Chapter 3

Design of Experimental Test-facilities

Contents

Design of an experiment (I)

Which quantities are important to measure (both independent and dependent) ?

⇨ Aim of experiment,

⇨ experience

⇨ dimensional analysis

In what range will the measured quantities vary ?

⇨ choice of measuring technique

Which quantities must be controlled ?

⇨ stationary and repeatable

Design of an experiment (II)

What is the required dynamic response of the measuring instrument ?
⇨ any correction or compensation needed?
How long is the measurement time needed?
⇨ given statistical variance for time-mean averaged quantities.
Has the experimental already been performed before ?
Does a theoretical solution exist ?

Moddelling & Similarity

In engineering,instead of complete similarity,We consider.

- Geomatric similarity (L-scale)
- Kinematic similarity (L- & t-scale)
- Dynamic similarity (L- & t- & m-scale)
- Thermal similarity

Introduction to the Wind-Tunnel (I)

Aims: Offering uniform velocity field (most commonly) or any controlled flow field

- Basic principle: from the relative motion concept, the effect moving air relative to a stationary object is the same as that of an object moving in a stationary air (at least since the time of Leonardo da Vinci).

- Development of wind tunnel:
  whirling arm first by Benjamin Robins(1707-1751), then modified by Sir George Cayley(1773-1857)
  The first real wind tunnel was constructed in 1871 by Frances Wenham in England.

Introduction to the Wind-Tunnel (II)

A wind tunnel includes a test section, where the model is mounted. The test section may be an open or closed channel, and the air-stream through the test section is usually produced by a propeller or fan if the air-stream through the test section is less the speed of sound. If a supersonic air-stream is required, large tanks of compressed gas usually are employed, producing the high velocity stream by allowing the gas to expand through a suitably shaped nozzle into the test section. Instrumentation is provided in the test section to permit measurement of forces and pressures acting on the model and to measure other quantities of interest. Techniques are available to allow visualization of the air flow as well.

Classifications of Wind-Tunnel(I)

According to wind speeds:

- Subsonic wind tunnel: $M \le 0.3$
- Transonic wind tunnel: $0.9 \le M \le 1.1$
- Supersonic wind tunnel: $1.0 < M \le 5$
- Hypersonic wind tunnel: $5 < M$

Here, M: Mach number = V/a

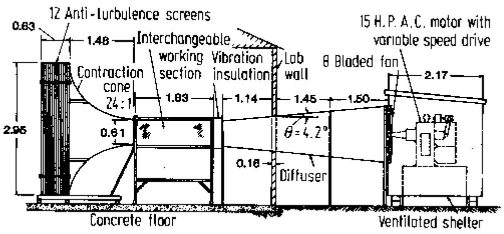
a: local speed of sound = $(kRT)^{1/2}$

at 25°C, $a_{air} = [(1.4)(287.1\text{J kg}^{-1}\text{K}^{-1})(298\text{K})]^{0.5}$

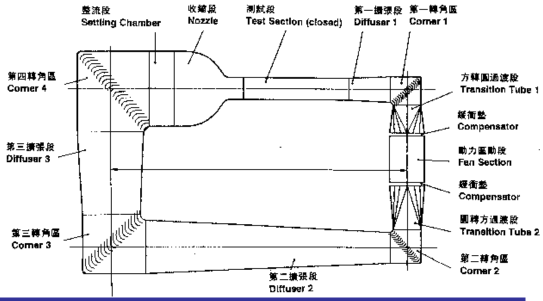
$= 346.1\text{m/s}$

Classifications of Wind-Tunnel(II)

Open Circuit Wind-Tunnel (Open jet or Eiffel type)



Closed Return Wind Tunnel (Prandtl / Göttingen type)



Open circuit Wind-Tunnel

Open circuit tunnel could be further classified as:
- Blow-down type
- Suction type

Advantages:

Lower construction cost; No purging problem;
Good for smoke visualization and combustion tests.

Disadvantages:

Need enhanced filter to get high quality streams.
Consume more power for operation.
Noisy affected by environmental conditions.

Closed return circuit Wind-Tunnel

http://grin.hq.nasa.gov/IMAGES/SMALL/GPN-2000-001285.jpg

Closed return circuit Wind-Tunnel(I)

Closed return tunnel could be further classified as:

Single, double or annular returns

Open or closed test section.

Advantages:

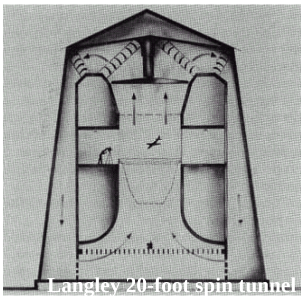
Easy to control the flow quality, quiet, consuming less energy

Disadvantages:

higher initial cost,

cooling problem,

purging problem



Langley 20-foot spin tunnel

Classification of Wind-Tunnels (II)

According to purposes:

➔High-Reynolds Number Tunnels:

- Pressurized tunnel
- Cryogenic tunnel
- Change working fluids

http://www.nasaexplores.com/lessons/01-059/images/icing_tunnel.gif

➔ Ice tunnels

- refrigeration system to reduce air temp to -40℃.
- atomizer upstream of the test section to produce water droplets that freeze.
- low-speed closed loop tunnel.

➔ Low-turbulence tunnels

- Honeycombs and Screens to damp out the turbulence
- Large settling chamber. (large contraction ratio)

Classification of Wind-Tunnels (III)

➔ V/STOL (vertical/short take-off and landing) tunnels
- Large test section, low speed
- ratio of model jet momentum to tunnel stream momentum (suggested <0.125) ratio of model jut area to tunnel area <0.15%
- Tandem test sections with two contractions

➔ Free-flight tunnels
- Dimensional and dynamically sealed model flow on the tunnel under the influence of gravity
- open return type

➔ Two-dimensional Tunnels
- H/W ratio of 2 or greater
- usually low turbulence and may be pressurized
- testing of airfoil sections

Classification of Wind-Tunnels (IV)

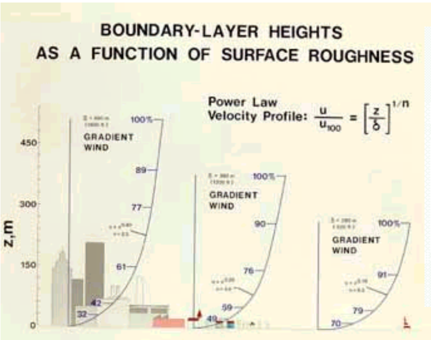
➔ Automobile tunnels
- Large test section (for full-scale cars)
- For testing aerodynamic parameters and performance of automobiles in stream

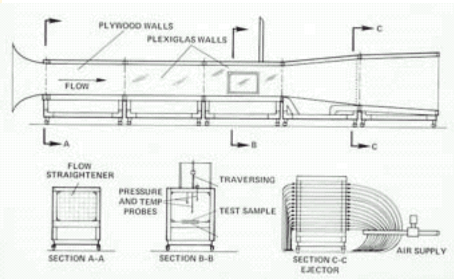
➔ Smoke tunnels
- usually non return type
- Favor vaporized light oils
- Filter and large contraction ratio
- Low speed (10~30m/s)

➔ Stability tunnels
- - two interchangeable test sections (one has a set of rotating vanes that create a swirl in the airstream, the other one was curved to simulate turning flight)

Classification of Wind-Tunnels (V)

➔ Meteorological-Environmental tunnels
- Simulate the earth's boundary layer (300~700m)
- For testing of wind loads on buildings and their surrounding area, air pollution, soil erosion, snow drift, etc.





