时代教育·国外高校优秀教材精选

测量系统应用与设计 下册

（英文版·原书第5版）

Measurement Systems Application and Design

（美） 欧内斯特 O. 德贝林
（ERNEST O. DOEBELIN） 著

机械工业出版社

CONTENTS

试读结束：需要全本请在线购买： www.ertongbook.com

教师信息反馈表

时代教育·国外高校优秀教材精选书目

CHAPTER 6

Pressure and Sound Measurement

6.1 STANDARDS AND CALIBRATION

Pressure is not a fundamental quantity, but rather is derived from force and area, which in turn are derived from mass, length, and time, the latter three being fundamental quantities whose standards have been discussed earlier. Pressure "standards" in the form of very accurate instruments are available, though, for calibration of less accurate instruments. However, these "standards" depend ultimately on the fundamental standards for their accuracy. The basic standards[1] for pressures ranging from medium vacuum (about 10^{-1} mmHg) up to several hundred thousand pounds per square inch are in the form of precision mercury columns (manometers) and deadweight piston gages. For pressures in the range 10^{-1} to 10^{-3} mmHg, the McLeod vacuum gage is considered the standard. For pressures below 10^{-3} mmHg, a pressure-dividing technique allows flow through a succession of accurate orifices to relate the low downstream pressure to a higher upstream pressure (which is accurately measured with a McLeod gage).[2]

This technique can be further improved by substituting a Schulz hot-cathode or radioactive ionization vacuum gage for the McLeod gage. Each of these must be calibrated against a McLeod gage at one point (about 9×10^{-2} mmHg), but their known linearity is then used to extend their accurate range to much lower pressures.[3]

---

[1] D. P. Johnson and D. H. Newhall, "The Piston Gage as a Precise Pressure-Measuring Instrument," *Instrum. Contr. Syst.*, p. 120, April 1962; "Errors in Mercury Barometers and Manometers," *Instrum. Contr. Syst.*, p. 121, March 1962; "2″ Range Hg Manometer," *Instrum. Contr. Syst.*, p. 152, September 1962.

[2] J. R. Roehrig and J. C. Simons, "Calibrating Vacuum Gages to 10^{-9} Torr," *Instrum. Contr. Syst.*, p. 107, April 1963.

[3] J. C. Simons, "On Uncertainties in Calibration of Vacuum Gages and the Problem of Traceability," *Transactions of 10th National Vacuum Symposium*, p. 246, Macmillan, New York, 1963.

Gage and Pressure Measurement Uncertainties

Type of Instrument	Range	Uncertainty
Gas-operated PG	1.4 kPa to 17 MPa	±57 ppm
Oil-operated PG	700 kPa to 100 MPa	±63 ppm
	100 MPa to 280 MPa	±60 to ±150 ppm
Oil-operated PG	40 to 400 MPa	±186 ppm

The inaccuracies of the above-mentioned pressure standards are summarized graphically in Fig. 6.1*a*,[4] with Fig. 6.1*b*[5] giving more recent data. Since the above-mentioned pressure standards are also pressure-measuring instruments (of the highest quality and used under carefully controlled conditions), their operating principles and characteristics are not discussed here since they are adequately covered later.

6.2 BASIC METHODS OF PRESSURE MEASUREMENT

Since pressure usually can be easily transduced to force by allowing it to act on a known area, the basic methods of measuring force and pressure are essentially the same, except for the high-vacuum region where a variety of special methods not directly related to force measurement are necessary. These special methods are described in the section on vacuum measurement. Other than the special vacuum techniques, most pressure measurement is based on comparison with known deadweights acting on known areas or on the deflection of elastic elements subjected to the unknown pressure. The deadweight methods are exemplified by manometers and piston gages while the elastic deflection devices take many different forms.

6.3 DEADWEIGHT GAGES AND MANOMETERS

Figure 6.2 shows the basic elements of a deadweight or piston gage. Such devices are employed mainly as standards for the calibration of less accurate gages or transducers. The gage to be calibrated is connected to a chamber filled with fluid whose pressure can be adjusted by some type of pump and bleed valve. The chamber also connects with a vertical piston-cylinder to which various standard weights may be applied. The pressure is slowly built up until the piston and weights are seen to "float," at which point the fluid "gage" pressure (pressure above atmosphere) must equal the deadweight supported by the piston, divided by the piston area.

