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Industrial Technology Research Institute

3D Pitot Tube Measurements and Calibration in the Wind Tunnel

Center for Measurement Standards
Industrial Technology Research Institute
Taiwan, R.O.C.

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April 20, 2015

About ITRI

- Founded in 1973









- **Total Staff：5,782**
- **Ph.D. ：1,295**
- **Total Patents：16,732**
- **Start-Ups ：171**

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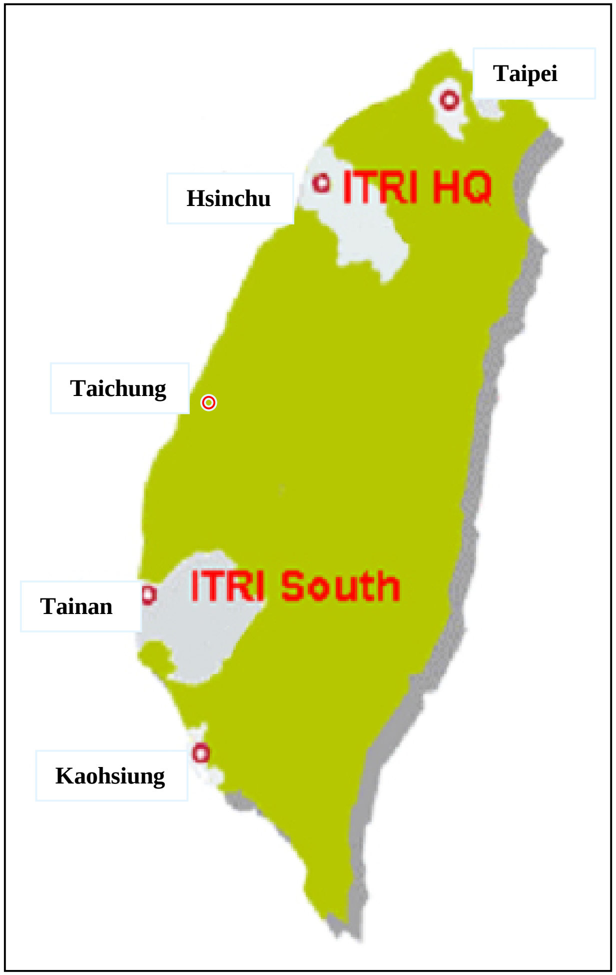
About ITRI

- A not-for-profit non-government R&D organization

- To create economic value through innovation and technology R&D
- To spearhead the development of emerging new industry
- To enhance the competitiveness of Taiwanese industries in the global market



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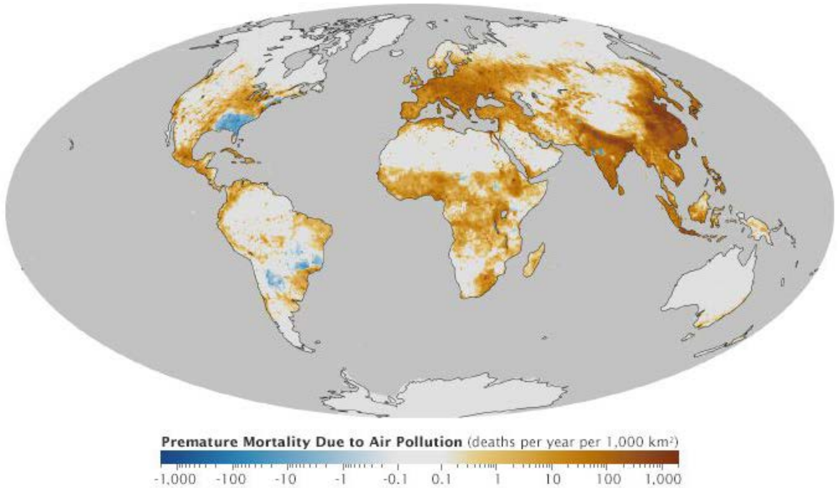
Beauty and Sadness of Taiwan

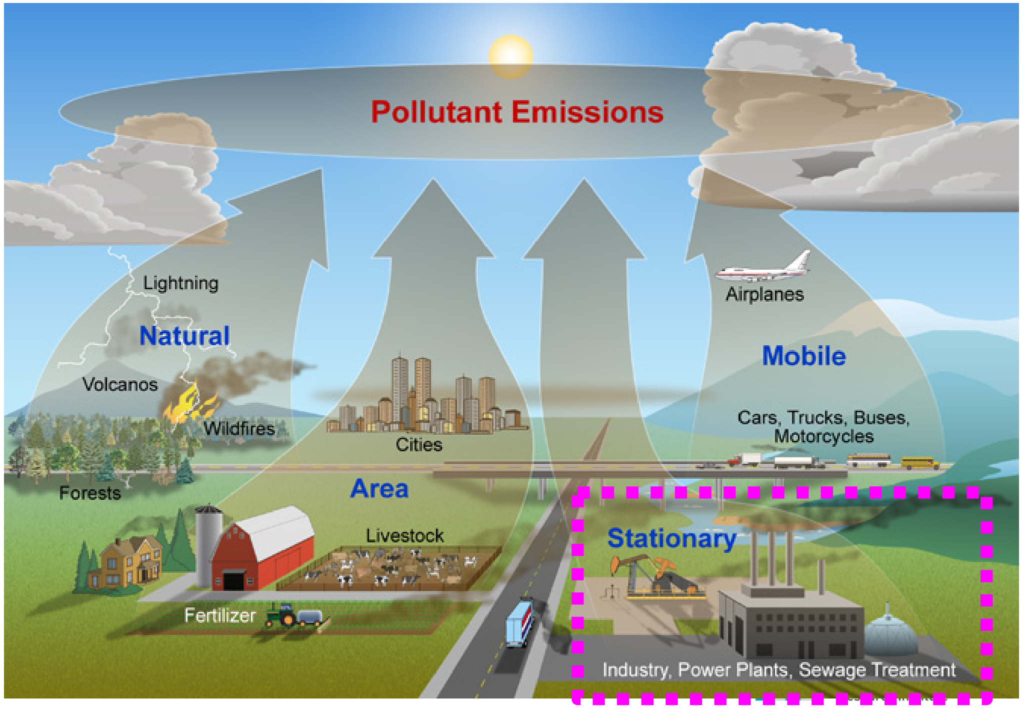
Introduction



Where on earth are you most likely to die early from air pollution?