www-mae.engr.ucdavis.edu/~wind/ facilities/ablwtthumb.jpg

Teaching Wind Tunnel at the NTU-IAM

NTU-IAM Wind-Tunnel model

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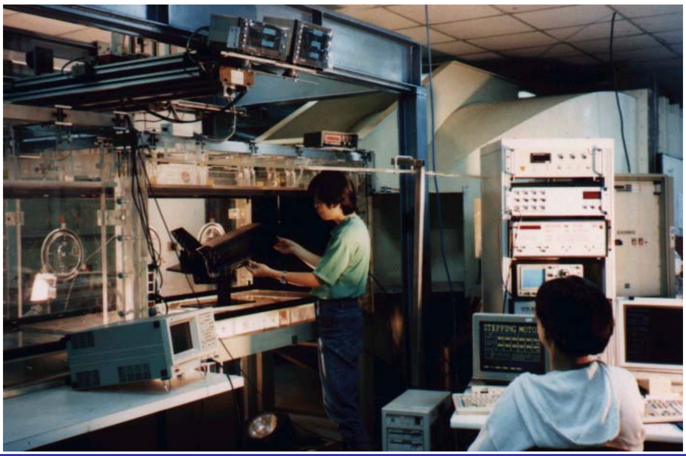
NTU-IAM Low-turbulence Wind-Tunnel

- **Test section: 0.8m x 0.6m x 3.8m; U_{max}:70 m/s**
- **T.I.: ~ 0.05%; Uniformity: < ±0.1%; Angularity：< ±0.1°**



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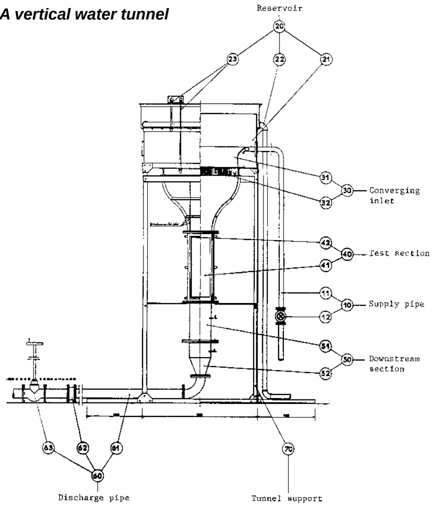
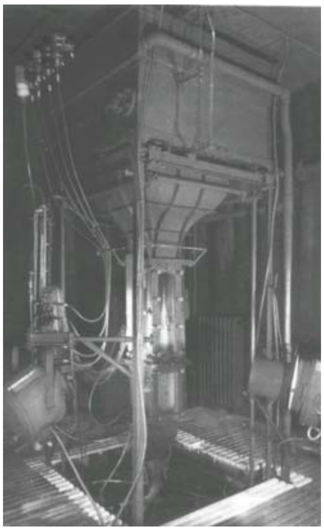
Water tunnel

ONERA vertical water tunnel





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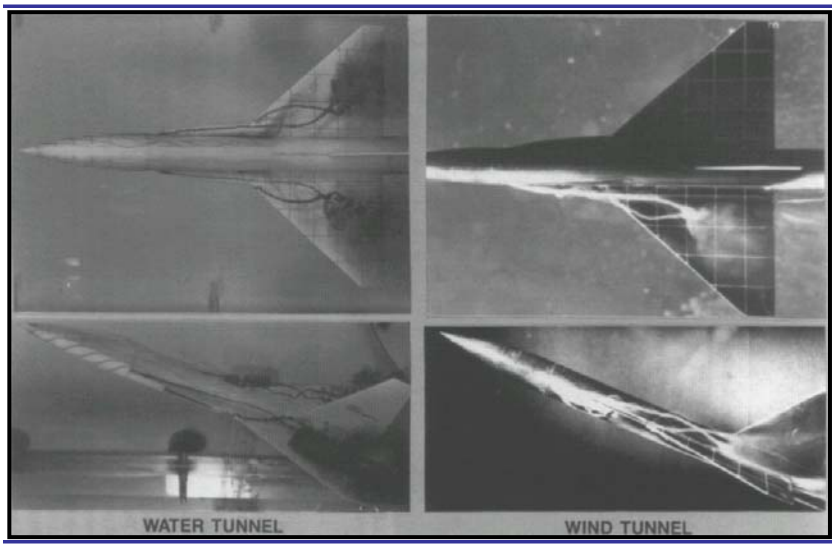
Wind Tunnel or Water tunnel ?



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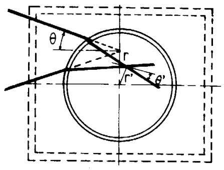
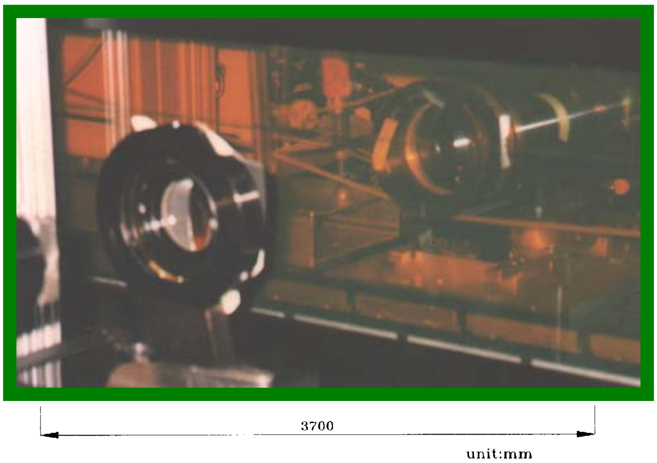
Oil tunnel

Refractive-Index Matching LDA-measuring Techniques

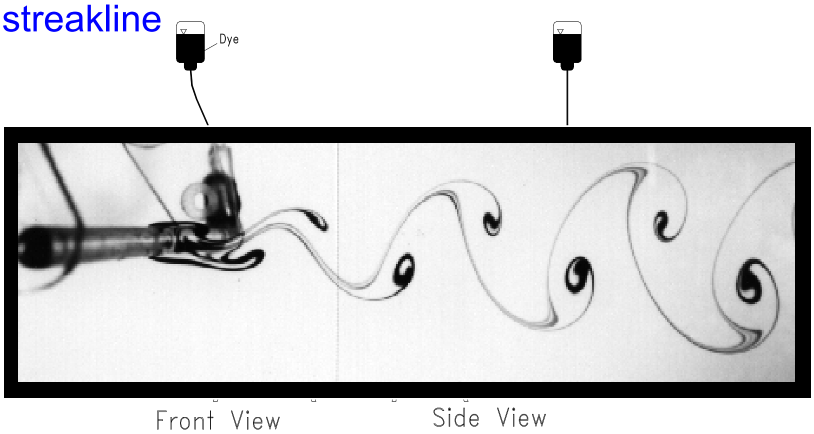




- Near wall measurements
- Linear correction
- Temperature control needed

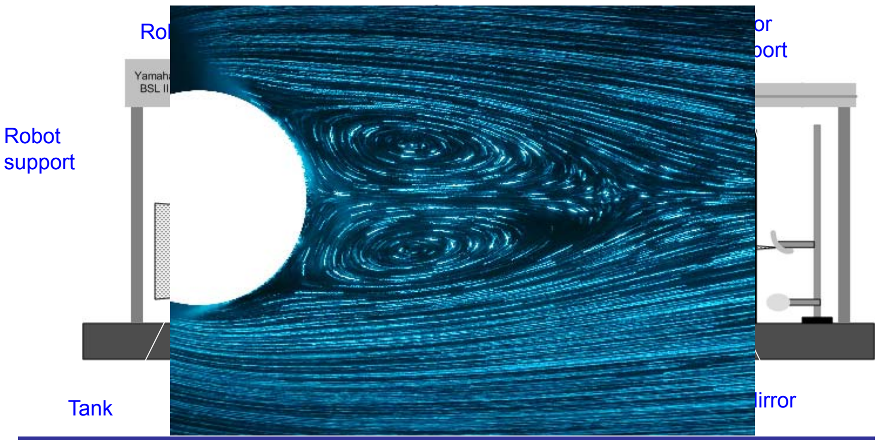
Towing Tank (I)

