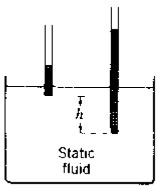
Chapter 4 Pressure Measurement

Contents

- Introduction
- Absolute pressure, Gauge pressure & differential pressure
- Pressure calibration
- Examples of pressure transducers
- Pressure measurement in fluid mechanics

What is pressure?

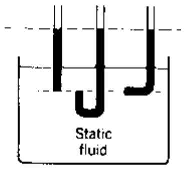
- In mechanics, pressure is force per unit area, i.e., $P = dF/dA$ (in a general sense, it is a type of compressive stress.)
- In hydraulics, pressure is specific weight times height , i.e., $\Delta P = \rho g \Delta h$.
  (Pressure is a local flow property and is position-dependent)
- In kinetics, pressure is molecular kinetic energy per unit volume, i.e., $P = 2\ KE / 3\ V$
- In thermodynamics, pressure is the work per unit volume, i.e., $P = (\delta Work + \delta Loss) / dV$

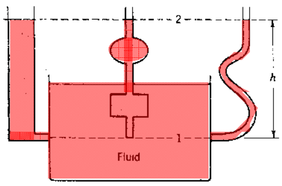


Phenomena observations

For fluid ***at rest***,

- Pressure measurements are usually expressed in the indirect means, e.g., a column of fluid.
- Pressure is the same in all directions at a given point
- Pressure is unaffected by the shape of the confining boundaries. (⇨a great variety of pressure transducers)
- Pressure is transferred undiminished throughout the confined fluid.





Units of pressure

- **Commonly used units of pressure:**
  1 Torr = 1 mmHg
  1 Pa (*pascal*) = 1 N/m^2 = 10 dyne/cm^2 (=1.4504 x10^{-4} lb$_f$/in^2)
  1 psi = 1 lb$_f$/in^2
- **1atm = 14.69595 psi = 760 Torr = 101,325 N/m^2**
  = 29.9213 in. Hg = 760 mmHg = 1.01325 bar
- **1 bar = 10^5 Pa = 14.5053 psi**
- **1 mmH_2O = 9.80665 Pa**

(standard atmosphere 1atm: 15°C, sea level)

Absolute & gauge pressure

There are customarily three ways to describe the pressure:

1.***Absolute pressure:(P_{abs})***

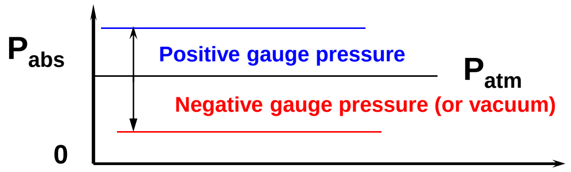
output pressure measured by an ideal vacuum pressure gauges.

2.***Gauge Pressure :(P_g)***

absolute pressure minus local atmospheric pressure

3.***Differential Pressure*** :

absolute pressure minus any known pressure



Pressure measuring instruments

Three major types of pressure measuring instruments:

(a) manometer: low range,

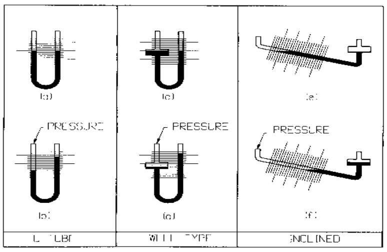
(b) dial gage: middle range,

(c) electronic transducers: remote, automatic recording

Pender (1997)

Characteristic	Manometer	Dial gage	Electronic transducer
Pressure range	62 Pa–339 kPa (0.25 in. H_2O–100 in. Hg)	62 Pa–700 MPa (0.01–100,000 psi)	25 Pa–700 MPa (0.004–100,000 psi)
Accuracy range	0.25 Pa (0.001 in. H_2O) to 2% full scale	0.066%–5% full scale	0.003%–3% full scale
Frequency response	< 10 Hz	< 10 Hz	DC to 1 MHz
Electronic output	No	No	Yes
Temperature range	−62°C to +66°C	−32°C to +54°C	−271°C to +400°C
Media compatibility	Gas	Gas or liquid	Gas or liquid
Cost (U.S.)	\$100–\$2000	\$10–\$3000	\$50–\$10,000

Manometer



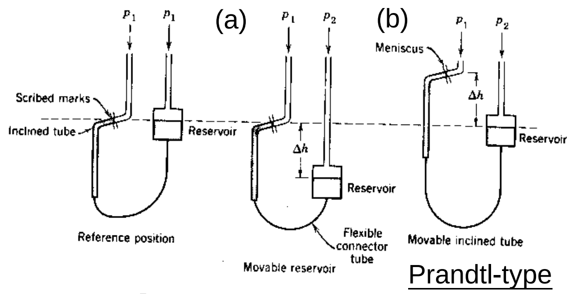
Pender (1997)

- Measuring range:
  62 Pa ~ 339kPa
- Accuracy:
  0.025% ~ 2% of full scale
- Disadvantages:
  result is ρ and g-dependent, lack of recording and limited frequency response

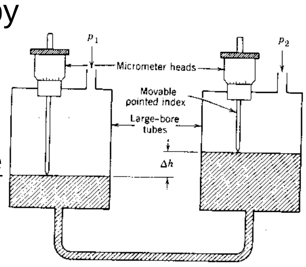
Type	Full scale range	Accuracy range
U-tube	500 Pa–339 kPa (2 in. H_2O–100 in. Hg)	0.25 Pa (0.001 in. H_2O)–2% of full scale
Well	1 kPa–339 kPa (4 in. H_2O–100 in. Hg)	0.01% of full scale–2% of full scale
Inclined	62 Pa–5 kPa (0.25 in. H_2O–20 in. H_2O)	0.025% of full Scale–1% of full scale