Stationary Source Emissions

in air quality terminology is any fixed emitter of air pollutants, such as fossil fuel burning power plants, petroleum refineries, petrochemical plants, food processing plants and other heavy industrial sources



Technology Needed for Smokestack Flow Measurements

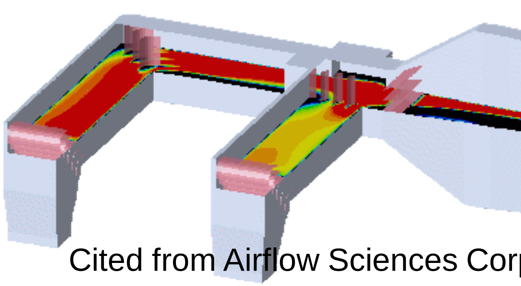
Touch panel manufacturers

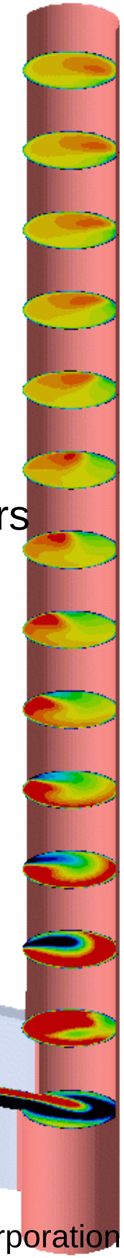
Waste incineration plants

Semiconductor manufacturers

Technical challenges

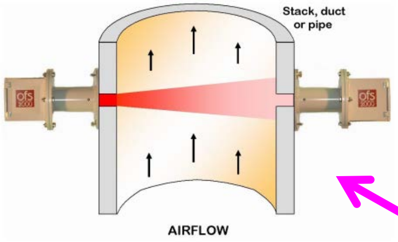
- Swirl and inhomogeneous flow
- Complicated compositions
- Location of measurements
- Calibration of instruments

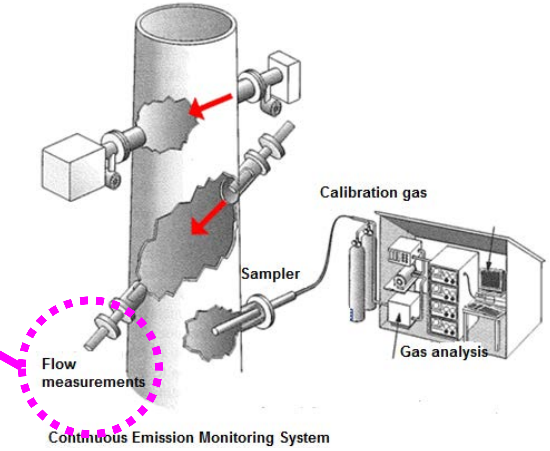




Cited from Airflow Sciences Corporation

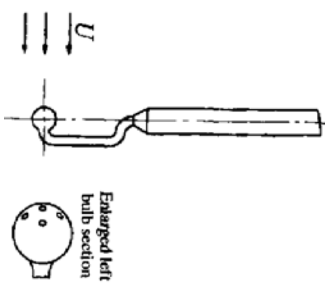
Characterization of Pitot Tubes
- Introduction





EPA Methods 2F, 2G, and 2H
(40 CFR Part 60, Appendices A-1 and A-2)

- Method 2 is fine for situations where there is a straight forward flow profile, however it is prone to bias if cyclonic flow and wall effects are ignored
- Method 2G is used for accurate velocity and volumetric flow rate measurements when stack gas has significant yaw angle; it may be conducted using either a Type S or 3-D probe
- Method 2F is used for accurate measurements when stack gas has significant yaw and pitch angle; it must be conducted using a three-dimensional (3-D) DAT or spherical probe
- Method 2H (or CTM-041 for rectangular ducts) is used for accurate measurements by accounting for velocity drop-off near the stack or duct wall