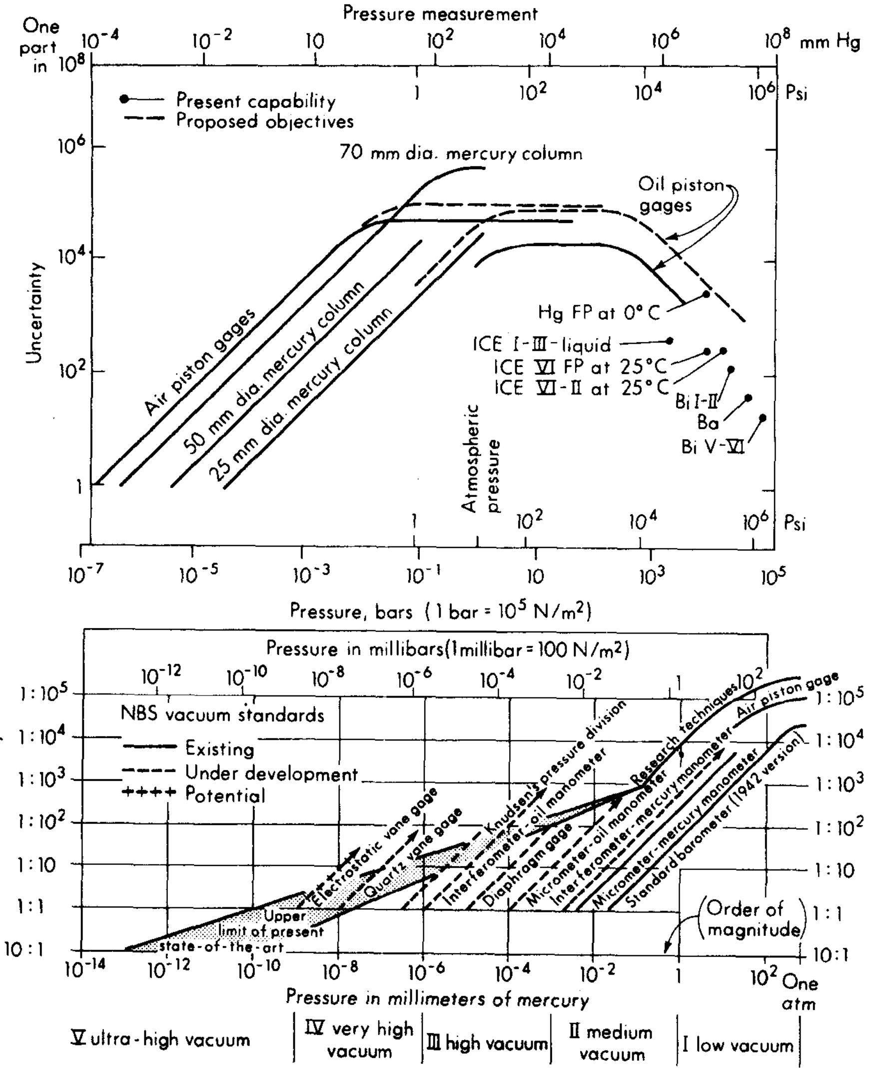
For highly accurate results, a number of refinements and corrections are necessary. The frictional force between the cylinder and piston must be reduced to a minimum and/or corrected for. This is generally accomplished by rotating either the piston or the cylinder. If there is no axial relative motion, this rotation should reduce the axial effects of dry friction to zero. There must, however, be a small clearance between the piston and the cylinder and thus an axial flow of fluid from

---

[4] "Accuracy in Measurements and Calibrations," *NBS Tech. Note* 262, 1965.

[5] *NBS Spec. Publ.* 250, 1987.