- Example test section: 1500 x 455 x 460 mm
- Towing speed: 0.06 ~ 120 cm/s
- streakline

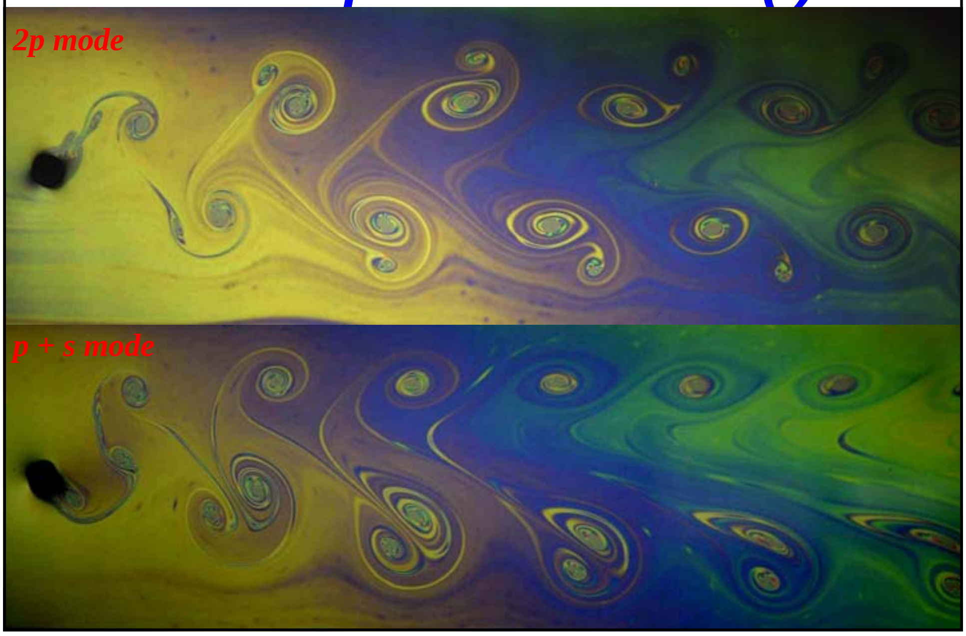


Towing Tank (II)

- Seeding particle: polymide (~50μm)
- pathline/streamline



Soap-film Tunnels (I)



Soap-film Tunnels (II)

Advantages:
- real 2-D flow
- simple
- cheap
- easy operation

Disadvantages:
- high measuring uncertainties mainly due to difficulty of determining the viscosity
- vibration sensitive
- temperature and relative humidity sensitive

Test Section (I)

RTRI's Large-Scale
Low-Noise Wind tunnel

Test Section (II)

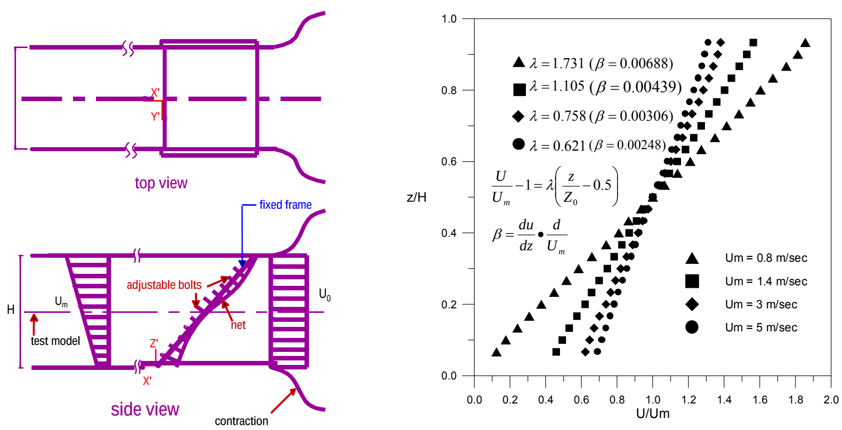
The Biggest test section

The largest wind tunnel in the world is at the National Full-Scale Aerodynamics Complex at NASA Ames Research Center. Its 80 foot by 120 foot test section can fit a life-sized Boeing 737 inside!

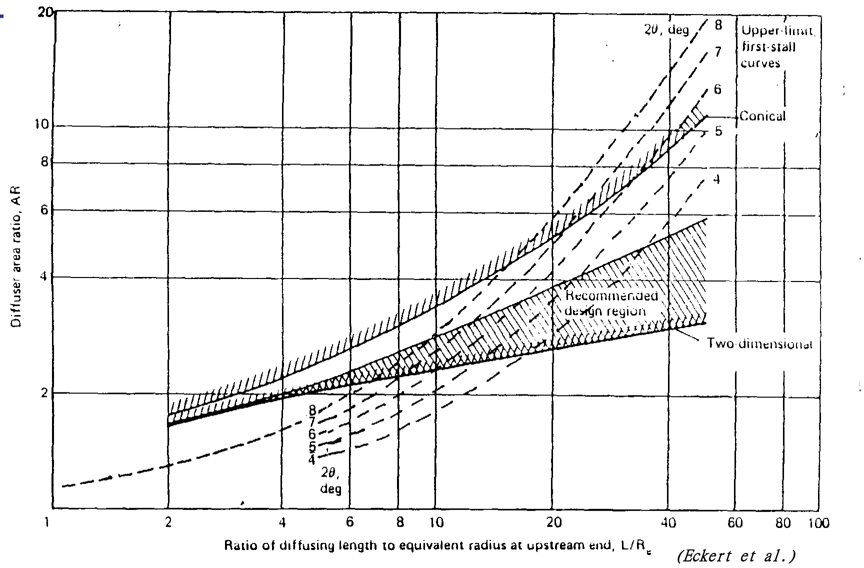
Test Section (III)

- The shape is based on utility purpose, aerodynamic considerations and operation convenience.
- Commonly used width-to-height ratio: 1~1.5
- Commonly used length-to-hydraulic diameter-ratio: 2~3
- To compensate the growth of the boundary layer, no exact design method is available that ensures the development of a constant static pressure. For instance, a divergent test-section (about 0.5~1°) or corner filleted test-section, or movable upper wall.
- A short constant area duct before the test section is used to relieve the non-uniform velocity distribution from the exit of the contraction, but increase the boundary layer.
- Alternative of open and closed test section is preferred.
- Measuring instruments & Illumination

Modification of Test Section



Design of Diffuser (I)



(Eckert et al.)