Micromanometer

- Measuring range:
  up to 20”H_2O
- Accuracy:
  0.001~0.0005”
- Simple
- Disadvantages:
  observing by eyes



Prandtl-type



Micrometer-type

Benedict (1984)

- Capillary and meniscus errors are minimized
- uncertainty of 0.001” of water

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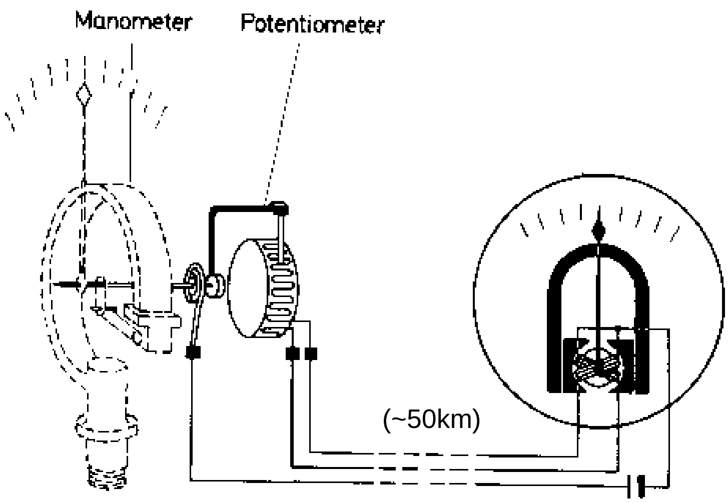
By An-Bang Wang
National Taiwan University Institute of Applied Mechanics

Manometer for remote use



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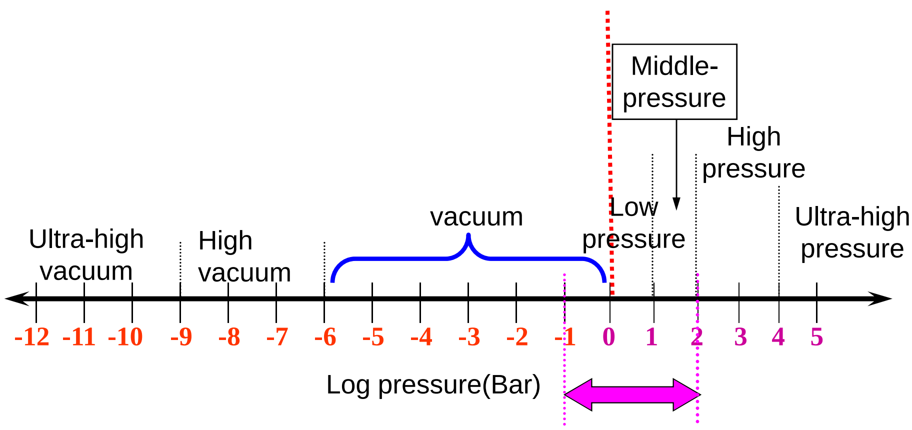
Range of pressure measurement



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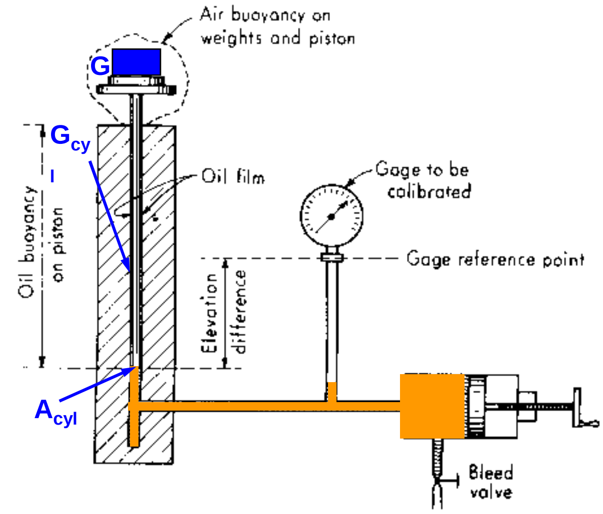
Deadweight gauge calibrator



$P = (G_{cyl} + G)/A_{cyl}$

Main error come from the friction

calibration uncertainty 0.01 ~ 0.05% of reading

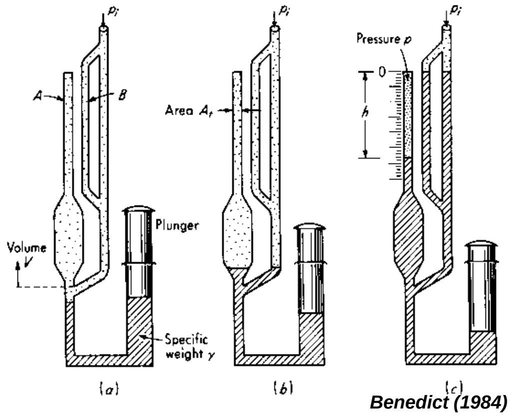
Doebelin (1990)

Low Pressure measurement

- For pressure from 1 to 10^{-5} mmHg, McLeod vacuum gage is commonly used.
- Uncertainty: 3~0.5% of reading
- lack of continuous out
- Based on Boyle's law

$$p_i V = p A_t h$$
$$= (p_i + \gamma h) A_t h$$

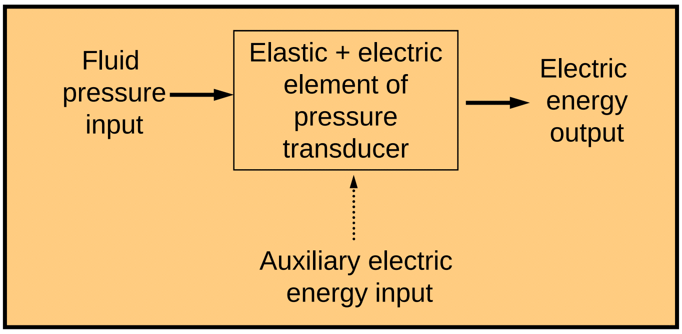
$$p_i = \frac{\gamma A_t h^2}{V - A_t h} \approx \frac{\gamma A_t h^2}{V}$$



Benedict (1984)

What is pressure transducer ?

