Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Energy Conversion

Pressure Measurements

Experimental Methods for Engineers

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Overview

- Total and static pressure
  - Boundary layer
- Static Pressure Tappings
- Pressure measurement techniques
  - Pitot tube
  - Pneumatic Probe
  - Fast Response Aerodynamic Probe (FRAP)
- Example

P_{tot} measurement required for efficiency

- P_{tot} is constant in a flow without work transfer (no friction, no heating)
- P_{tot} is a direct measure of efficiency → Need to know P_{tot} to calculate machine's efficiency:

$$\eta_{Compressor} = \frac{\left(\dfrac{P_{tot,ex}}{P_{tot,in}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\dfrac{T_{tot,ex}}{T_{tot,in}} - 1}$$

$P_{tot,ex} > P_{tot,in}$

$T_{tot,ex} > T_{tot,in}$

$$\eta_{turbine} = \frac{\dfrac{T_{tot,ex}}{T_{tot,in}} - 1}{\left(\dfrac{P_{tot,ex}}{P_{tot,in}}\right)^{\frac{\gamma-1}{\gamma}} - 1}$$

$P_{tot,ex} < P_{tot,in}$

$T_{tot,ex} < T_{tot,in}$

$P_{tot} = P_S + P_{dyn}$

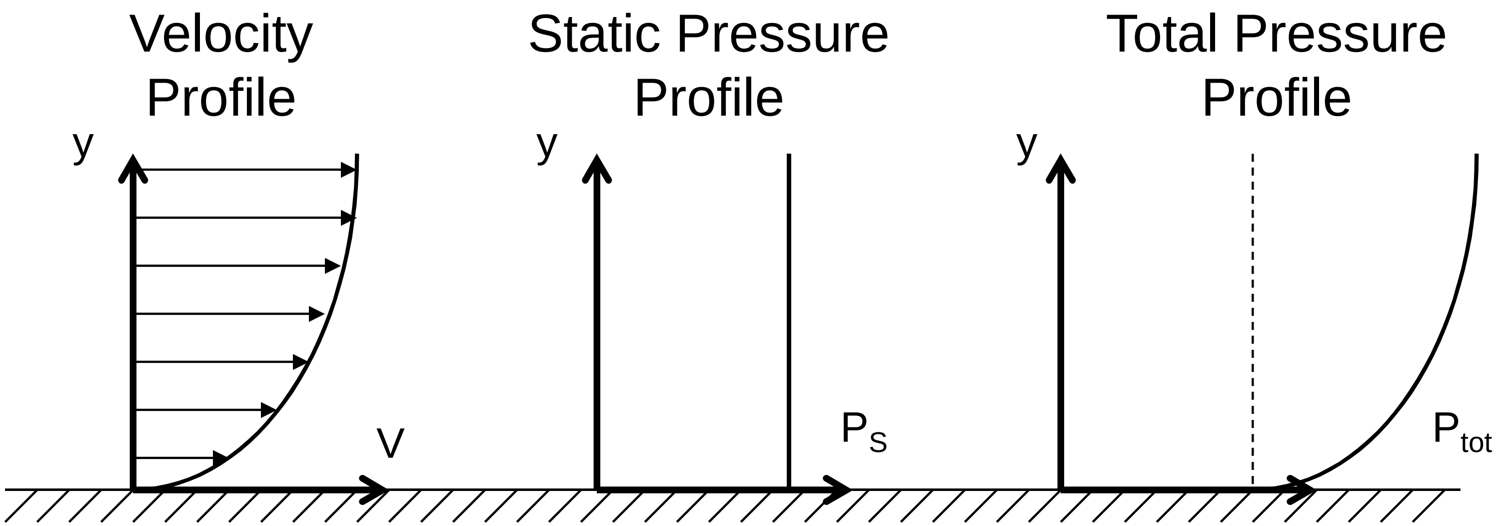
- Total pressure = static pressure + dynamic pressure

$$P_{tot} = P_S + \tfrac{1}{2} \cdot \rho \cdot V^2$$

ρ = fluid density
V = fluid velocity

- Static pressure is equal to total pressure, if V = 0m/s.
- Different names for the same thing:
  - stagnation pressure = total pressure
  - $P_{tot} = P_0$
  - Dynamic head = dynamic pressure

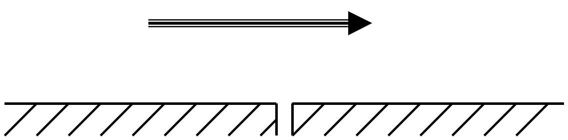
P_{tot} and P_S in Boundary Layer



$$P_{tot} = P_S + \frac{1}{2} \cdot \rho \cdot V^2$$

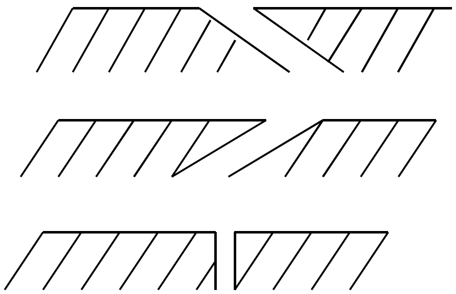
- Static pressure travels through a shear layer such as Boundary Layer
- A perpendicular hole on a surface wall measures P equal to the centre of the field