试读结束：需要全本请在线购买： www.ertongbook.com



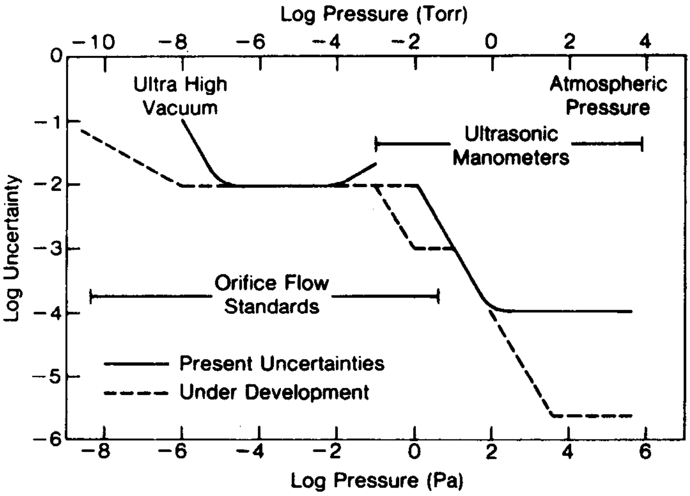
(a)

Figure 6.1
Pressure/vacuum standards.

the high-pressure end to the low-pressure end. This flow produces a viscous shear force tending to support part of the deadweight. This effect can be estimated from theoretical calculations.[6] However, it varies somewhat with pressure since the

---

[6] R. J. Sweeney, "Measurement Techniques in Mechanical Engineering," p. 104, Wiley, New York, 1953.



(*b*)

Figure 6.1
(Concluded)

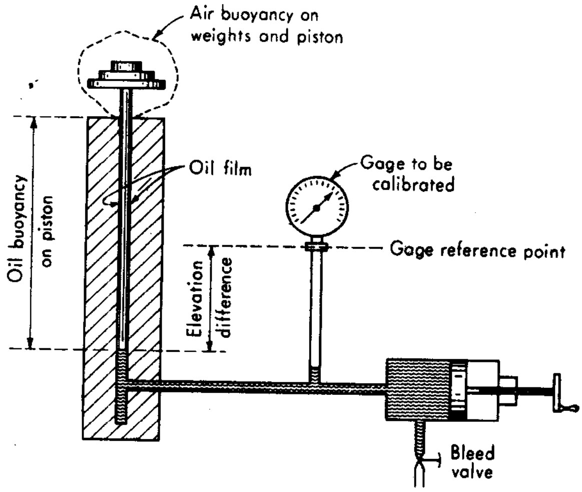


Figure 6.2
Deadweight gage calibrator.

piston and cylinder deform under pressure, thereby changing the clearance. The clearance between the piston and cylinder also raises the question of which area is to be used in computing pressure. The effective area generally is taken as the average of the piston and cylinder areas. Further corrections are needed for temperature effects on areas of piston and cylinder, air and pressure-medium buoyancy effects, local gravity conditions, and height differences between the lower end of the piston and the reference point for the gage being calibrated. Special designs and techniques allow use of deadweight gages for pressures up to several hundred thousand pounds per square inch. An improved design, the controlled-clearance piston gage,[7] employs a separately pressurized cylinder jacket to maintain the effective area constant (and thus achieve greater accuracy) at high pressures, which cause expansion and error in uncompensated gages.

Since the piston assembly itself has weight, conventional deadweight gages are not capable of measuring pressures lower than the piston weight/area ratio ("tare" pressure). This difficulty is overcome by the tilting-piston gage[8] in which the cylinder and piston can be tilted from vertical through an accurately measured angle, thus giving a continuously adjustable pressure from 0 lb/in^2 gage up to the tare pressure. The described gage uses nitrogen or other inert gas as the pressure medium and covers the range 0 to 600 lb/in^2 gage, having two interchangeable piston-cylinders and 14 weights. The accuracy is 0.01 percent of reading in the range 0.3 to 15 lb/in^2 gage and 0.015 percent of reading in the range 2 to 600 lb/in^2 gage. The tilting feature is used for the ranges 0 to 0.3 and 0 to 2.0 lb/in^2 gage; higher pressures are obtained in increments by the addition of discrete weights.