Pressure transducers are devices those convert an applied pressure into a sensible signal (electric signal or others) through a sensor (displacement, strain, piezoelectric response…etc.).



Choose a Pressure transducer

- Common classifications ：
  (a) displacement type (includes diaphragm type)
  (b) piezoelectric type
  (c) piezoresistive type
  (d) capacitance type
  (e) reluctance type

- The choice of transducer varies greatly depending on many factor like: pressure range, dynamic response, pressure media, dimensional restrictions, budget…etc.

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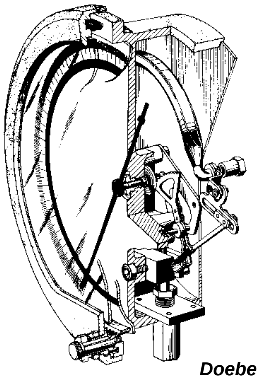
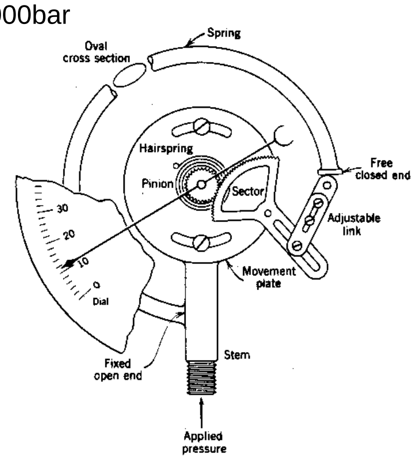
National Taiwan University Institute of Applied Mechanics

Bourdon gage

- Simple & robust
- Max. measuring range: 0.6 ~ 10,000bar
- Min. resolution: ~10 Torr
- accuracy: 1~1.6% of F.S.

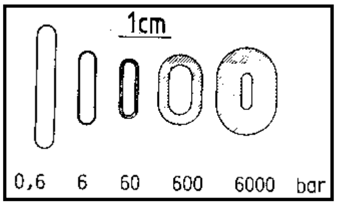


Doebelin (1990)

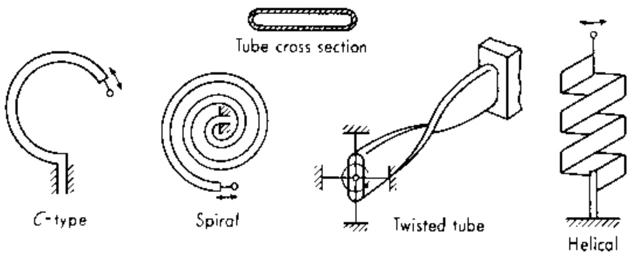


Benedict (1984)

Elastic element of pressure transducer



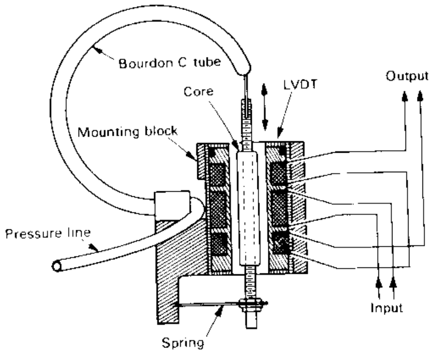
Ewald (1990)



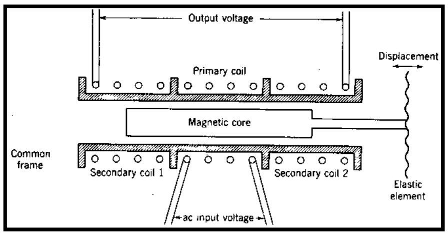
Doebelin (1990)

LVDT pressure transducer

- LVDT: Linear Variable Differential Transformer
- Limit frequency response ~ 10Hz



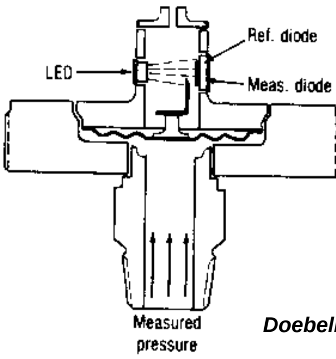
Doebelin (1990)



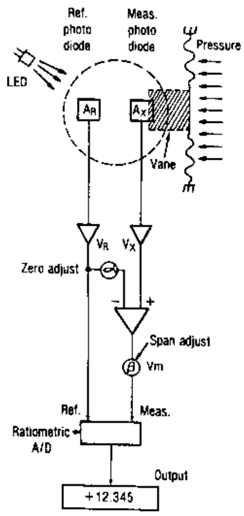
Benedict (1984)

Electro-optic transducer

- Infrared LED
- The reference and measurement photodiodes are equally affected by temperature change

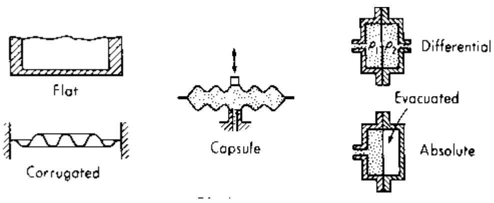


Doebelin (1990)

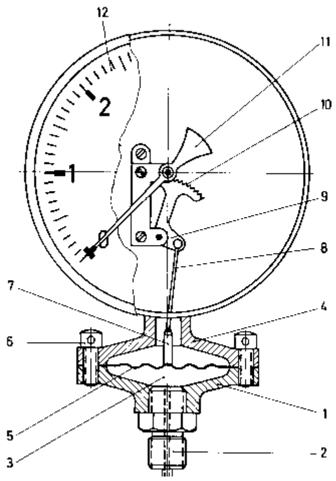


Diaphragm gage

- For low- and middle-pressure measuring range: 0.01 ~ 25bar
- min. resolution: ~10^{-3} Torr
- accuracy: < ~1.6% of F.S.