Static Pressure Tappings



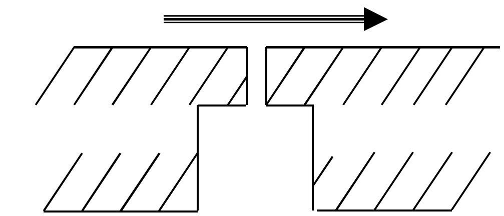
Static pressure taping parallel to the flow

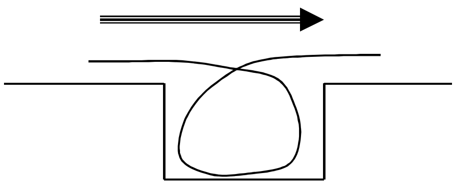
- Tappings on solid wall
- Local velocity zero
- Any pressure measurement on the wall is **static**



- Tapping inclination affects accuracy
- Ideally perpendicular to wall surface

Static Pressure Tapping manufacturing



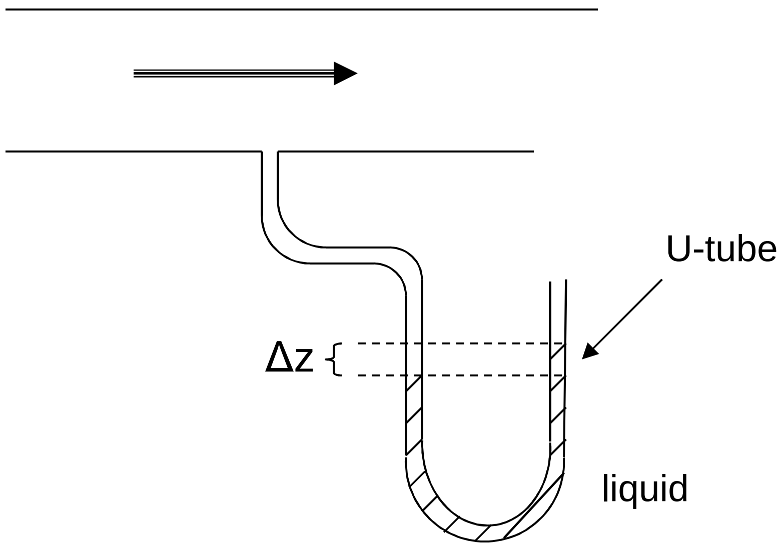


Whistling hole

- Drill from both sides
- Connect tube (one side)
- Small hole (other side)

- Accuracy in location
- Avoid unsteady effect / interactions
- Improve stability

Pressure measurement



Pressure can be calculated using Pascal's law:

$$\Delta P = \rho \cdot g \cdot \Delta z$$

Challenges:

- 1 bar corresponds to ~10m of H_2O
  → Limited range

- **Poor dynamic response**

Liquids used:
- Water
- Alcohol
- Quicksilver (Historic!)

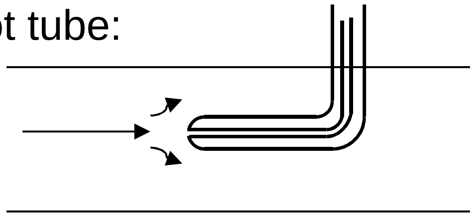
→ Today, commercial products are used to measure the pressure (Keller, Scanivalve, etc.)