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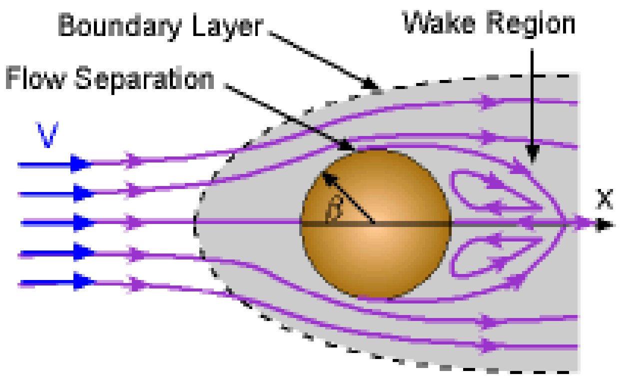
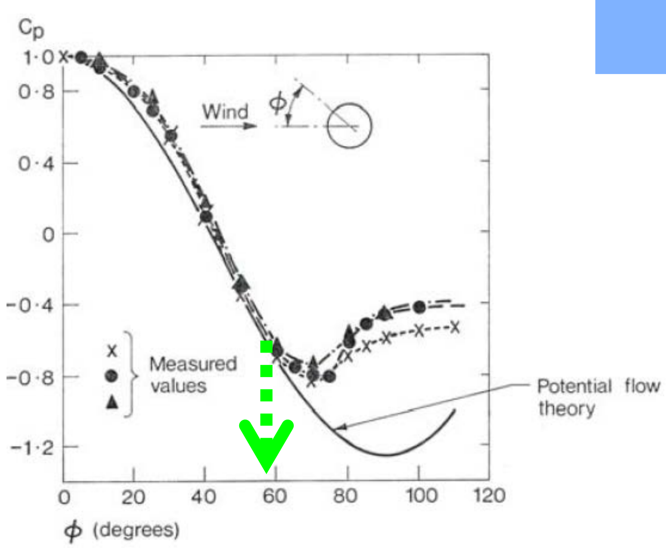
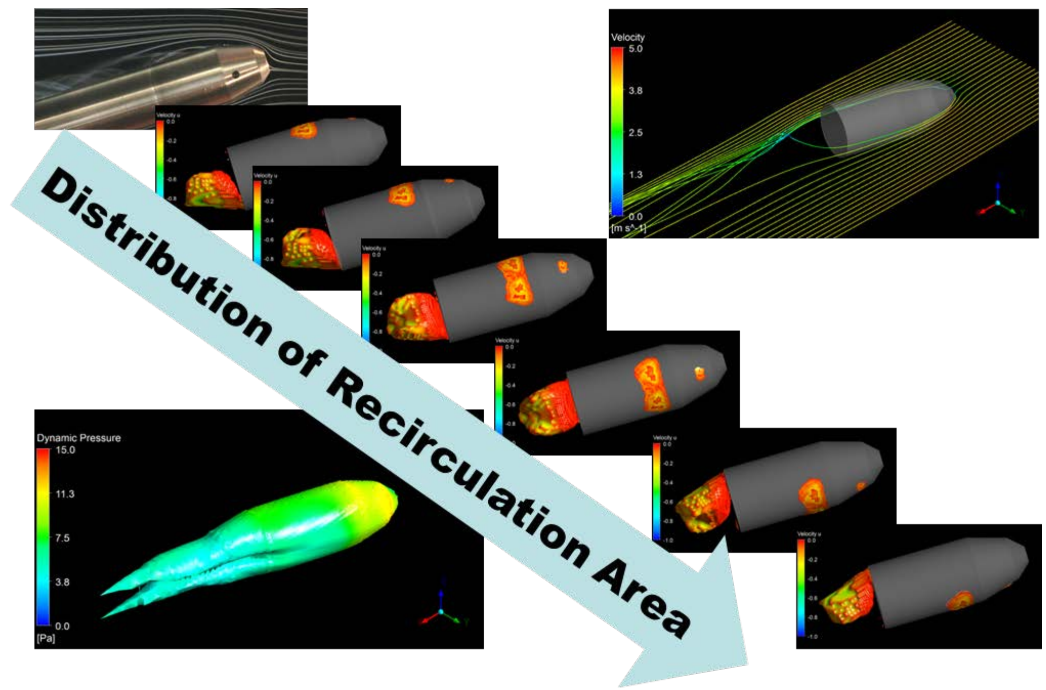
Characterization of Pitot Tubes

- Flow visualization of pitot probes by CFD





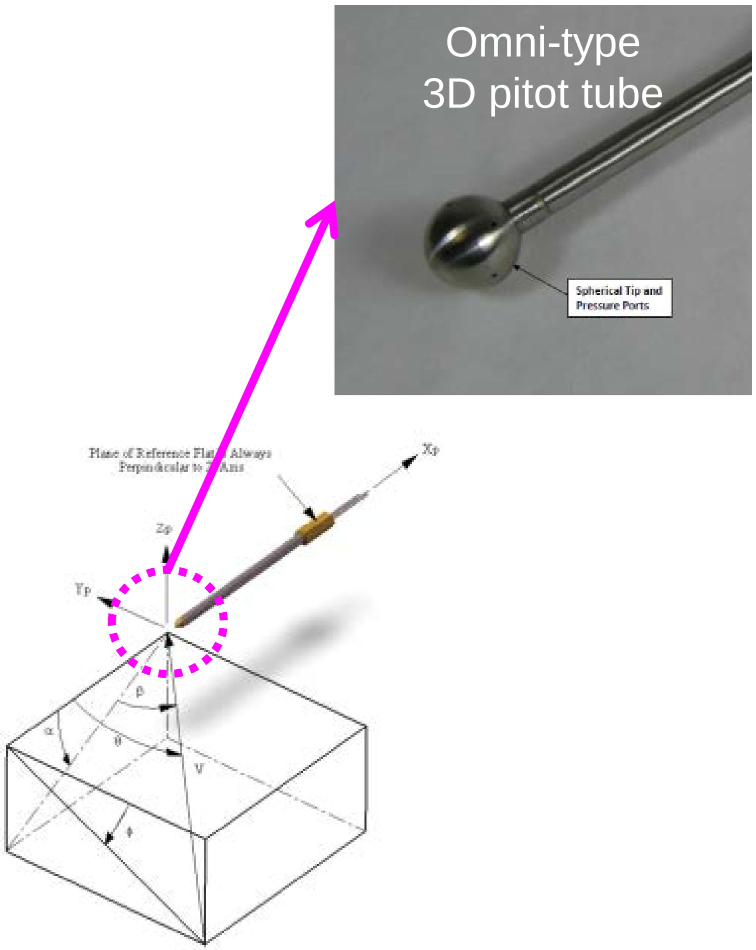


Governing equation: $\frac{p}{\rho} + \frac{V^2}{2} + gz = \text{constant}$

Assumptions:
(1) Steady flow.
(2) Incompressible flow.
(3) Flow along a streamline.
(4) Frictionless deceleration along stagnation streamline.