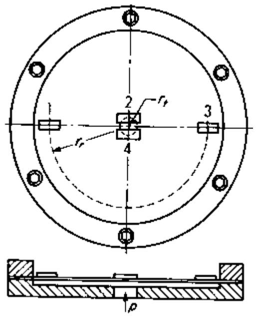


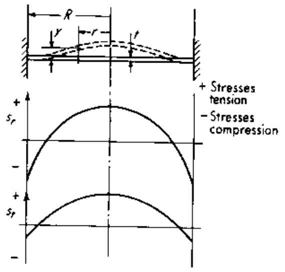
Doebelin (1990)

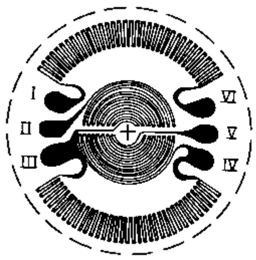


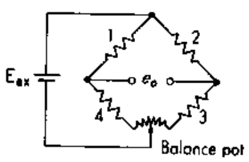
Bohl (1991)

Diaphragm type strain-gage pickup





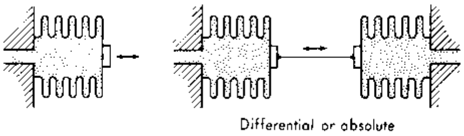




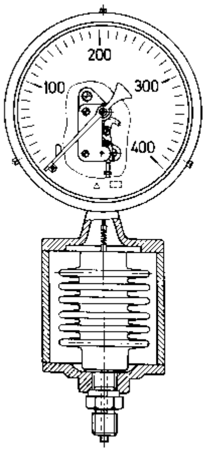
$$p = \frac{16Et^4}{3R^4(1-\nu^2)}\left[\frac{y_c}{t} + 0.488\left(\frac{y_c}{t}\right)^3\right]$$

- For y_c/t < 0.25, linearity within 0.3%
- Measuring range: 0 - 10 ~ 3,000 bar.
- Dynamic frequency: DC ~ 10kHz
- Accuracy: ~ 0.1%

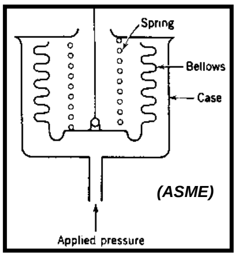
Bellow pressure transducer



Doebelin (1990)

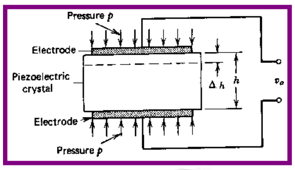


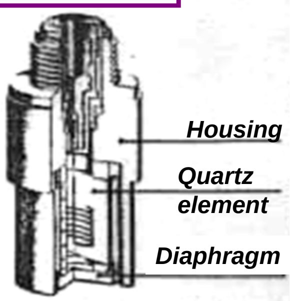
- Advantage: good linearity
- Measuring range: 6 ~ 100 mbar
- Min. resolution: ~ 0.1 Torr



Bohl (1991)

Piezoelectric transducer

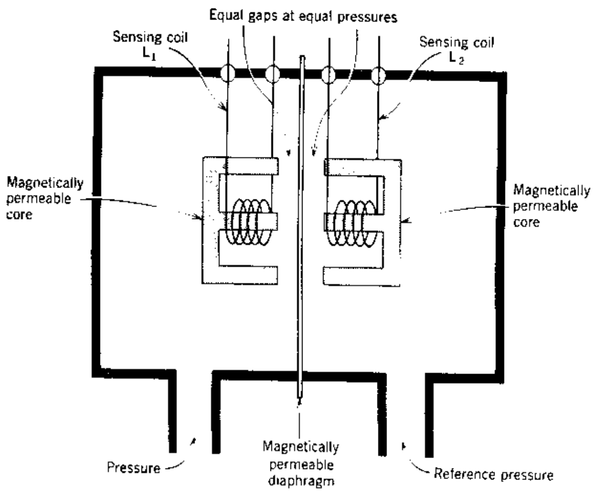




(Kistler Instrument Corp.)