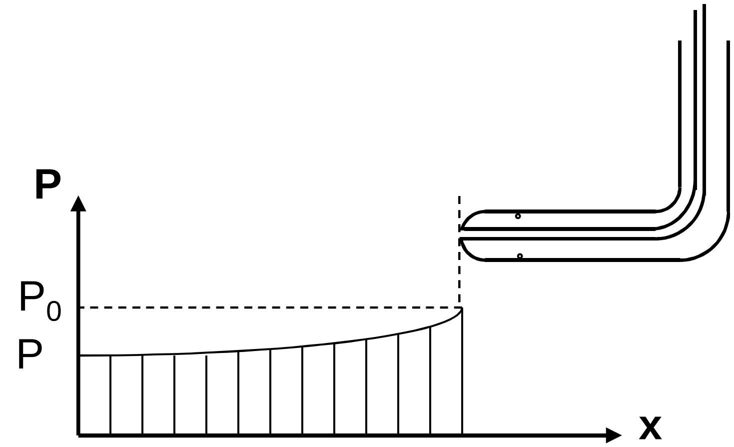
Total pressure measurement: Pitot tube

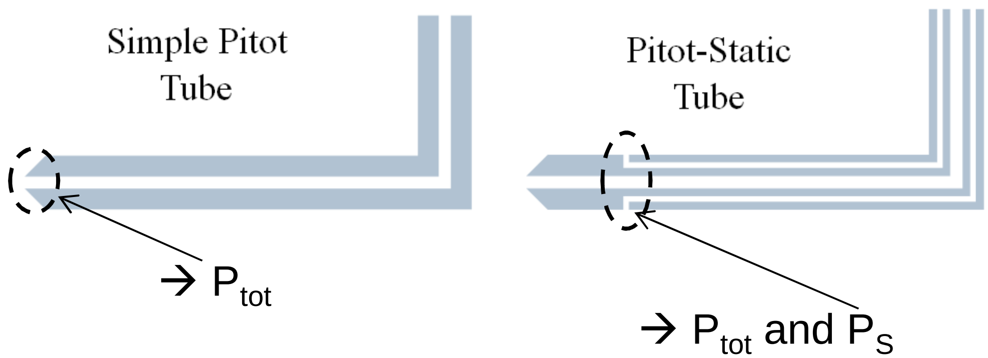
Total pressure is more difficult to be measured:

- Need to reduce the flow velocity to zero: V=0m/s
- Use stagnation point

Pitot tube:

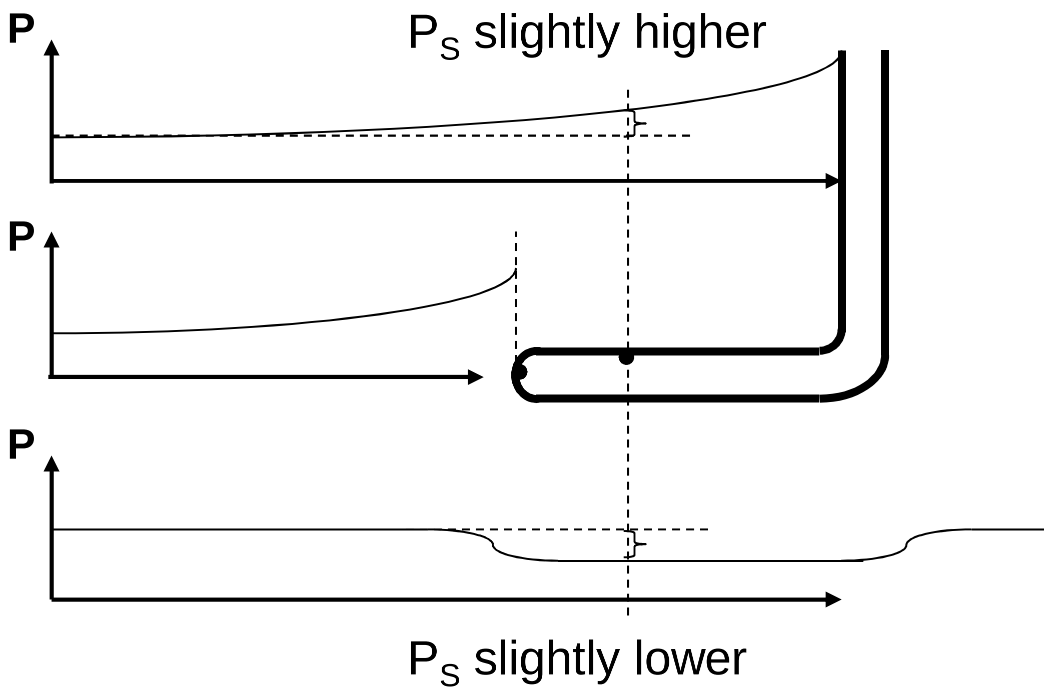


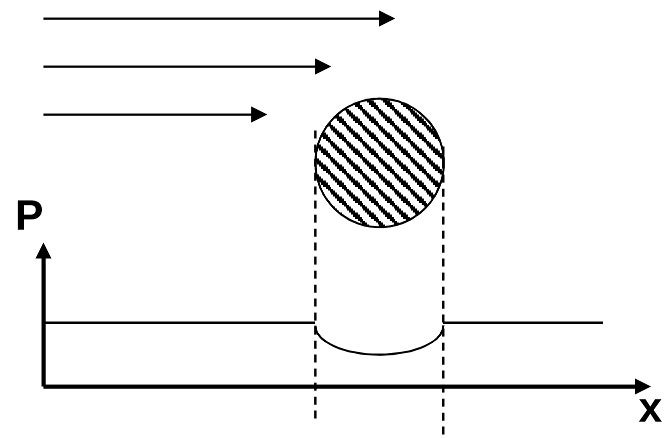




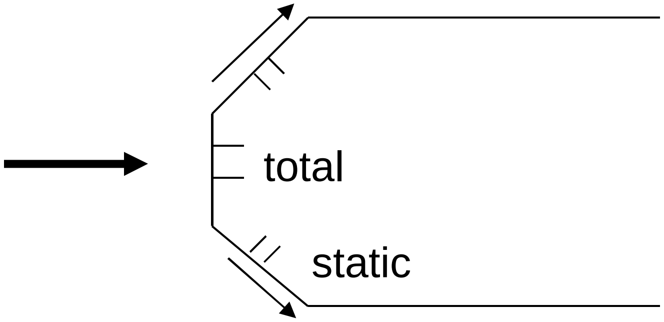
$$V = \sqrt{\frac{2\left(P_{tot} - P_S\right)}{\rho}}$$

Pitot Tube: Where to put the static pressure holes?