$$V = \sqrt{\frac{2(p_0 - p)}{\rho_{air}}}$$

Characterization of Pitot Tubes
- Design of 3D pitot tubes



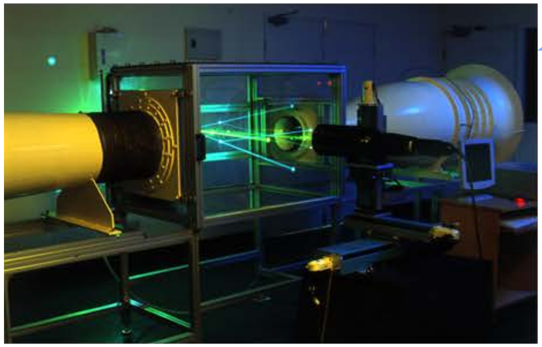
Geometry and Construction		Measurement Accuracy (w/Aeroprobe Calibration)	
Probe Geometry	Straight, L-Shaped	Flow Angles	< 1°
Number of Holes	12	Total Flow Velocity	< 1%*
Tip Geometry	Spherical	Required Auxiliary Data**	Reference Pressure, Total Temperature
Tip Diameter	6.35 mm, 9.53 mm	Flow Angle of Receptivity	120°
Material	All-Stainless Steel Construction	Calibration Flow Speeds	5 m/s to 315 m/s (Mach = 1.0)
Pneumatic Connection	Tygon R3603 Formulation, 1/32" ID, 3/32" OD Standard for Exit Tubing of 0.89 mm – 1.6 mm (0.035" – 0.063") OD.	Pressure Data Reduction	Omnipro Software
		Frequency Response	Low, Best for Determining Time-Averaged Flows
Mounting	Hex Prism (standard)	Media	Non-Reactive Gases
Probe Reference	Flat on Hex Mount with "R"	*Utilizing 0.1% Accurate Pressure Sensors Properly Rated for Flow Speed	
Flow Temp. Limits	0°C – 150°C	**For Most Accurate Compressible P-V Reduction	

Calibration Facilities

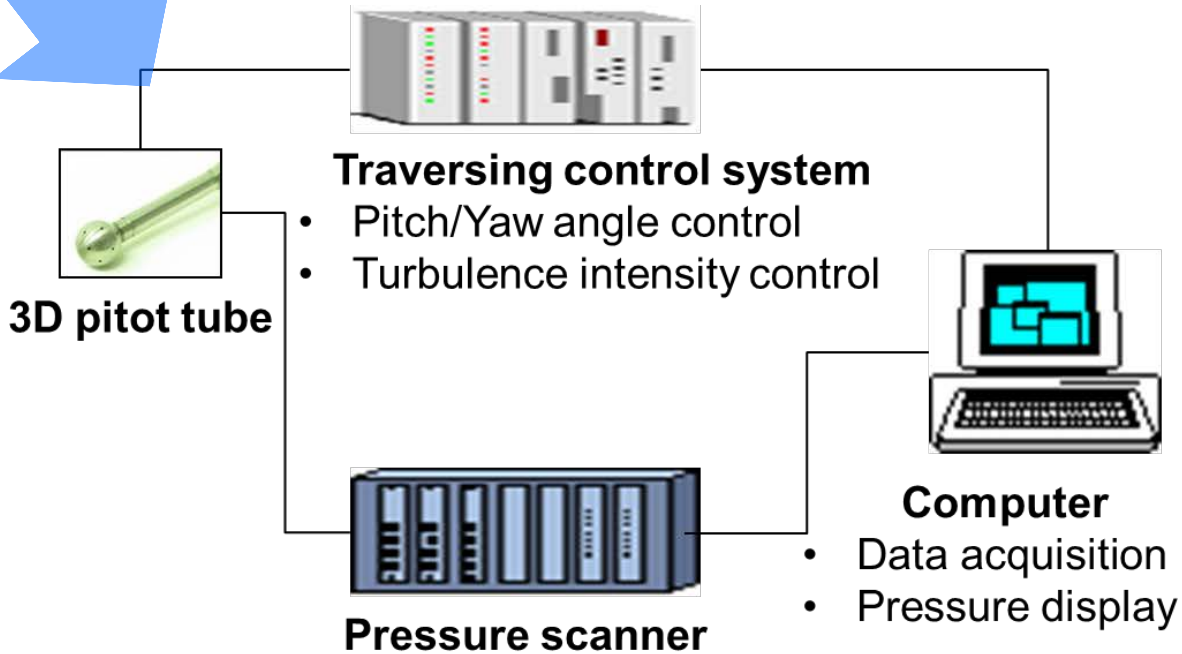
- Calibration system construction at CMS

3D Motion → 3D Measurements

3D Calibration is needed !!