Design of Diffuser (II)

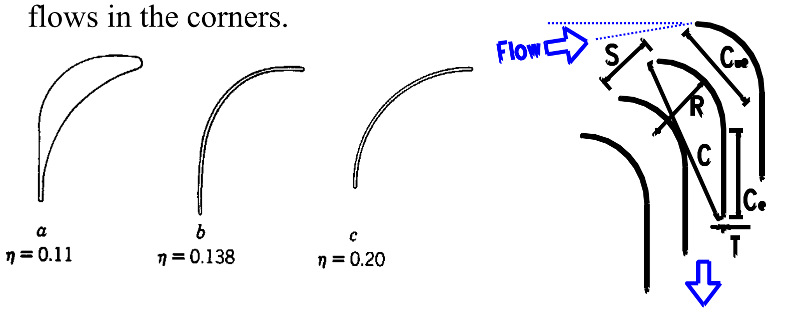
- For closed return tunnels, to achieve large expansion ratios to fit to the large inlet of the settling chamber a second diffuser with wide angle of 45 and expansion ratio of about 74 is usually used.
- Rectangular or circular cross-section diffuser are commonly used. Fillet could prevent the corner recirculation flow for rectangular cross-section.
- If the flow in the diffuser is separated or it is suspected that it is separated, some ways must be taken to recognize the location of separation. And after that the following fixes may cure the problem: ***Splitters, Windmills, Vortex Generators, Boundary Layer Control, and Safety Screens***.

Design of corners (I)

- In the closed return tunnels corners are required to direct the stream expelled from downstream of test section to the settling chamber.
- Corners are named as 1st, 2nd, 3rd and 4th corner from the test-section toward the downstream.
- The added expense is usually not justified for building 180° curved corners. Most corners are 90° bends.
- An abrupt corner without vanes show a loss of 100% of the dynamic head. With carefully designed vanes a 15% loss is reasonable. The shape of the vanes varies from bent plates to highly cambered airfoils. The tilt angle of the vanes should be adjusted to ensure a uniform velocity profile at the fan.

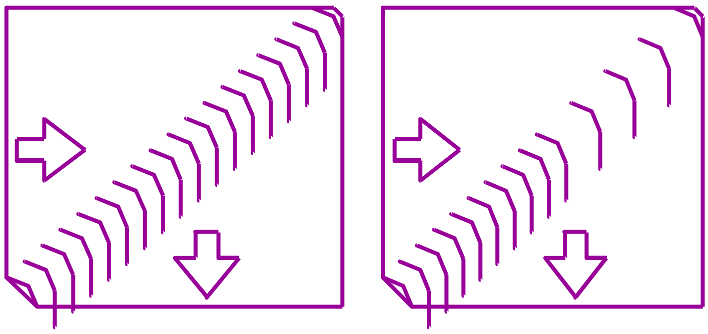
Design of corners (II)

- The efficiency of the guide vane (static pressure drop/dynamic pressure) is evaluated from the dimensionless pressure loss $\eta = \Delta p/q$
- The screens installed in the turning corners are helpful for smoothing the velocity gradient induced by the secondary flows in the corners.



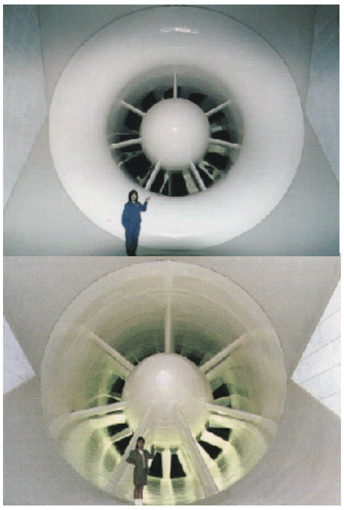
Design of corners (III)

- Non-uniformly distributed vanes have been proved have the same efficiency to smoothing flow but with lower pressure drop.



Design of Fan section (I)

- The fan section includes the fan nacelle, the fan, pre-rotation vanes, and flow-straightener vanes after the fan.
- The fan of the closed return wind tunnel is commonly located at downstream of the second corner. The reasons are, (a) the fan develops its highest efficiency if it is placed in a stream of a fairly high velocity, and (b) fan cost is partially proportional to its diameter square.



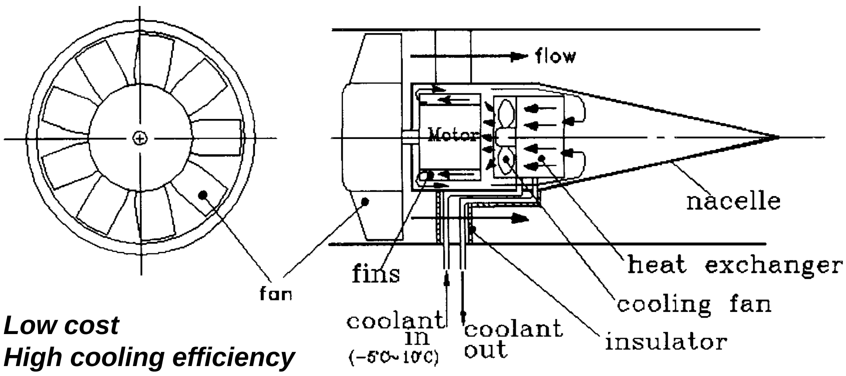
Design of Fan section (II)

- The prerotation vanes are designed to produce a swirl opposite to the fan's swirl and hence zero swirl after the fan. This may not occur at all rpms. Thus, in most cases flow straightners or antiswirl vanes are installed after the fan as a safety factor.
- Another function of the antiswirl vanes is to reduce the crossflow velocity gradient in the test section which is induced from the secondary flows that produced as the flow makes turns at the third and forth corners.(It was discovered by Shindo et.al.in 1978 at the University of Washington that when the antiswirl vanes were deflected either positively to reduce fan swirl or negatively to increase fan swirl the corners were filled and the cross-flow gradient was reduced, but not eliminated.)

Design of Fan section (III)

- The fan-nacelle diameter is about 30-50% of the fan section diameter and the length to diameter ratio of about 3 with 30-40% of its length of constant diameter. The closing cone angle should be 5° or less.
- Area ratio between the fan and the test section ~ 2 or 3 to 1.
  the area ratio ↗ ⇨ the risk of a poor velocity profile before the fan and increasing the fan cost.
  the area ratio ↘ ⇨ higher incoming velocity, larger fan rpm to maintain reasonable blade angles and higher noise.
- Choice of a variable-pitch fan .
- The main purpose of the duct fan is to compensate the static pressure losses of the tunnel and model and to provide the dynamic pressure of the wind stream.

Design of Fan section (IV)



Low cost
High cooling efficiency
Low pressure loss
Easy maintenance

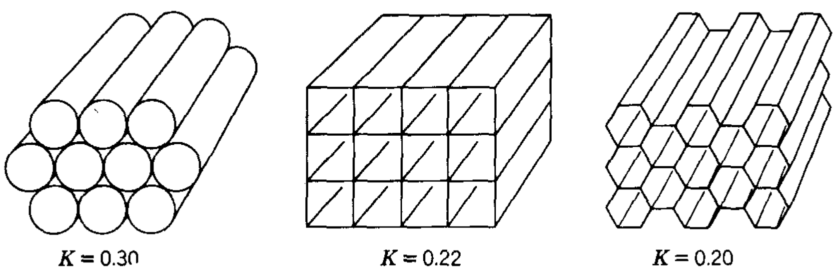
By Wang (1995)

Design of Settling chamber (I)

- Settling chamber, including honeycombs and/or screens, is used to (a) reduce the turbulence before the contraction, and thus that of the test section, and (b) increase the isotropy of the flow turbulence.
- Screens reduce the axial turbulence more than the lateral turbulence, but cause large pressure drop.
- Honeycombs have small pressure drops and thus have less effect on velocity, but owing to their large length/cell-size ratio, they reduce the lateral velocities. The minimum length/cell-size ratio should be at least 6-10.
- Distance between honeycomb and screen: 30 mesh size or 500 wire diameters.