5-Hole Probe



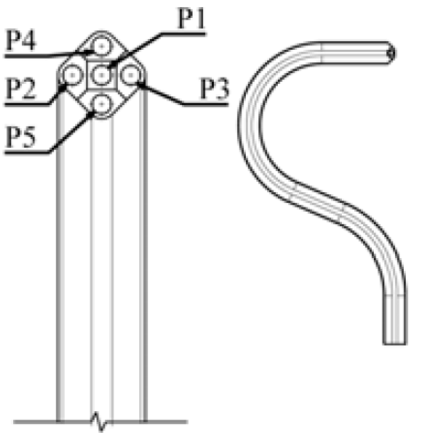
$$P_{ave} = \frac{P_2 + P_3 + P_4 + P_5}{4}$$

$$\Delta P = P_2 - P_3 \rightarrow \alpha$$

$$\Delta P = P_4 - P_5 \rightarrow \beta$$

$P_1 = P_0$ when probe is aligned with flow

$P_{ave} \neq$ static pressure, but an approximation

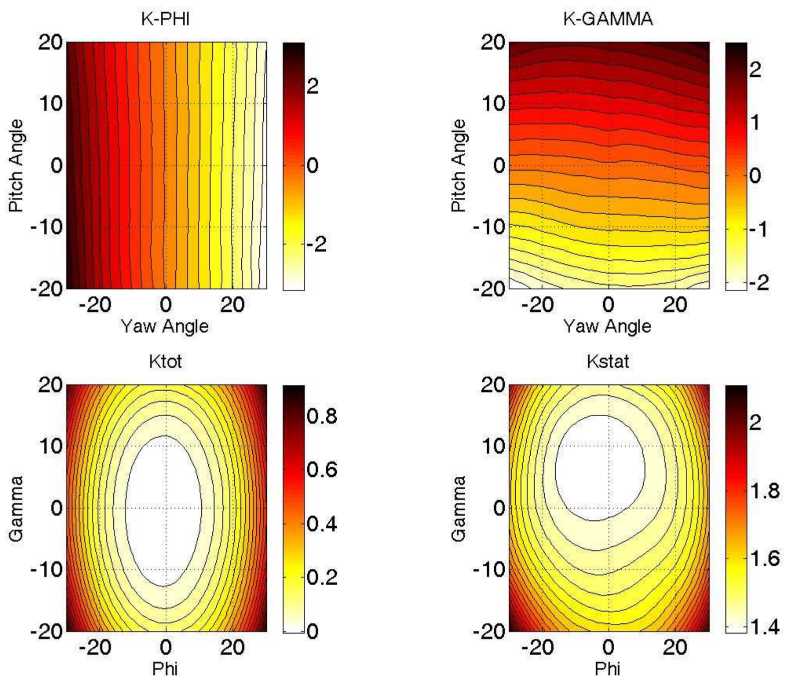


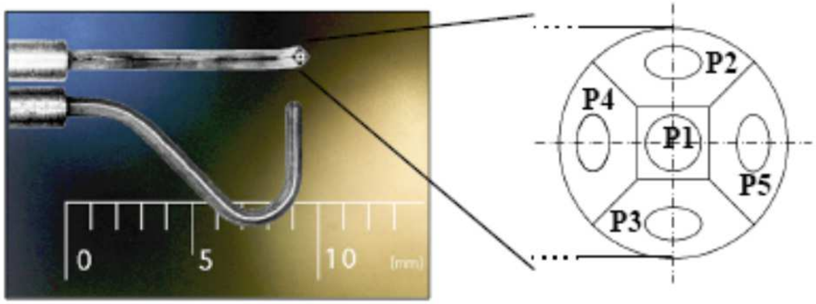
5 Hole Probe Calibration

$$\frac{P_2 - P_3}{P_1 - P_{ave}} \rightarrow \beta \qquad \frac{P_4 - P_5}{P_1 - P_{ave}} \rightarrow \alpha$$