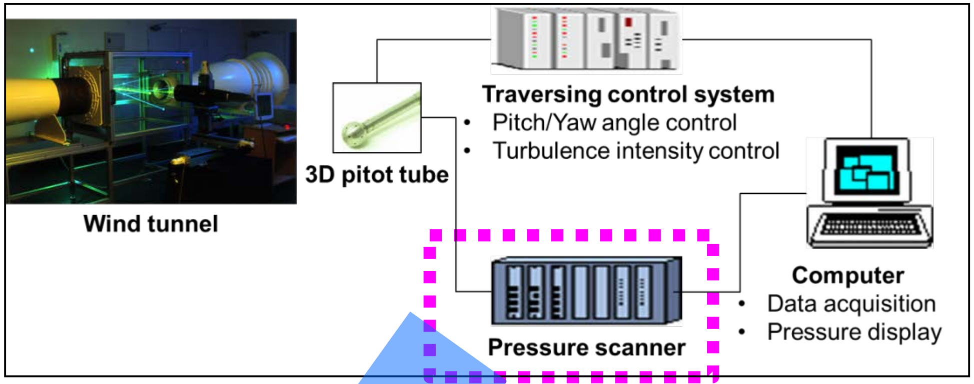


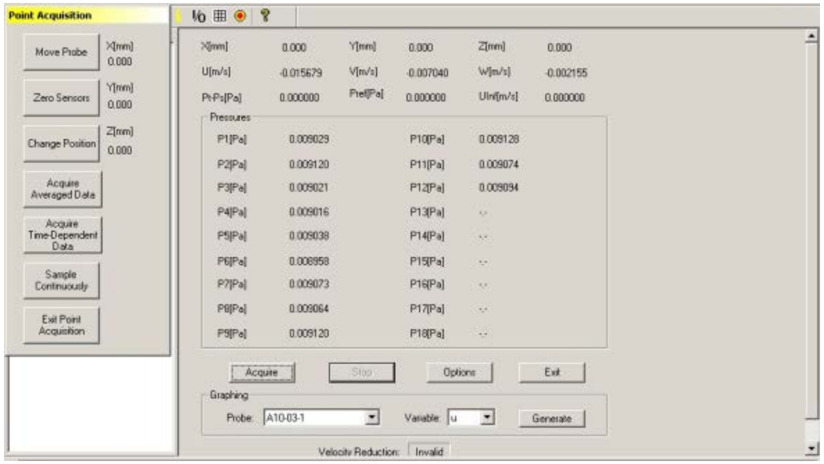
Wind tunnel

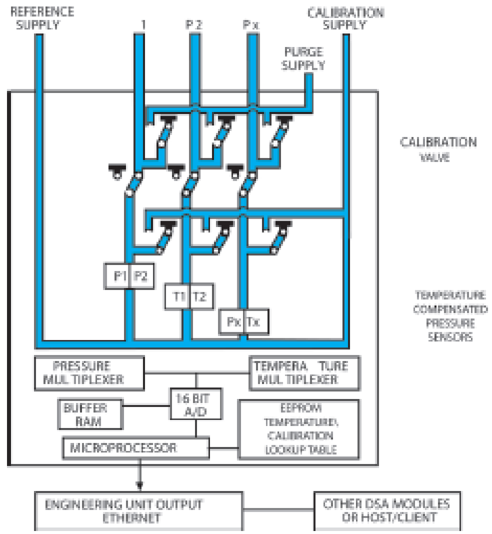


Calibration Facilities

- Pressure measurements and calibration







DIGITAL SENSOR ARRAY

Sensor Pressure Range	Static Accuracy (% F.S.)
±10 inch H_2O (2.5 kPa)	±.20%