Design of Settling chamber (II)

- The effect of the lateral reduction by a honeycomb (1/4 inch cell) is the same as three 20mesh screens and the axial reduction as one 20 mesh screed. The honeycombs are commonly installed upstream of the screens.
- The shape of the honeycomb could be like follows:



Design of Settling chamber (III)

- Screens have a relatively large pressure drop in the flow direction, which reduces the higher velocities more than the lower, and thus promote a more uniform axial velocity profile.
- Screen open-area-ratio: 0.57 (optimal)
- Screens have high effect on the power loss (a single screen with 58% porosity accounts for 25% of the circuit losses at high speed is possible).
- Number of screens: 0~12. Depends on the design considerations.
- Cleaning possibility due to the accumulation of dust and the quality of the test section flow must be monitored.
- A full-sized screen is preferred than the spliced small pieces of screens, except for large tunnels.

Design of Settling chamber (IV)

- Screens used for turbulence reduction should have the projected open area to total area ratio, β, greater than 0.57. Screens with smaller ratios (large wire diameter or too dense) suffer from flow instability that appears in the test section. The Reynolds number based on the wire diameter should be less than 80.
- Most of the theoretical treatments of the ability of the filtering of turbulence by the screens start from the assumption of the homogeneous and isotropic turbulence created behind the screens. But, in general the mechanism of turbulence and its manipulation is very complex and not completely understood. These facts often lead to the unpleasant results deviate much from the measurements.

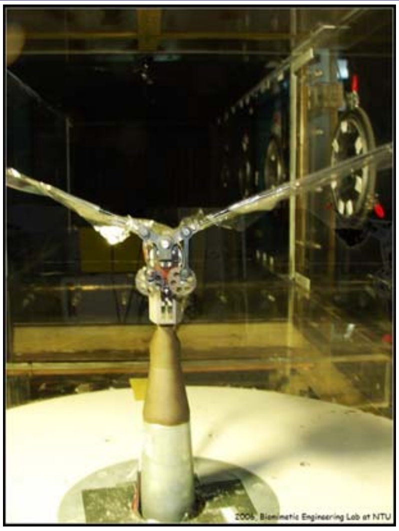
Design of Contraction (I)

- Objectives: (a) accelerate the stream to the designed velocity and profile, (b) reduce mean flow non-uniformity, (c) reduce turbulence intensity (axial direction) and (d) reduce dynamic loads and losses in screens & honeycombs
- For incompressible flow either Polynomial (say, cubic or fifth order) equation, Batchelor-Show, ASME β-series contours, Witoszynski (1924) or Boerger (1975) could be employed. The last one has shortest contraction length.
- Different contraction (area) ratio ***CR*** have been used (from 1:1 to 35:1), the higher the ***CR*** is, the smaller the test-section (or larger space needed)

Design of Contraction (II)

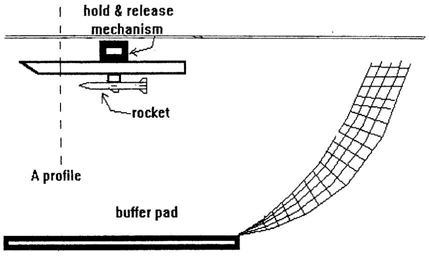
- The turbulence intensities of the cubic profile and the Batchelor-Show contour are similar. The ASME β-series has thicker exit boundary layer, higher turbulence intensity, and higher rate of entrainment (Hussain and Ramjee, 1976).
- There must be a setting section (with a length about 0.5 to 1.5 times of diffuser exit diameter) connected to the contraction exit to allow the velocity to become uniform.
- The rectangular contraction may cause secondary flow in the corner. The problem could be alleviated by making the contraction octagonal. This is done by starting a 45° fillet at the start of the contraction cone and carrying the fillet through the test section and first diffuser.

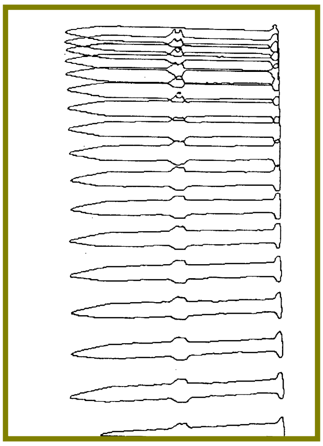
Corresponding Instrumentation (I)



Corresponding Instrumentation (II)

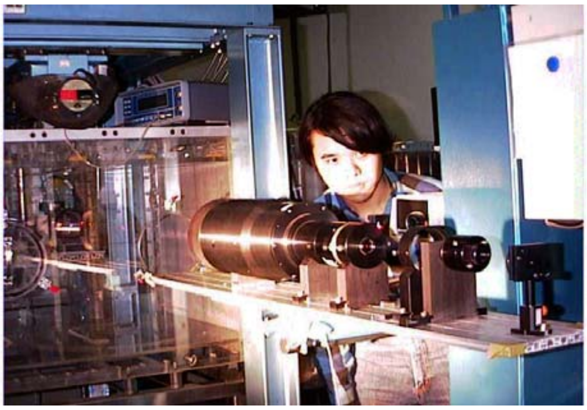
Dynamic flow visualization techniques (Wong et al. (1996)



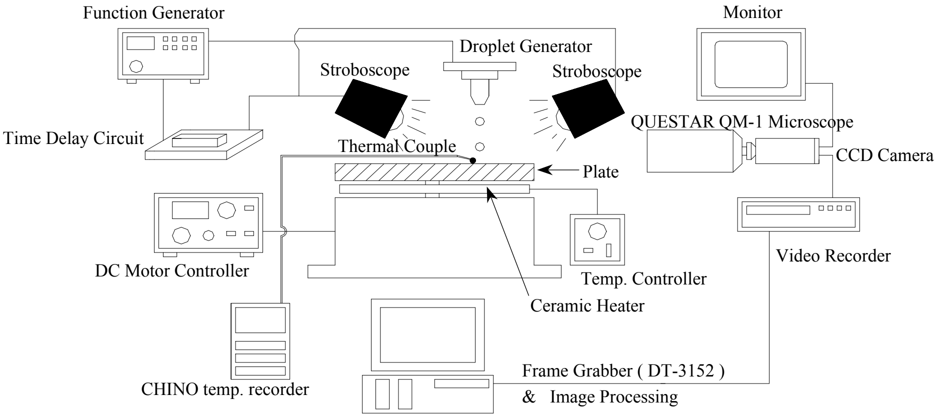


NTU-IAM Extremely Low-speed Wind-Tunnel

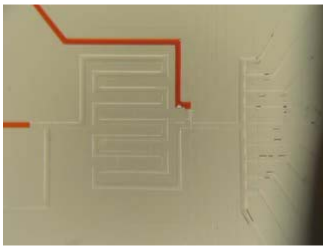
Test section:
  90cm(L)x70cm(W) x50cm(H)
Umax：2m/s ;
  Res.:0.003m/s
Turbulence Intensity ~ 0.2 %
Velocity Uniformity ≤ 2%
No artificial seeding is added

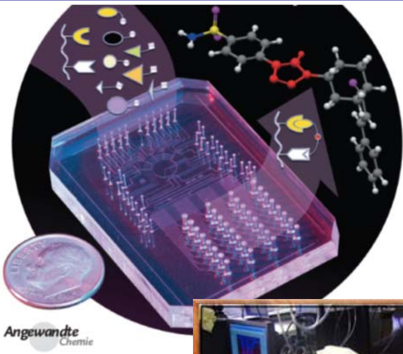


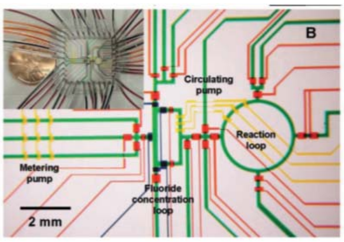
Experimental set-up for Microsystems



Experimental set-up for Microsystems







labs.pharmacology.ucla.edu/.../researchimage.htm

Micro Manufacturing Technologies

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Overview of Micro Manufacturing Technologies

Technologies used to produce MEMS and microsystems are significantly different from those used for conventional products in macro scale.