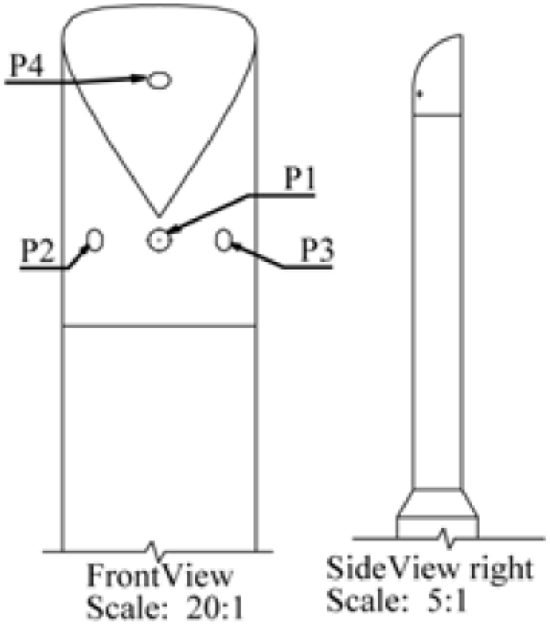
$$\frac{P_{tot} - P_1}{P_1 - P_{ave}} \rightarrow \mathrm{K}_{tot} \qquad \frac{P_{tot} - P_S}{P_1 - P_{ave}} \rightarrow \mathrm{K}_{static}$$

Non dimensionalizing using any Δ_p





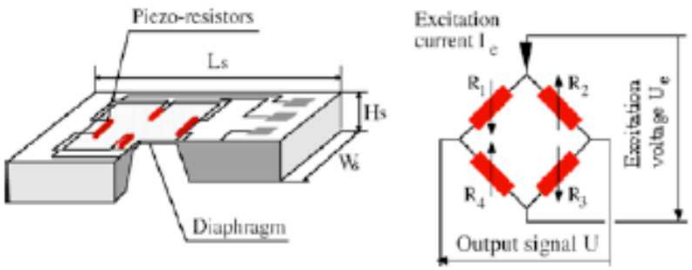
4 Hole Probe



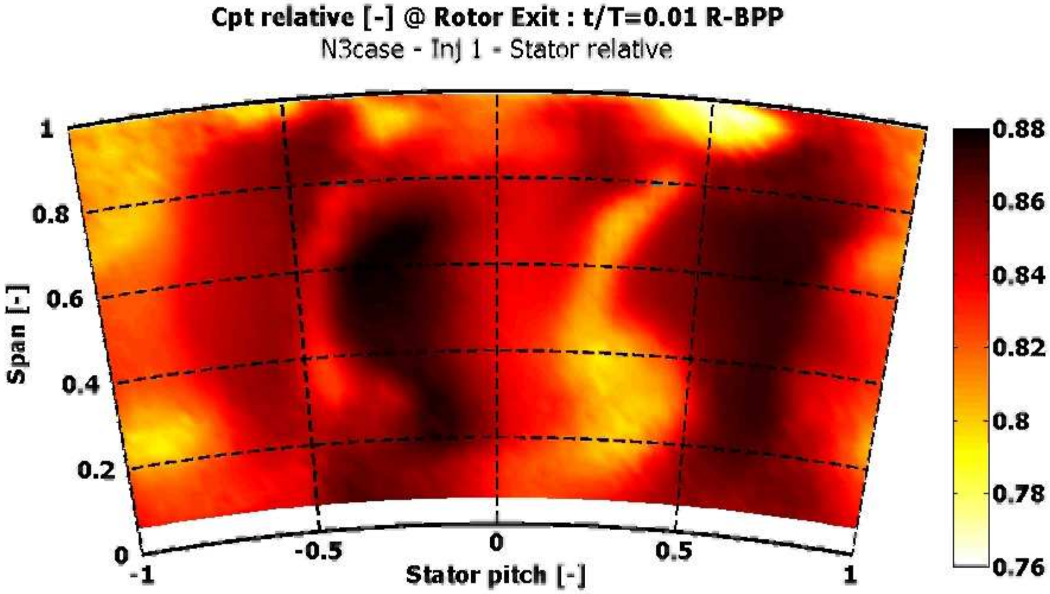
- 4 Hole Probe has a different tip shape
- Reduced pitch sensitivity (no P5)
- Other pneumatic probes:
  - 7HP
  - Multihole