±1, ±2.5 psid	±.12%
±5 to 500 psid	±.05%
±501 to 750 psid	±.08%

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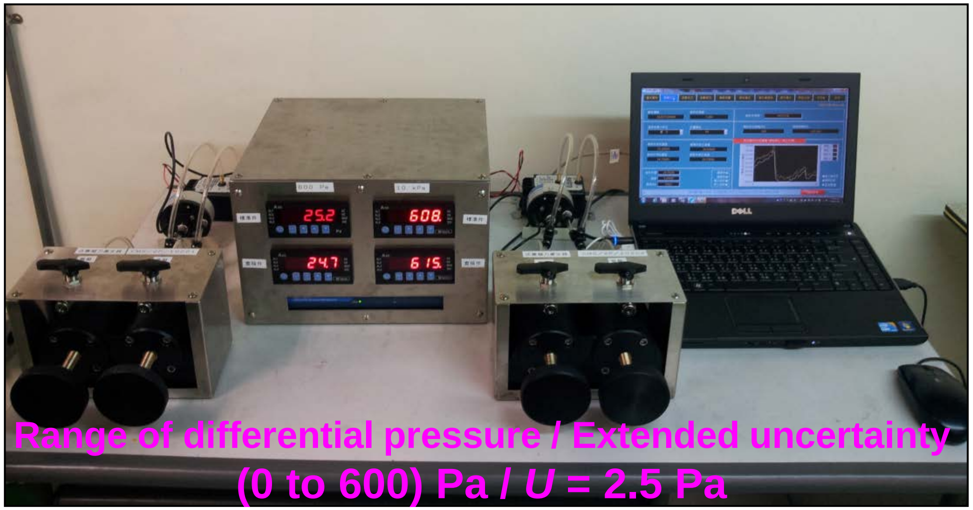
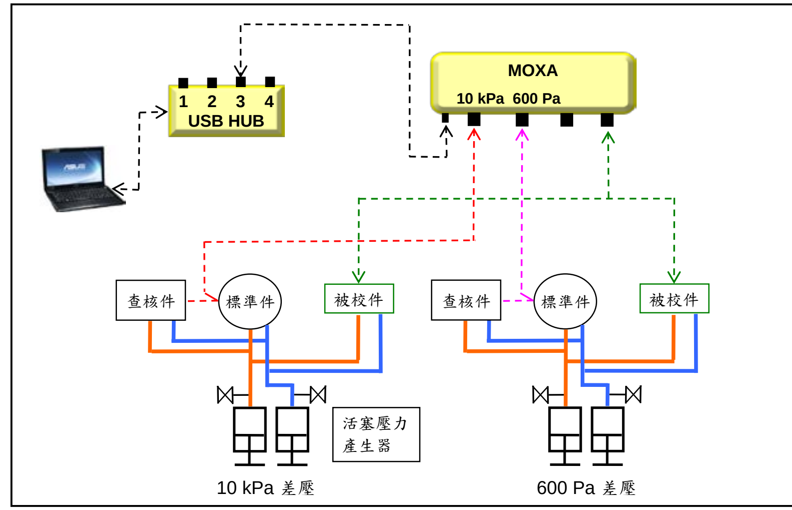
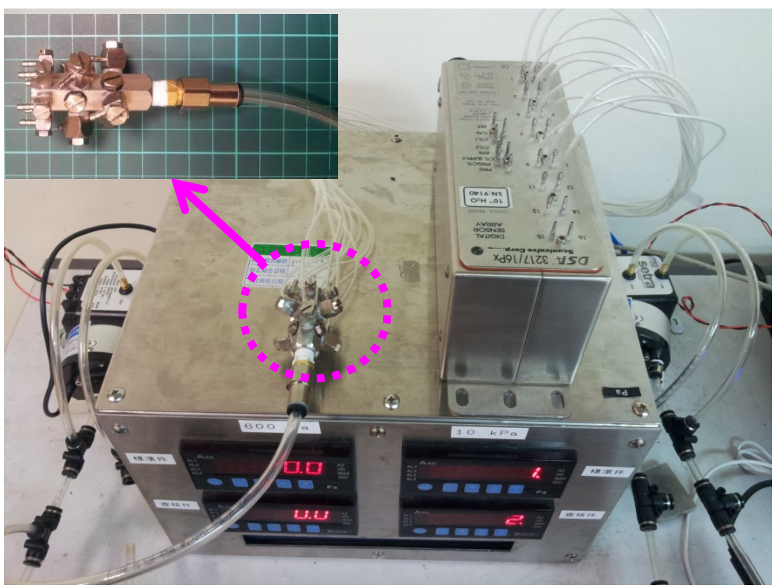
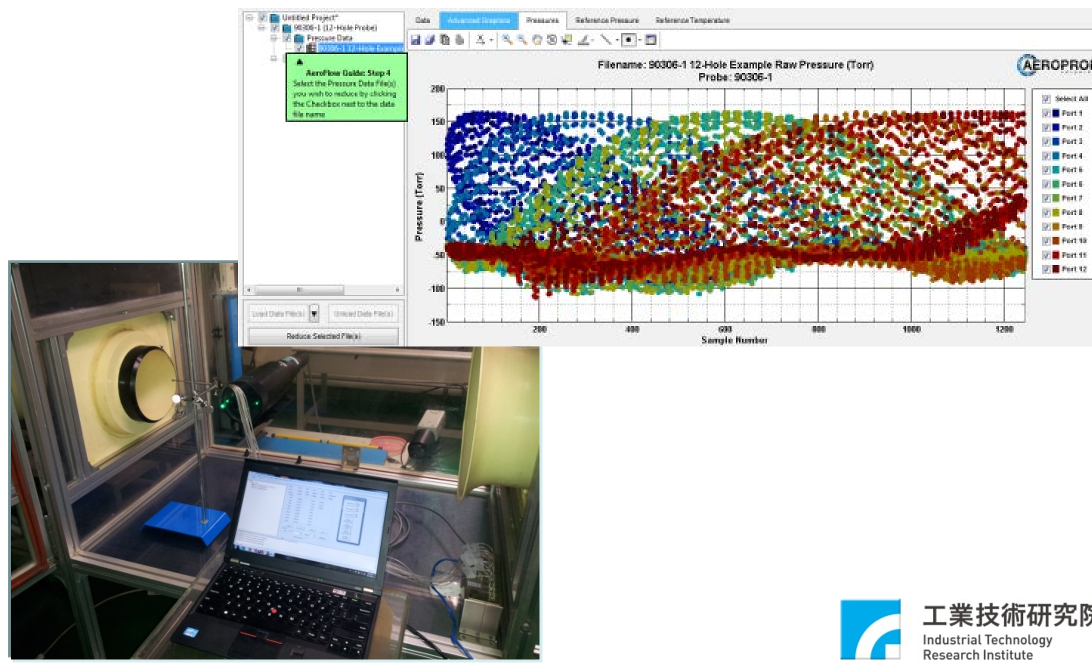