- Suitable for high-frequency-changing and large pressure measurement, not suitable for low-frequency measurement
- Measuring range 100mbar ~ 100kpsi.
- Accuracy: 1 ~ 3%
- Resonant frequency: 0.25 ~ 0.5 MHz
- Temperature range: -200 up to 350^{o}C (error <1%)
- Max. gas temp 2000 ^{o}C (for short time)

Reluctance type transducer

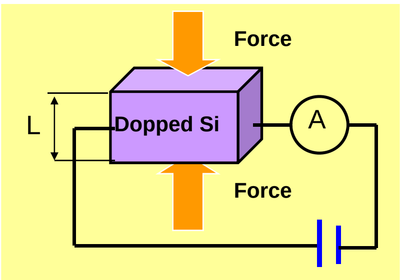


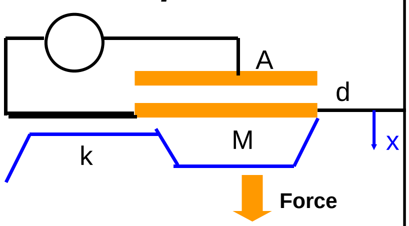
Benedict (1984)

MEMS-pressure transducers

- Based on sensing principle: piezo-resistive & capacitive

piezo-resistive ***capacitive***



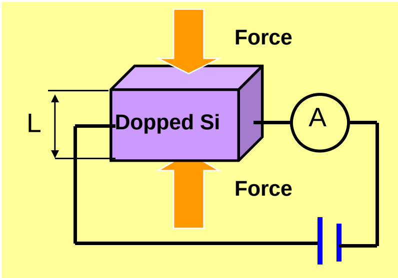


$$a = F / M = kx / M$$
$$C = C(a) = \varepsilon A / (d + x)$$
$$= \varepsilon A / (d + [M / k]\, a)$$

Piezoresistive effect

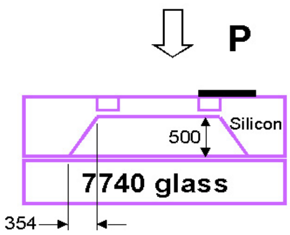
Force ➔volume changes
➔change of energy gap between the valence and the conduction bands
➔resistivity changes

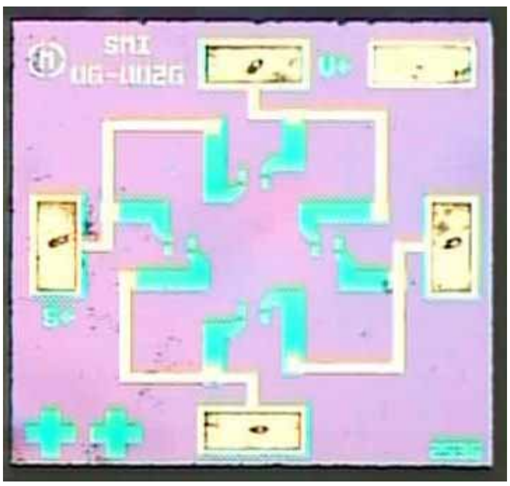
- $\boldsymbol{R = \rho L / A}$
  ➔$dR/R = d\rho/\rho + dL/L - dA/A$
  $= d\rho/\rho + (1+2\nu)dL/L$
  $= d\rho/\rho + (1+2\nu)\varepsilon$
- where ρ: resistivity, ν: Poisson ratio
- Gauge factor $G=(dR/R)/(dL/L)$
  $= d\rho/\rho\varepsilon + (1+2\nu)$



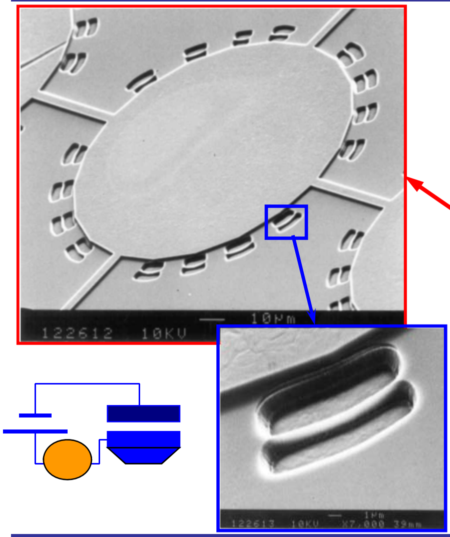
Characteristics:
- Gauge factor G= 50 ~ 100 (e.g., strain gage ~ 2)
- low cast
- Thermal zero drift
- $d\rho/\rho = [\pi_{ij}]\,\sigma$

Piezoresistive pressure transducer

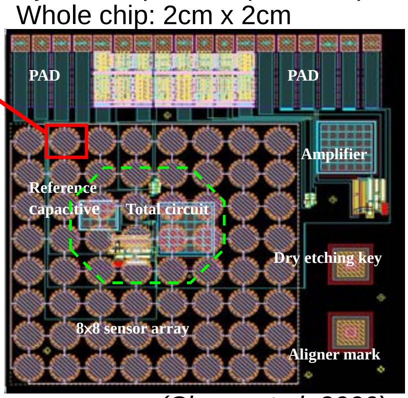




Capacitive Pressure Sensors

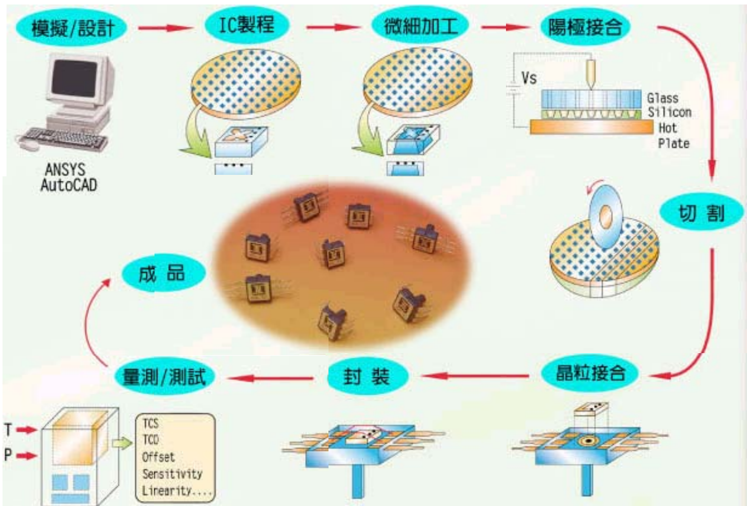


Insensitive to temperature
High sensitivity & precision
Low power consumption
By CMOS process (Low cost)
Whole chip: 2cm x 2cm