Time resolved measurements: FRAP

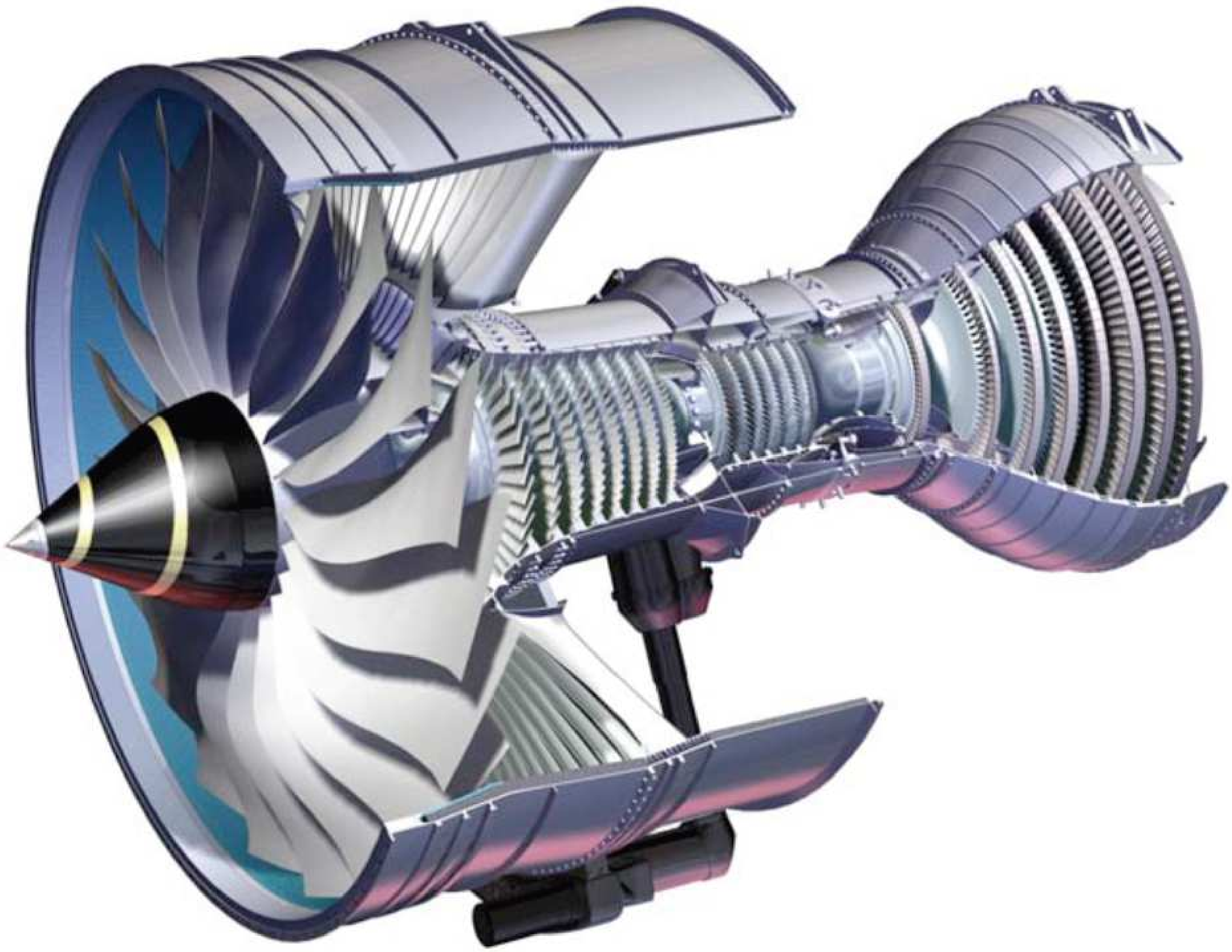
- FRAP = **F**ast **R**esponse **A**erodynamic **P**robe
- Probe has two holes:
  1 yaw hole (for yaw angle sensitivity) and
  1 pitch hole (for pitch angle sensitivity)
- Piezo resistors on membranes directly at the holes
- Deformation of membranes ~ pressure signal
- Enables time resolved measurements
- Calibration analogue to pneumatic probes