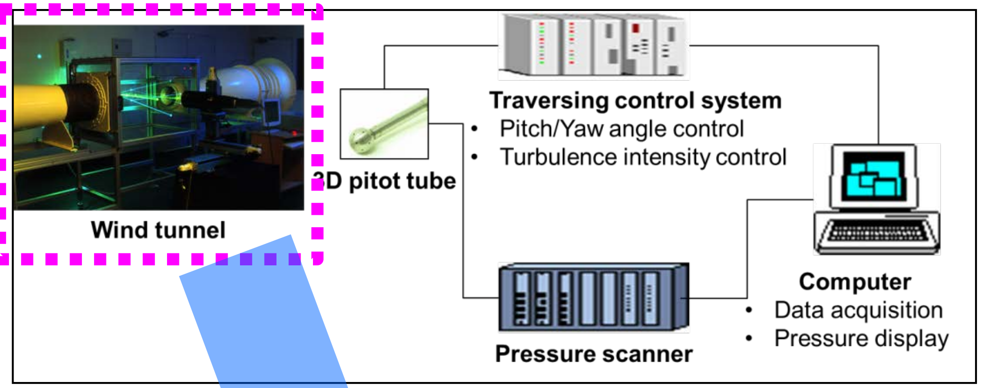
Piston-type Pressure Calibrator

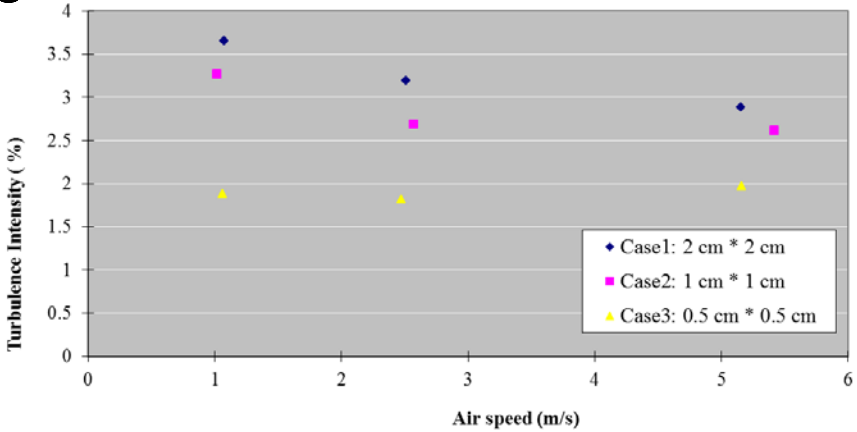




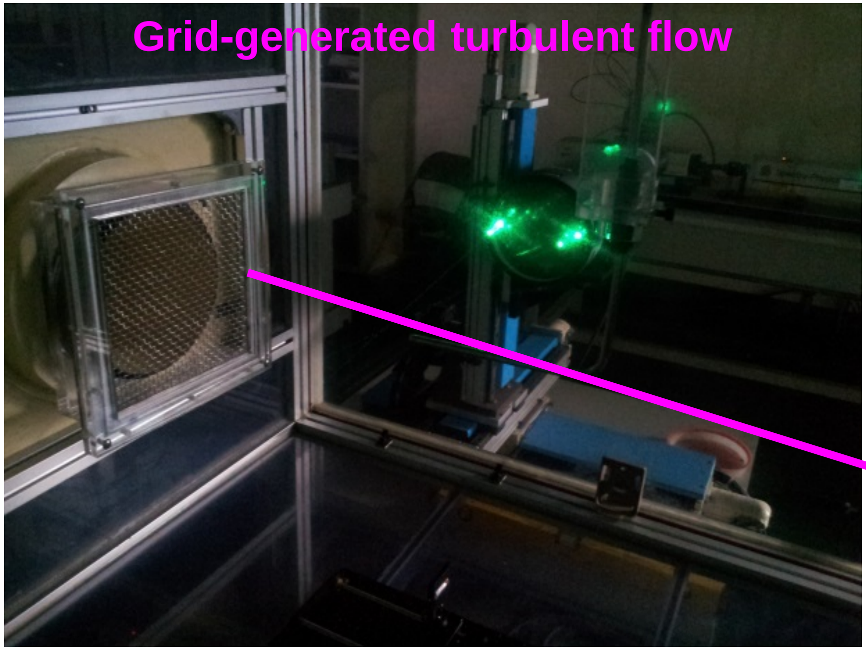
Calibration Facilities

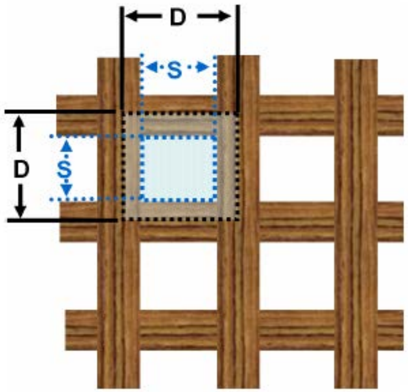
- Turbulence generation

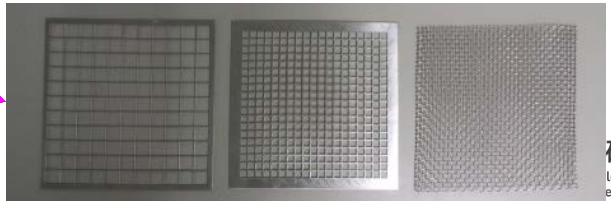




- Without grids: T.I.= (0.7 to 1.4) %
- With grid No.4: T.I.= (1.7 to 4.4) %

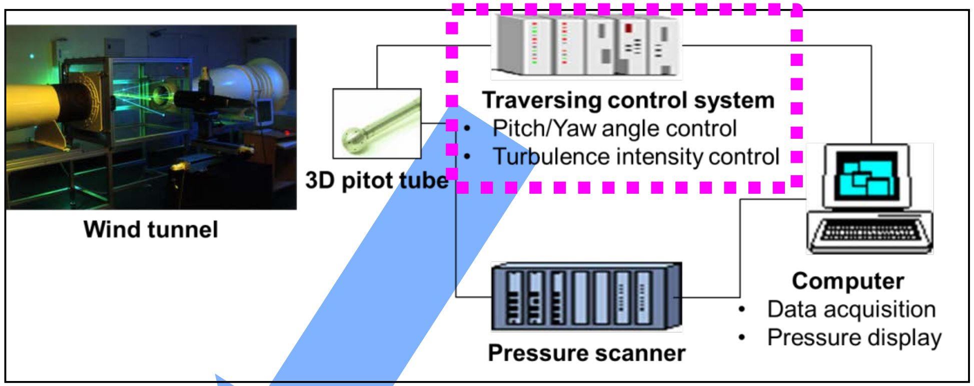


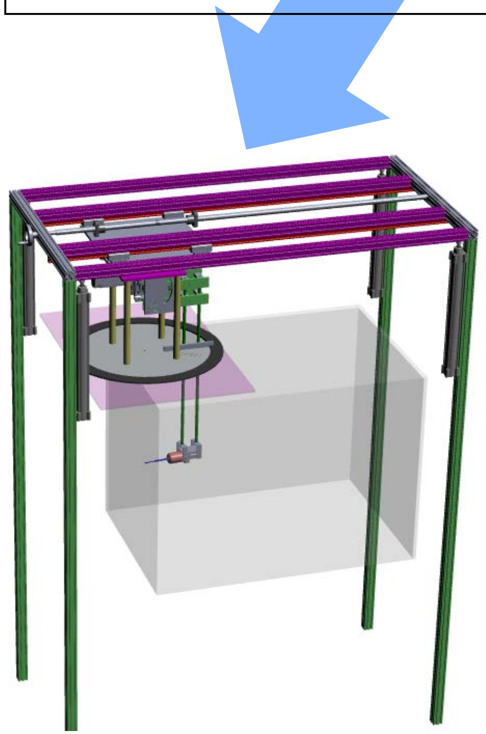