(Chang et al. 2000)

MEMS-Pressure sensor manufacturing



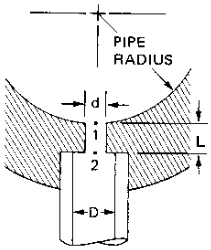
http://www.itri.org.tw/mems/chinese/result/result1.htm

Pressure measurements in moving fluid

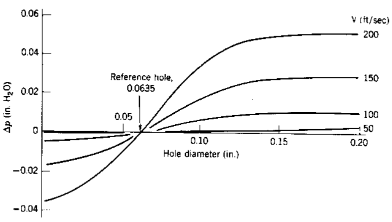
- **Difficulties: (a) sensing small pressure in large pressures, (b)interface with different liquid**
- **$P_0 = P_s + P_d$**
  P_0 : total (stagnation) pressure
  P_s : static pressure
  P_d : dynamics pressure
- **For laminar flow, all pressure are steady, but the pressure are time-dependent for turbulent case. Kilohertz response of pressure transducer is needed for the latter case.**

Static pressure measurement

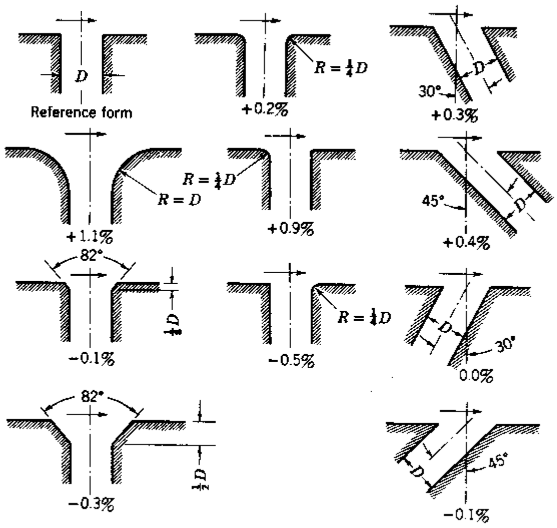
- Pressure tap are small circular hole drilled perpendicular to the wall surface for measuring static pressure.
- The corner of the hole should be sharp and squared off.
- The recommended geometries are all from experimental determination.
- The orifice must be burr-free, for burr heights less than 1/30d, errors are less than 1% of $\rho V^2/2$
- In pipe flows, several taps around the circumference can be made and connected together in ring.



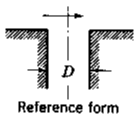
d ~ 1-3mm
1.5 < L/d < 6
D ≥ 2d

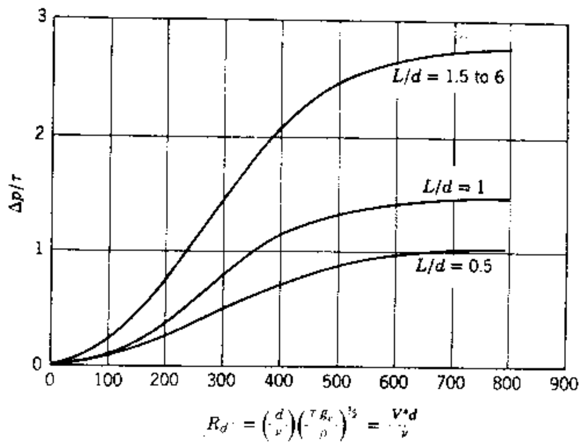


Static pressure measurement



Static pressure measurement





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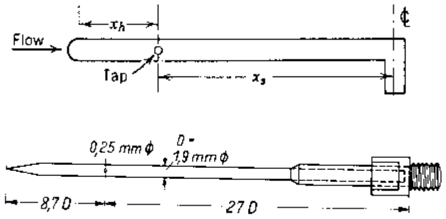
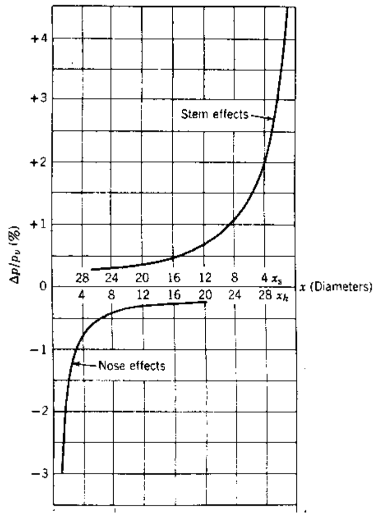
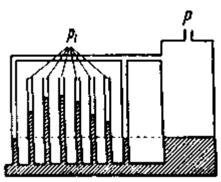
Static pressure tube



Supersonic static tube
(by Pankhurst & Holder)