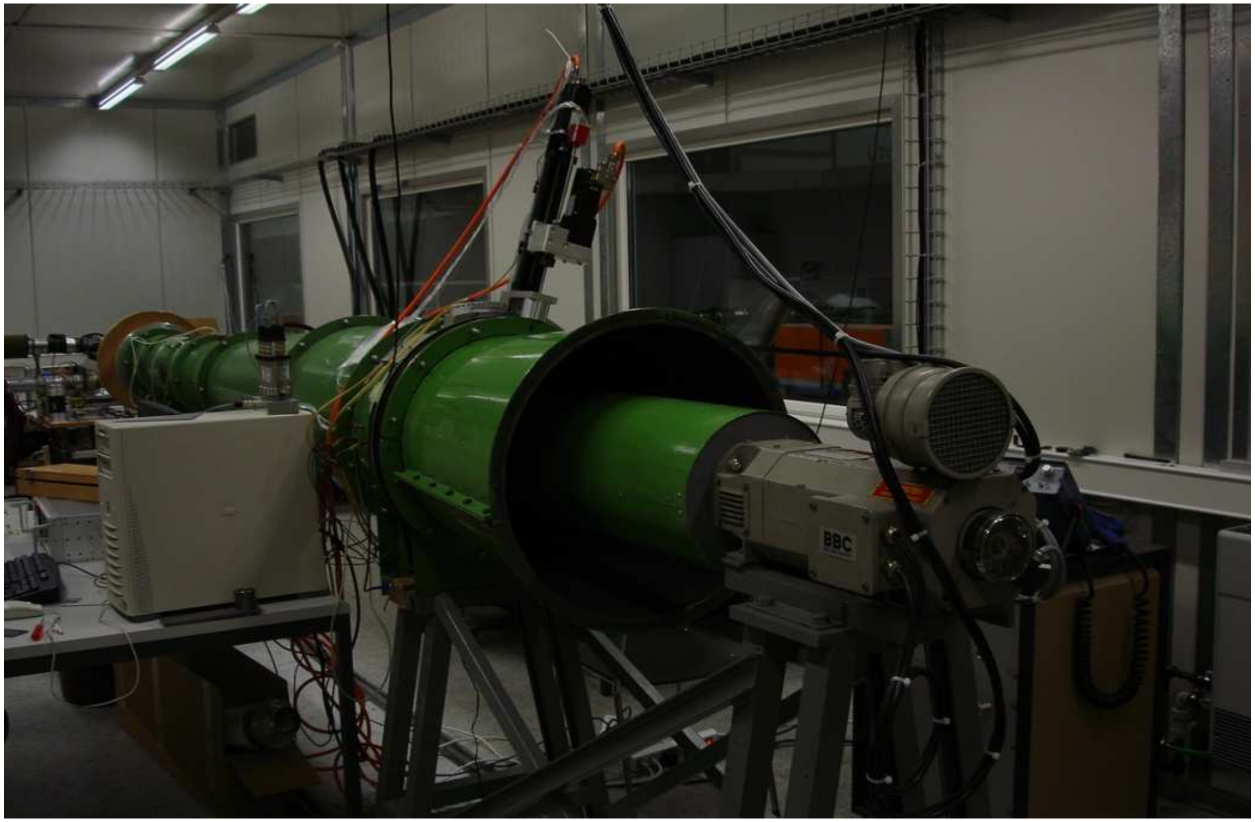
Unsteady measurement example



- Stator Relative total pressure measurement at the exit of turbine rotor
- Measured with FRAP
- Blade passing frequency = 2430Hz



Laboratory: Intrusive Probe Measurement Technique in Turbomachinery



→ Pressure measurements at the exit of an axial compressor using 5HP

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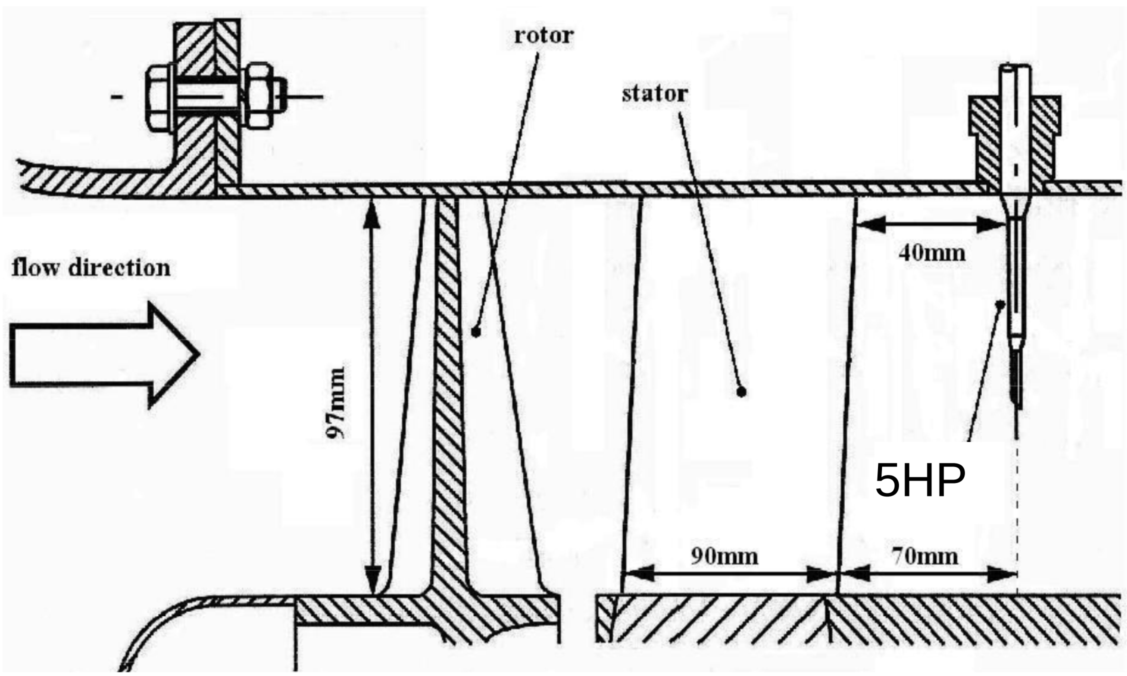
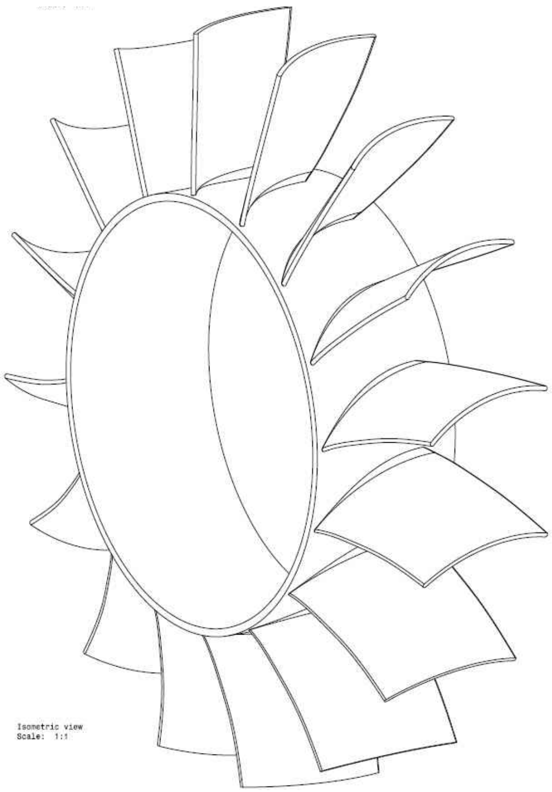
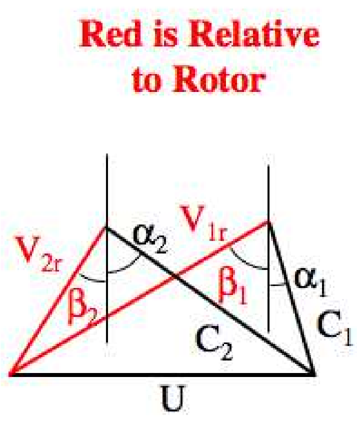