Micro manufacturing technologies are exclusively ***process-oriented***, whereas traditional manufacturing technologies involve machine tools, such as lathe, milling machines, etc.

There are three (3) principal micro manufacturing technologies available for producing MEMS and microsystems at the present time:

(1) Bulk micromanufacturing,
(2) Surface micromachining, and
(3) The LIGA process.

Both Bulk micromanufacturing and Surface micromachining are primarily used for MEMS and microsystems using ***silicon*** as primary substrate material, whereas no such restriction applies to the LIGA process.

Bulk Micromanufacturing

Bulk micromanufacturing was used to produce integrated circuits in the 1960s. It is the **most well-established** micro manufacturing technology of the three micro manufacturing technologies.

It is a popular technique for producing micro sensors and accelerometers.

Bulk micromanufacturing involves the ***removal*** of materials from the bulk substrates, usually silicon wafers to create the desired geometry of MEMS and microsystems - ***a technique that is similar to shaping a geometry by sculpting***.

The principal method used to remove materials from substrates is **Etching**.

Micromanufacturing is thus commonly focused on etching.

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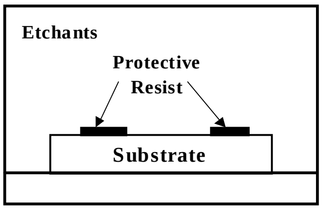
By An-Bang Wang
National Taiwan University Institute of Applied Mechanics

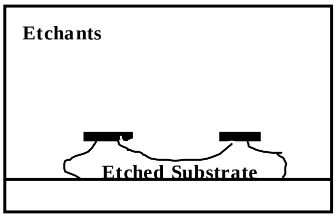
Isotropic etching

Isotropic wet etching or Isotropic plasma etching means the chemistry (etchant or plasma gas) etches the substrates with total disregard for their crystal planes.

It etches in all directions at the same rate.



(a) Substrate in wet etching



(b) Partially etched substrate

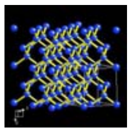
Isotropic etchants are available for oxide, nitride, aluminum, polysilicon, gold and silicon. Hydrofluoric acid (HF) is the most commonly used chemistry for silicon.

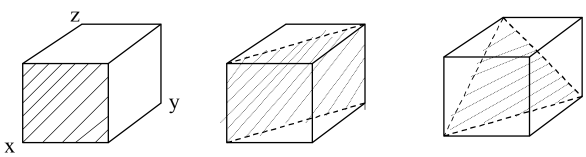
Isotropic etching is not desirable in micromanufacturing because lack of control of the geometry of the finished product.

Anisotropic etching (I)

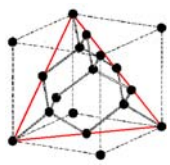
Silicon crystals are not isotropic in nature. Some planes are stronger and more resistant to etching chemicals than others.

There are three planes in silicon crystal on which etching take place:





(100) plane (110) plane (111) plane



The (100) plane is easiest to be etched,
The (110) plane results in most clear etched surface,
The (111) plane is toughest plane to be etched.

The uneven resistance to etching chemicals by various planes in the silicon crystal result in different amount of materials that can be etched away using the same etching chemical for the same duration.

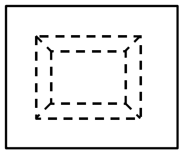
Gallery of BALSAC (and other) pictures

Anisotropic etching (II)

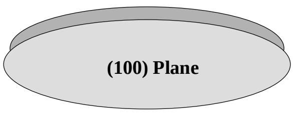
One may prove that the (111) plane in a silicon crystal-the toughest plane to etching makes an off-normal angle of 54.74º angle with the (100) plane-the plane that is easiest to be etched.

The complementary angle to the (110) plane is 35.26º.

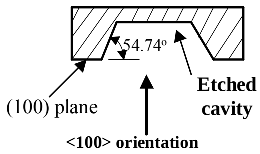
If etching is taken place on the (100) plane, i.e. in the normal direction of <100>, then we can expect having a cavity in the shape as follows:



Unetched wafer:



Wafer etched in the <100> direction



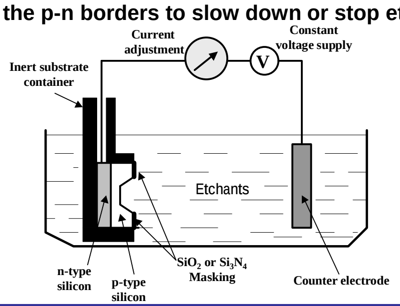
Etch stop - a control of wet etching

Dopant-controlled etch stop:

In general, doped silicon can dissolve in etchants faster than the undoped silicon. Thus, one may dope the parts of the silicon substrate that need to be etched away faster than the other parts of the substrate.

Electrochemical etch stop:

Since doping in silicon may alter the etching rates in wet chemicals, we may use the p-n borders to slow down or stop etching, as illustrated in the following set-up:



The electric current is used to prompt the functioning of the p-n junction. The difference in electric resistance in the p- and n-silicon produces the different etching rates for the control of the etching in the doped substrate.

Dry etching of silicon substrates

Dry etching involves the removal of substrate materials by gaseous etchants without wet chemicals or rinsing.

There are generally 3 dry etching techniques:
(1) Plasma. (2) Ion milling. (3) Reactive ion etch.

Common practice, however, involves Plasma and Reactive ion etch.
Recent develop has been in the **Deep Reactive Ion Etching**, or **DRIE**.

- **Dry etching of silicon substrates typically is faster and cleaner than wet etching**. A typical dry etching rate is 5 μm/min, which is about 5 times faster than that by wet etching.

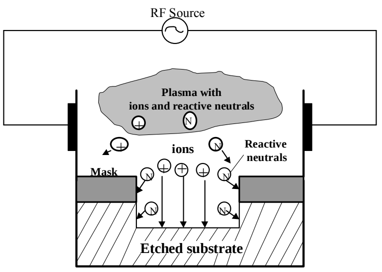
- However, dry etching requires more costly equipment.

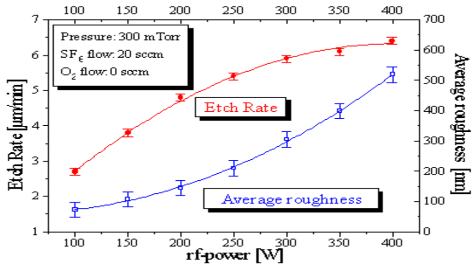
- It is the only way to produce deep trenches with near-vertical side walls using the DRIE process, which is critical for many MEMS and microsystems components.

Plasma etching process:

The neutrals (N) produced by ionization of the reactive gas chemical in the plasma attack the substrate in all directions, with simultaneous chemical reactions with the contacted substrate material.