Some piston gages have been highly instrumented and automated to allow more convenient and rapid use. One such line[9] includes sensors for relative humidity, barometric pressure, ambient temperature, piston/cylinder temperature, piston rotation speed and acceleration, and piston drop rate. These readings are manipulated in the software to provide a readout of the calibration pressure. A typical formula[10] showing the relations is

$$\text{Gauge pressure} = \frac{Mg_l\left(1 - \dfrac{\rho_{\text{air}}}{\rho_{\text{mass}}}\right) + \pi D T}{A_{(20,0)} \cdot [1 + (\alpha_p + \alpha_c)\cdot(\theta - 20)] \cdot (1 + \lambda P)} - (\rho_{\text{fluid}} - \rho_{\text{air}}) \cdot g_l\, h \qquad \textbf{(6.1)}$$

where M = the total mass load
g_l = the local acceleration of gravity
ρ = density
D = piston diameter (computed from $A_{(20,0)}$, the piston/cylinder effective area at 20°C and 0 gage pressure)

---

[7] D. H. Newhall and L. H. Abbot, "Controlled-Clearance Piston Gage," *Meas. & Data*, January–February 1970.

[8] Ruska Instrument Corp., Houston, TX, www.ruska.com.

[9] DH Instruments, Inc., Phoenix, AZ, 602-431-9100 (www.dhinstruments.com).

[10] DH Instruments, "Precision Pressure Measurement Handbook," Ametek, Largo, FL, 727-536-7831 (www.ametek.com/tci). The handbook contains the following relevant entries: "Uncertainty Analysis for Pressure Defined by a PG7601, 7102 or 7302 Piston Gage"; "PG7000 Differential Mode for Defining Low and Negative Differential Pressure at Various Static Pressures"; "Increasing the Accuracy of Pressure Measurement Through Improved Piston Gage Effective Area Determination"; "Fundamental Differential Pressure Calibrations."

T = gage-fluid surface tension

α_p, α_c = thermal expansion coefficients of piston and cylinder, respectively

θ = the piston/cylinder temperature

λ = piston/cylinder elastic deformation coefficient

h = the height difference between piston gage reference level and the reference level of the unit under calibration

This equation makes clear how various error sources must be corrected to achieve the highest possible accuracy.

A very convenient pressure standard[11] (although not really a deadweight gage) combines a precision piston gage with a magnetic null-balance laboratory scale[12] (Fig. 6.3). The gas or liquid pressure to be measured (generated and regulated by a system external to the pressure standard) is applied to one end of a rotating piston; the other end of the piston is supported by the "weighing platform" of the laboratory scale, which measures the pressure force and gives a digital readout of 40,000 counts full scale. Tungsten carbide piston/cylinders allow clearances less than 1 μm; the high hardness and elastic modulus maintain precision in the face of potential wear and pressure expansion. Piston-cylinder pairs are easily interchanged to give five full-scale ranges from 80 to 1,200 lb/in^2. Since deadweights are *not* utilized to measure the pressure force, periodic recalibration against a set of four precision masses is required. However, this is made quick and easy by using the scale's autotare feature and a simple screwdriver span adjustment. Instrument uncertainty on the 80 lb/in^2 range (other ranges are proportional) is $\pm(0.004 + 10^{-4}p)$ lb/in^2, where p is the actual pressure in pounds per square inch and repeatability is ±1 count.

Deadweight gages may be employed for absolute- rather than gage-pressure measurement by placing them inside an evacuated enclosure at (ideally) 0 lb/in^2 absolute pressure. Since the degree of vacuum (absolute pressure) inside the enclosure must be known, this really requires an additional independent measurement of absolute pressure.

The manometer in its various forms is closely related to the piston gage, since both are based on the comparison of the unknown pressure force with the gravity force on a known mass. The manometer differs, however, in that it is self-balancing, is a deflection rather than a null instrument, and has continuous rather than stepwise output. The accuracies of deadweight gages and manometers of similar ranges are quite comparable; however, manometers become unwieldy at high pressures because of the long liquid columns involved. The U-tube manometer of Fig. 6.4 usually is considered the basic form and has the following relation between input and output for static conditions:

$$h = \frac{p_1 - p_2}{\rho g} \tag{6.2}$$

---

[11] Model 20400, DH Instruments, Inc.; P. Delajoud and M. Girard, "The Development of a Digital Read-Out Primary Pressure Standard," DH Instruments, Pittsburgh, PA, 1981, www.dhinstruments.com.

[12] Mettler Instrument Corp., Hightstown, NJ, www.mt.com/pro.