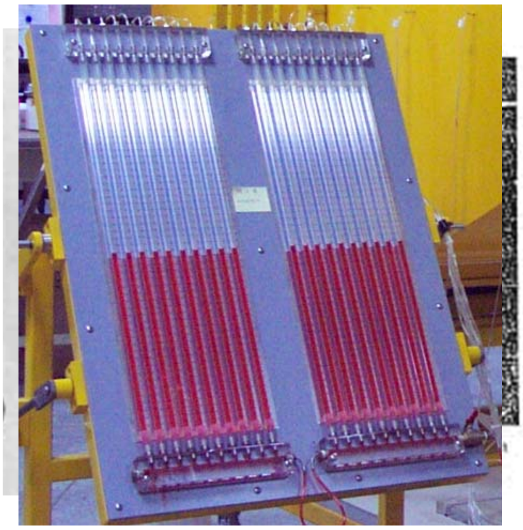


Multi-manometer



principle

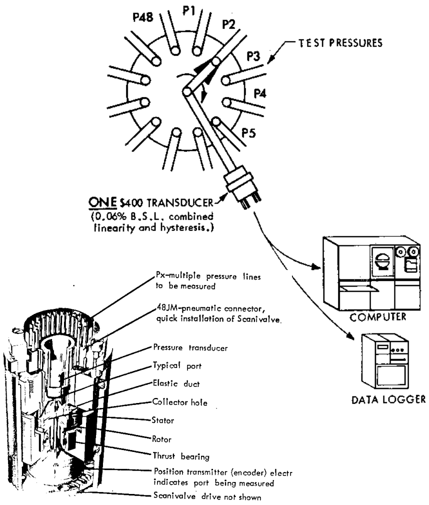
Recorded by camera



Scanivalve

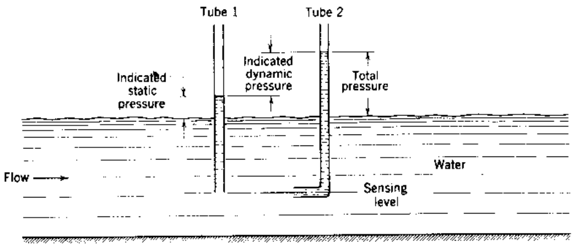
Advantage of scanivalve:
only one pressure sensor (and also one calibration) is needed

- Mechanical type :
  range:±70 mbar ~ 34 bar
  time resolution :
  3~5 measurements/s
- Electronic type :
  range :± 350mbar ~ 7bar
  time resolution : 10,000 measurements/s
  (all pressure sensor in one chip + multiplexer-preamplifier.)

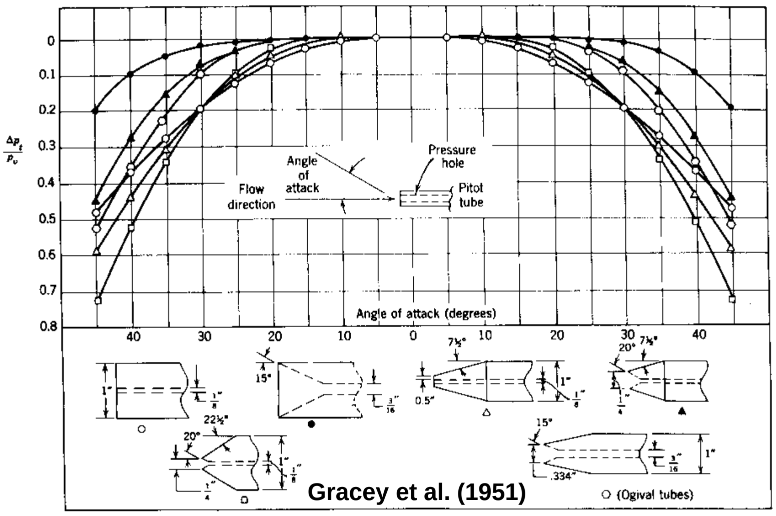


Total pressure measurement (I)

- Pitot tube since 1732
- Based on Bernoulli equation $P_0 = P_s + P_d$
- The mechanical leading on the stem is roughly estimated as two times of the dynamic head.
- A total head tube with hemispherical tip will read the total head accurately independent of the size of the orifice opening as long as the yaw is less than30.



Total pressure measurement (II)

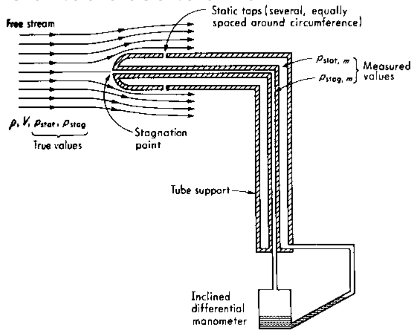


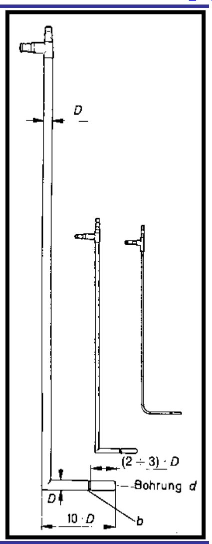
Gracey et al. (1951)

Dynamic pressure measurement (I)

Measurement of dynamic pressure

- Pitot-static tube (or Prandtl tube) is used to measure dynamic pressure and hence flow velocity.
- It should not be used at too low Reynolds numbers or too close to a wall.





Dynamic pressure measurement (II)

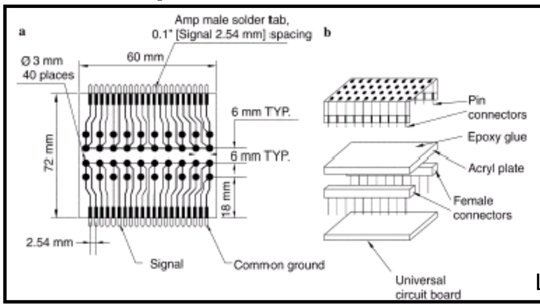
Other operation notes for Pitot-static tube

- Time constant :
  the response rate for Pitot-static tubes depends on (a) length and diameter of pressure passages and (b) displacement volume of manometer
  e.g. 1.6 mm-O.D tube: 15~60seconds in air
  0.8mm -O.D tube   up to 15min in air
  (standard tubes are usually over 1.6mm O.D)