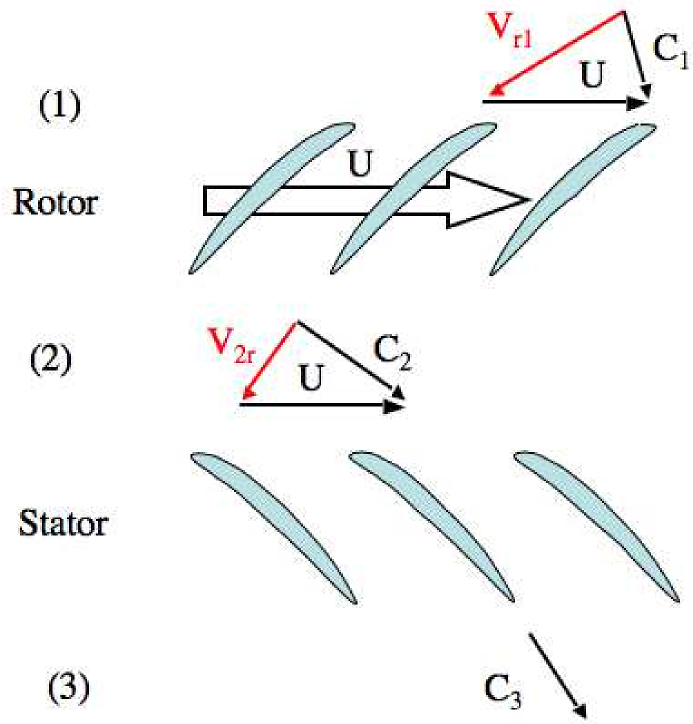


Stator

Laboratory: Intrusive Probe Measurement Technique in Turbomachinery



Conventional Way of Plotting Velocity Triangles



→ Velocity Triangles

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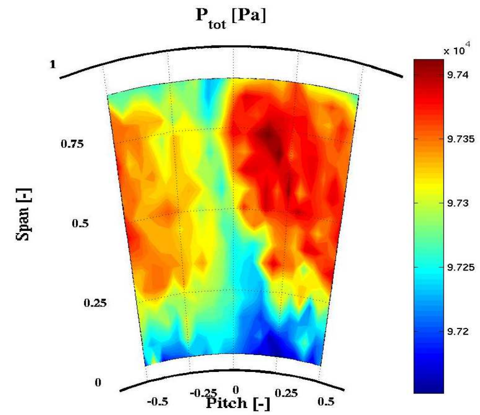
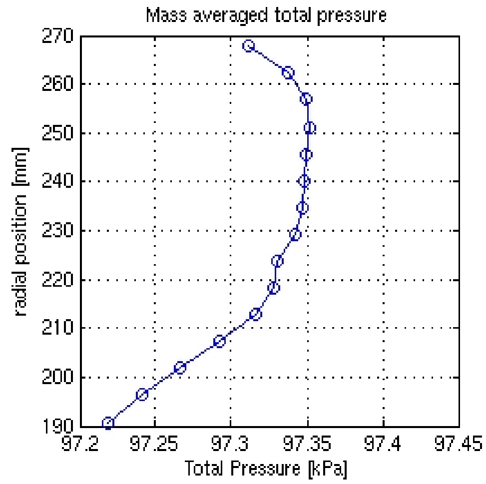


- Post Process the data with **MATLAB** and present the following flow parameters:
  - P_{tot}, P_{stat}
  - Mach number
  - Yaw angle, Pitch angle
  - Velocities V_x, V_r, V_Θ



- The data should be presented in two main forms:
  - 2D plots over the pitch
  - mass averaged plots over the span

- Produce Velocity Triangles