The ions (+) in the plasma itself attack the substrate only in the normal direction. Etching of the substrate material is accomplished by instant local evaporation of substrate material after high energy impingement of (N)-neutrals and (+) ions.



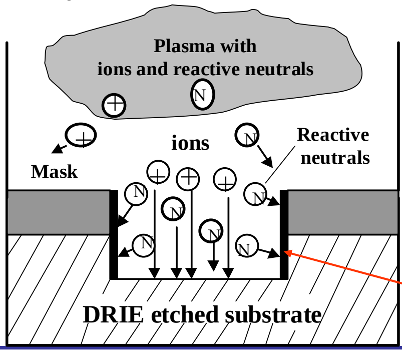


Plasma etching rate is in the order of 2 μm/min. **Rate and quality of plasma etching**

Working principle of DRIE

DRIE works on a similar principle as the plasma etching. A major difference, however, is that DRIE involves the production of thin protective polymer films on the side walls during the etching process. These thin protective films prevent etching of the side walls. As result etching can only take place in the normal (the depth) direction in the trench.

The DRIE process is illustrated below:



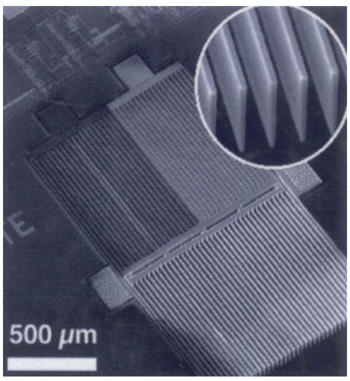
The reactants that can produce thin protective polymer films is fluoropolymers (nCF2) in the plasma Argon gas ions.

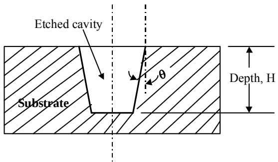
The rate of DRIE is in the range of 2 - 3 μm/min.

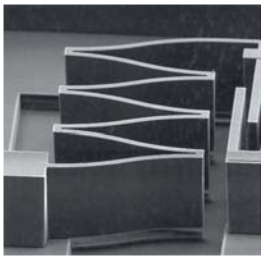
Sidewall protection materials	Selectivity ratio	Aspect ratio, A/P
Polymer		30:1
Photoresists	50:1	100:1
Silicon dioxide	120:1	200:1

Deep reactive ion etching (DRIE) for silicon substrates

DRIE is the only etching technique that is capable of producing trenches with aspect ratio up to 300 and a near vertical walls at θ = ±2°.







A micro spring

These trenches are of typically high aspect ratio (The ratio of the dimension in the thickness (H) to those of the surface).

Wet etching and conventional dry etching could not accomplish deep etching with vertical walls.

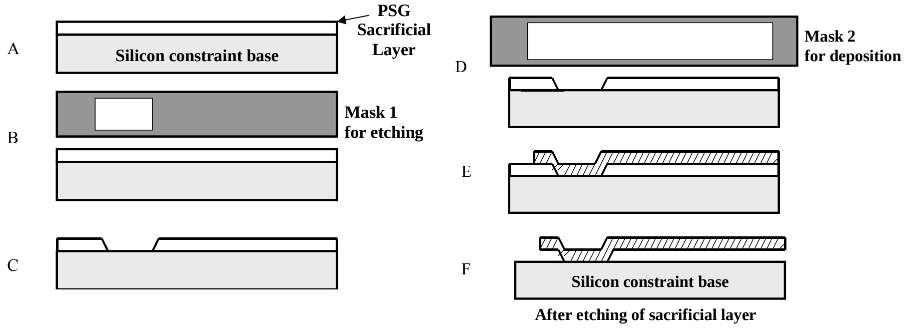
Comparison of wet versus dry etching

Parameters	Dry etching	Wet etching
Directionality	Good for most materials	Only with single crystal materials (aspect ratio up to 100)
Production-automation	Good	Poor
Environmental impact	Low	High
Masking film adherence	Not as critical	Very critical
Selectivity	Poor	Very good
Materials to be etched	Only certain materials	All
Process scale up	Difficult	Easy
Cleanliness	Conditionally clean	Good to very good
Critical dimensional control	Very good (< 0.1 μm)	Poor
Equipment cost	Expensive	Less expensive
Typical etch rate	Slow (0.1 μm/min) to fast (6 μm/min)	Fast (1 μm/min and up)
Operational parameters	Many	Few
Control of etch rate	Good in case of slow etch	Difficult

Surface Micromachining

Unlike bulk micromanufacturing, surface micromachining builds the 3-dimensional geometry of MEMS and microsystems by adding (depositing) materials to the substrates.

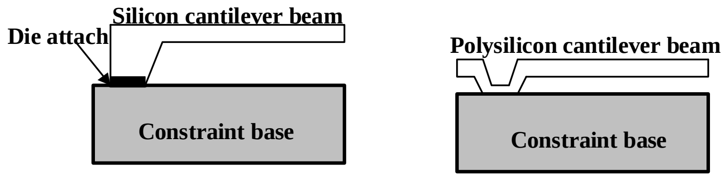
Illustration of surface micromachining process for a cantilever beam:



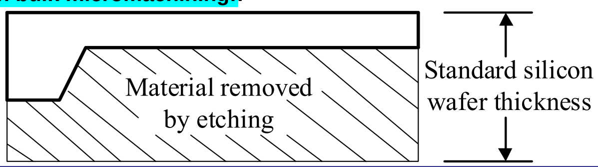
Why surface micromachining?

Major advantages of surface micromachining are that it offers much flexibility in terms of the type of materials that could be deposited to the substrates, as well as better control of geometry of the MEMS products.
Another major advantage is on the saving of materials as illustrated below:

by bulk manufacturing: by surface micromachining:



Waste of material in bulk micromachining::



Surface Micromachining Process in general:

Three typical components:

(1) A sacrificial component (or "spacer layer").
(2) A microstructural component, e.g. the cantilever beam.
(3) An insulator component, e.g. the constraint base.

The sacrificial components:

The sacrificial components are used to support the microstructural components during the deposition process. They are later removed by etching after the microstructural component is fabricated.

Common sacrificial materials are: phosphosilicate glass (PSG) and SiO_2, usually deposited on substrate using LPCVD technique.

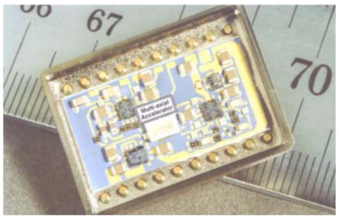
The size of sacrificial layer can be (0.1 - 5 μm) thick x (1 - 2000 μm) long.

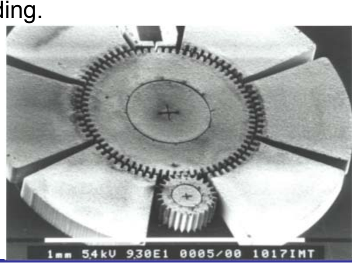
Common etchant for sacrificial layer is HF, normally with 1:1 HF:H_2) + 1:1 HCl:H_2O.

PSG can be etched much faster than SiO_2.

The LIGA Process

The term **LIGA** is an acronym for the German terms:
Lithography (Lithographie), Electroplating (Galvanoformung),
and Molding (Abformung) = **LIGA**
The technique was first developed at the Karlsruhe Nuclear Research Center in Karlsruhe, Germany.
The LIGA micro manufacturing process offers three major advantages:
(1) It is NOT limited to silicon-based materials.
(2) It has virtually no limitation on the aspect ratio in micro structural geometry.
(3) It is the only technique that has good potential for mass production of MEMS components through injection molding.