- Turbulence effect :
  the measured pressure in isotropic turbulence is by Chue (1975): $\rho V^2/2 + \alpha \rho q^2$
  where is 1/6 for small scale turbulence and
  5/6 for large scale turbulence

Surface pressure measurement

- **Applications: flow unsteadiness, aerodynamic noise**
- **pin-holes produce measuring distortion**
- **piezoelectric film, e.g. Polyvinylidenfluorid PVDF (t ~ 25μm), is flexible and smooth and can be glued directly on the surface of measuring object (Nitsche et al. 1989).**



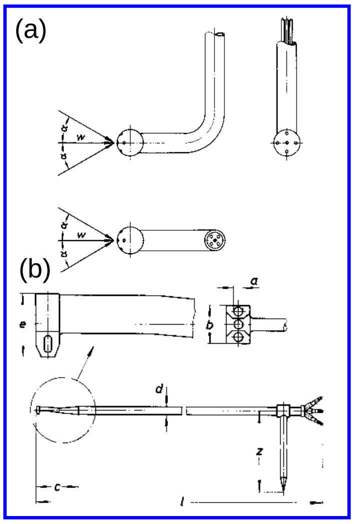
4 x 10 arrays
circular electrode: 3mm
spacing: 6mm

Lee & Sung (1999)

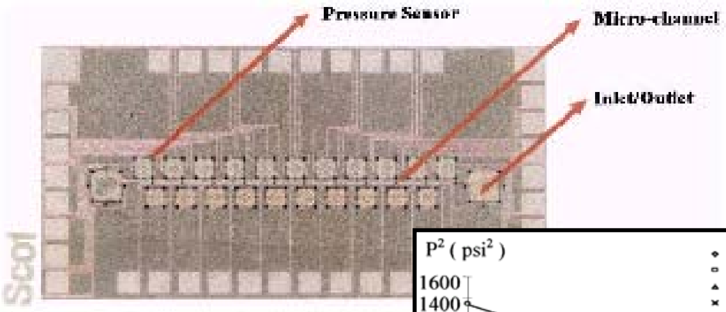
Modern Measuring Techniques of Thermo-fluids Mechanics *By An-Bang Wang* *National Taiwan University Institute of Applied Mechanics*

Flow direction measurement

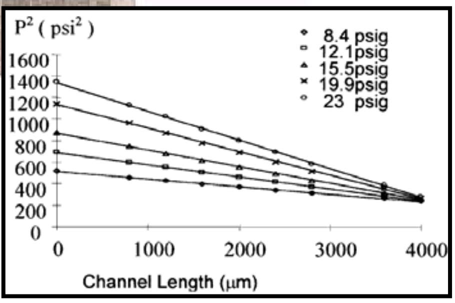
- Multi-hole pressure probes are used when both velocity magnitude and direction are to be determined. For applications in need of high spatial resolution, the three -hole probe (or 'cobra' probe can be used. In both pitch and yaw angles are required, the five-hole probe is used.
- The probe is rotated in the flow until the pitch angle is then known.
- Once calibrated, the (three-hole / five-hole) probe also allows the yaw angle to be measured.



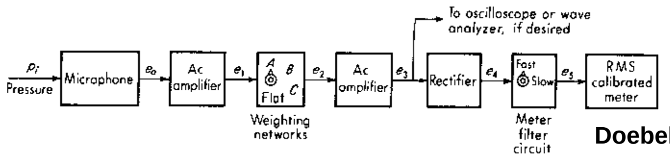
Pressure sensor in Micro-channel



(Pond et al. 1994)

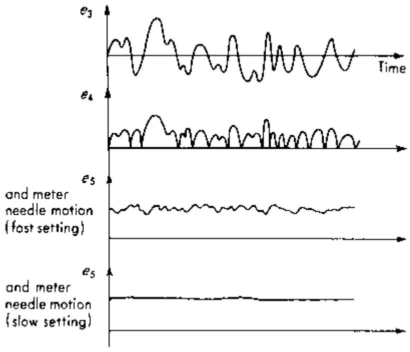


Sound pressure measurement



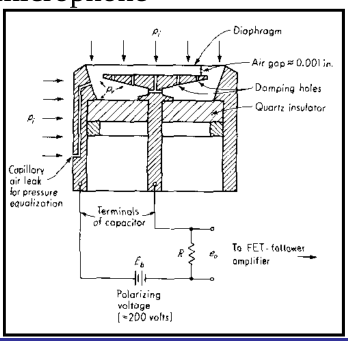
Doebelin (1990)

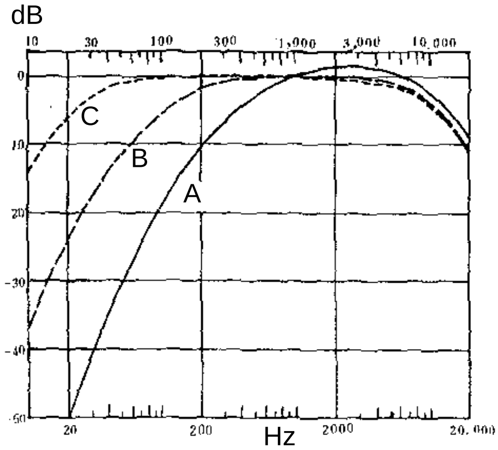
- Sound pressure level (SPL): SPL = 20 $\log_{10}(p/0.0002)$ decibels (dB) where p = rms sound pressure (μbar or dyne/cm^2)
- The transducer of commonly used sound-level meter includes capacitance, piezoelectric, or moving-coil types.



Sound pressure measurement

- Three filters (or weighting networks): A , B and C. A scale is commonly used.
- Free-field response of a microphone





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