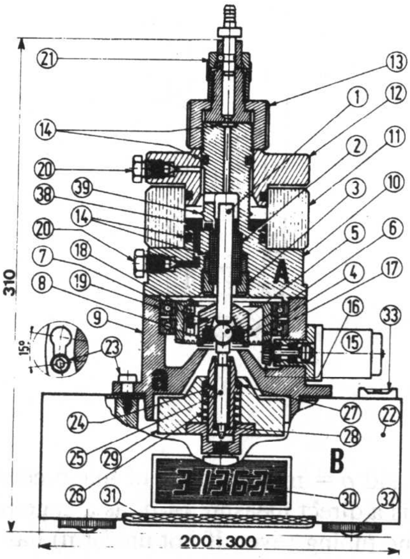


Figure 6.3
Pressure standard using electromagnetic balance. The digital standard is made up of a piston-cylinder measuring element (A + a) and an electronic dynamometer (B) manufactured Mettler Instrument.

Measuring element (A + a):

1. Piston in tungsten carbide
2. Cylinder in tungsten carbide
3. Cylinder retaining nut
4. Piston head
5. Ball in tungsten carbide
6. Ball bearing to center the ball (5)
7. Drive bearing
8. Retaining ring for ball (5)
9. Rotation mechanism housing
10. Piston-cylinder housing
11. Acrylic sight glass
12. Cover
13. Retaining nut
14. O-ring seals
15. Electric drive motor
16. Drive pinion
17. Toothed drive wheel
18. Drive bearing pin
19. Toothed wheel bearings
20. Purge screws
21. Quick-connect system (standard threads available)

Electronic dynamometer B:

22. Housing

23. 3 pins giving a quick release facility for the measuring assembly (A + a). (*After 15° rotation on the pins a locking mechanism secures the measuring element* to *the dynamometer.*)

24. Force-limiting guide

25. Coupling rod

26. Force-limiting spring

27–28. 2 vibration dampers

29. Force receiving plate

30. 40,000 points, 5-digit display

31. Auto-zero bar

32. 2 leveling screws

33. Bubble level

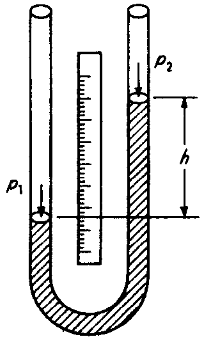


Figure 6.4
U-tube manometer.

where $g \triangleq$ local gravity and $\rho \triangleq$ mass density of manometer fluid. If p_2 is atmospheric pressure, then h is a direct measure of p_1 as a gage pressure. Note that the cross-sectional area of the tubing (even if not uniform) has no effect. At a given location (given value of g) the sensitivity depends on only the density of the manometer fluid. Water and mercury are the most commonly used fluids. To realize the high accuracy possible with manometers, often a number of corrections must be applied. When visual reading of the height h is employed, the engraved scale's temperature expansion must be considered. The variation of ρ with temperature for the manometer fluid used must be corrected and the local value of g determined. Additional sources of error are found in the nonverticality of the tubes and the difficulty in reading h because of the meniscus formed by capillarity. Considerable care must be exercised in order to keep inaccuracies as small as 0.01 mmHg for the overall measurement.[13]

A number of practically useful variations on the basic manometer principle are shown in Fig. 6.5. The *cistern* or *well-type manometer* is widely utilized because of its convenience in requiring reading of only a single leg. The well area is made very large compared with the tube; thus the zero level moves very little when pressure is applied. Even this small error is compensated by suitably distorting the length scale. However, such an arrangement, unlike a U tube, is sensitive to nonuniformity of the tube cross-sectional area and thus is considered somewhat less accurate.

Given that manometers inherently measure the pressure *difference* between the two ends of the liquid column, if one end is at zero absolute pressure, then h is an indication of absolute pressure. This is the principle of the *barometer* of Fig. 6.5. Although it is a "single-leg" instrument, high accuracy is achieved by setting the zero level of the well at the zero level of the scale before each reading is taken. The pressure in the evacuated portion of the barometer is not really absolute zero, but rather the vapor pressure of the filling fluid, mercury, at ambient temperature. This is about 10^{-4} lb/in^2 absolute at 70°F and usually is negligible as a correction.

---

[13] A. J. Eberlein, "Laboratory Pressure Measurement Requirements for Evaluating the Air Data Computer," *Aeronaut. Eng. Rev.*, p. 53, April 1958.

试读结束：需要全本请在线购买： www.ertongbook.com