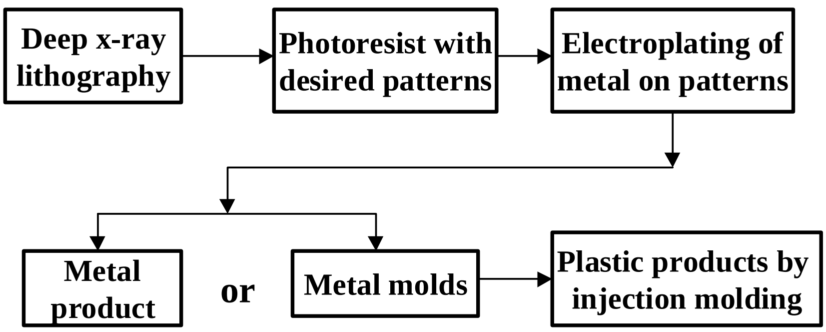




LIGA process in general

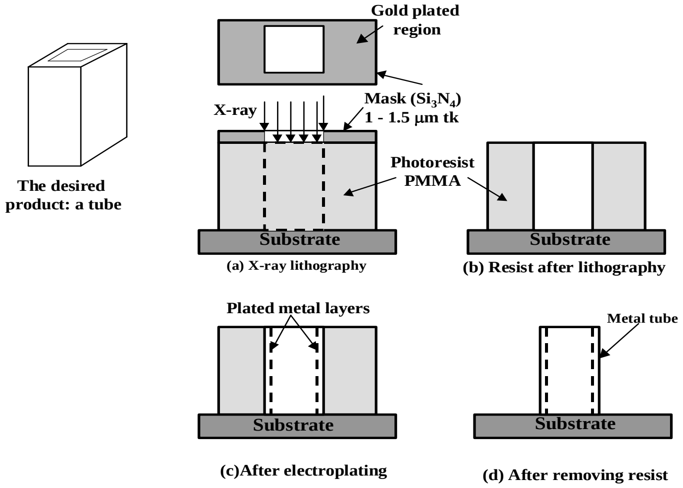
The LIGA process, as indicated in the abbreviation of the name of the process, includes the following major fabrication processes:

Lithography - Electroplating - Metal Molds and Molding



Case illustration of LIGA manufacturing process

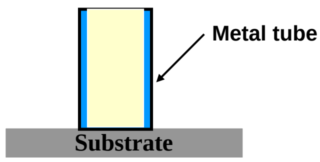
- Manufacturing of a long square micro tube:



The SLIGA Process

In the example of using the LIGA process in producing a square metal tube, the finished tube after electroplating is attached to the substrate.

The SLIGA process is developed to separate the finished product from the substrates.



The SLIGA process is a combination of the surface micromachining and the LIGA processes.

It involves applying a sacrificial layer between the photoresist and the substrate during deep x-ray lithography. This layer is then etched away after electroplating, and thereby separating the finished product from the substrate.

The sacrificial layer used in the SLIGA process must be electrically conductive for electroplating.

Common material for this purpose is polyimide with metal film coating.

Summary of Micromanufacturing (I)

Bulk micromanufacturing:

- Straightforward, involving well-documented fabrication process, e.g. etching.
- Less expensive in the process, but material loss is high.
- Suitable for MEMS and microsystems involving simple geometry.
- Limited to MEMS and microsystems with low aspect ratio.
- The total height is limited by the standard wafer thickness.

Surface micromachining:

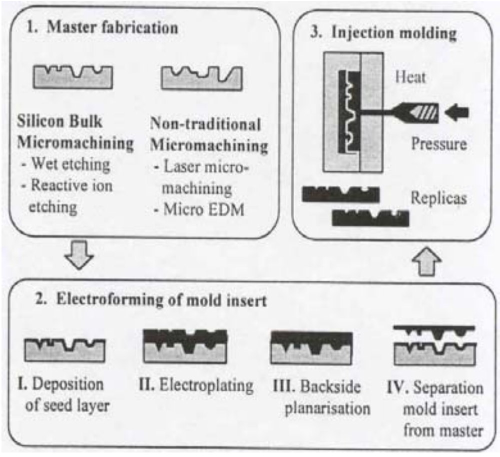
- Requires the building of thin layers of materials on substrate.
- Require complex masking design and productions.
- Etching of sacrificial layers is necessary.
- The processes are tedious and expensive.
- There are serious mechanical problems, e.g. interfacial fracture and stiction.
- Major advantages are:
  (i) not constrained by wafer thickness in the height,
  (ii) wide choice of thin film materials,
  (iii) suitable for MEMS involving complex geometry.

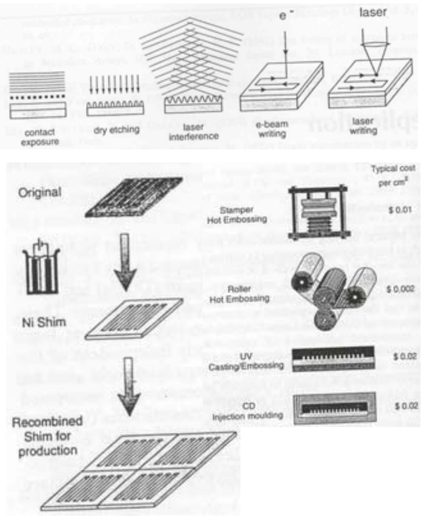
Summary of Micromanufacturing (II)

The LIGA and SLIGA processes:

- The technique is radically different from those of silicon-based micromanufacturing techniques.
- Unfortunately, it is the most expensive process of all.
- Requires a special synchrotron radiation facility for deep x-ray lithography.
- Electroplating of thin metal films over the cavity wall of photoresist surface requires tight control of the process in order to achieve good quality.
- Requires the development of micro injection molding technology and facility to maximize the benefits of the LIGA process for mass production.
- Major advantages are:
  (i) virtually unlimited aspect ratio of the micro structure's geometry.
  (ii) flexible microstructure configurations and geometry.
  (iii) the only one of the 3 micromanufacturing techniques that accommodates metals.
  (iv) the best of the 3 micromanufacturing techniques for mass production, with the provision for injection molding.

Replication of μ– Structure/Systems



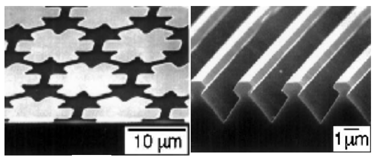


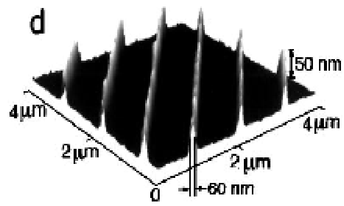
Source: Micro Optics

ed. by H. P. Herzig

Why Polymers?

- Biocompatibility
- High replication
- Low weight
- Large structures with tiny features of < 0.1 μm
- Huge materials selection





(From Dr. Bruce K. Gale, Louisiana Tech. Univ.)

Polymers for Microfabrication

- **Examples:**
  - **PDMS (Polydimethylsiloxane)**
  - **PMMA**
  - **polyurethane**
  - **polyimide**
  - **polystyren**

- **Advantages:**
  - **inexpensive**
  - **flexible**
  - **transparent to visible/UV**
  - **easily molded**
  - **surface properties easily modified**

- **Disadvantages:**
  - **low thermal stability**
  - **low thermal and electrical conductivity**
  - **μ-fabrication is still developing**

(From Dr. Bruce K. Gale, Louisiana Tech. Univ.)

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