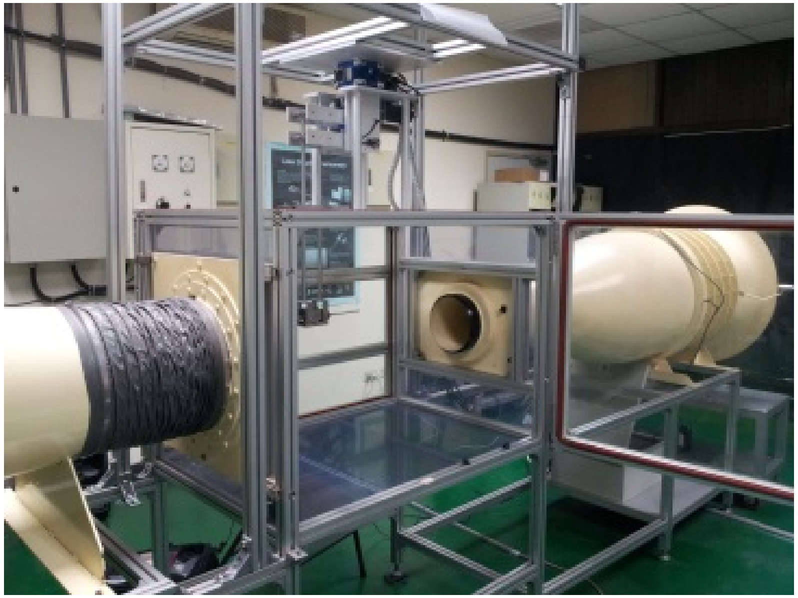


Calibration Facilities

- Traverse stage

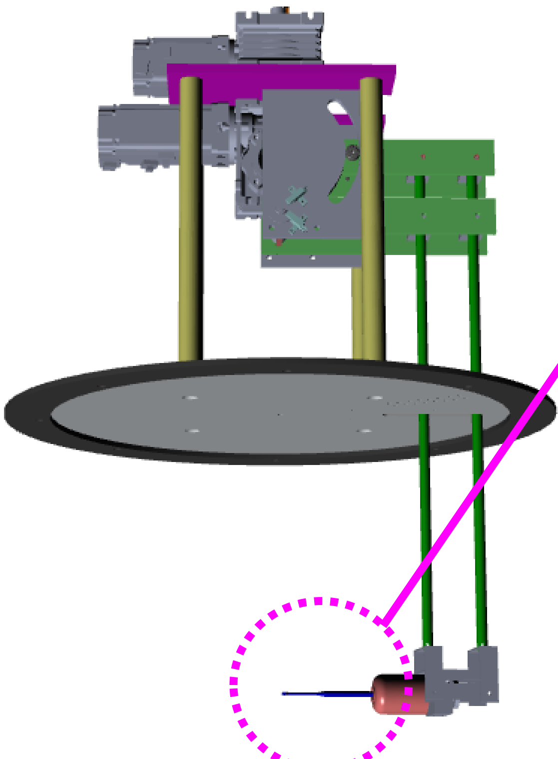


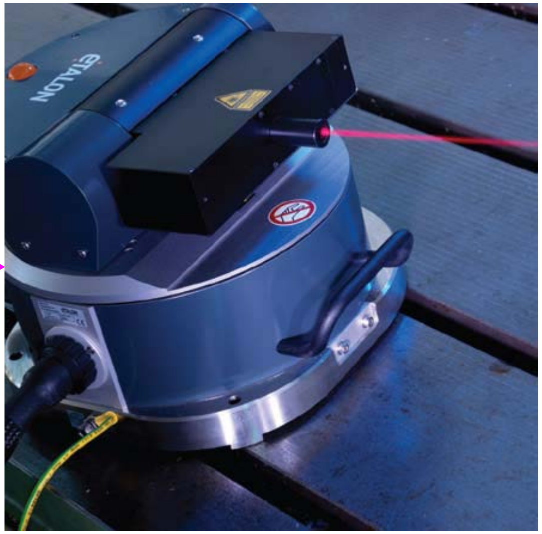


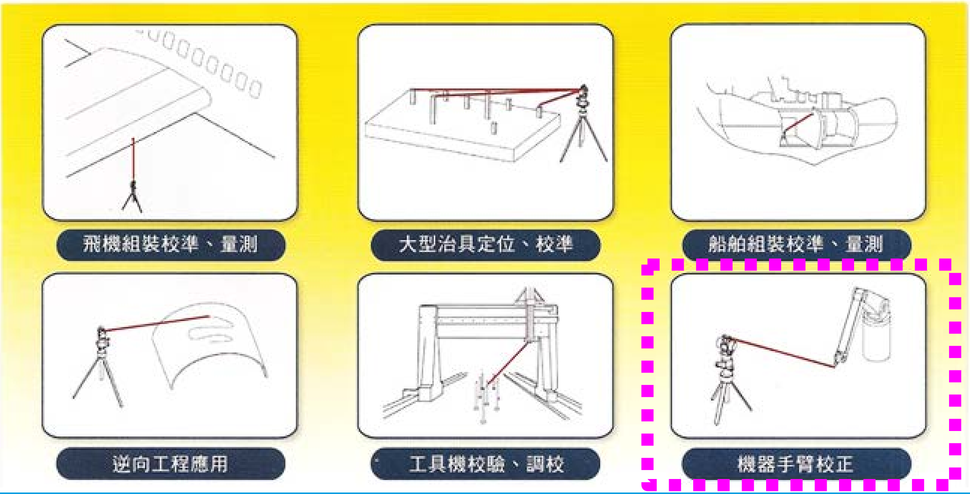


Calibration Facilities

- Angle measurements







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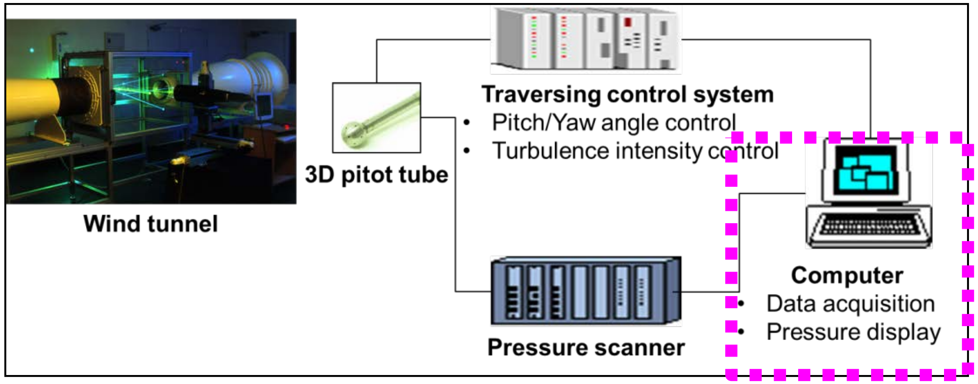
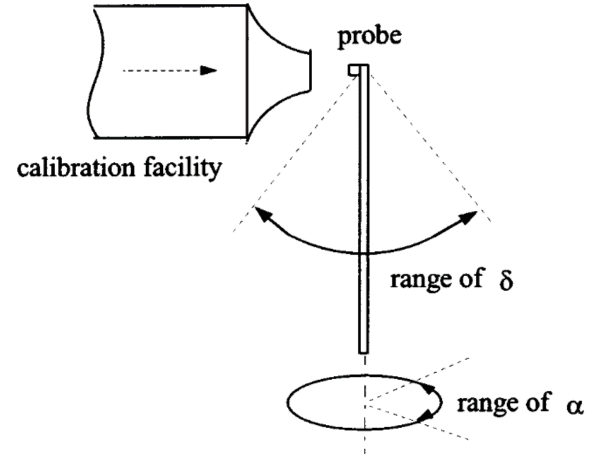
Calibration Data Analysis

- Definition of pressure coefficients





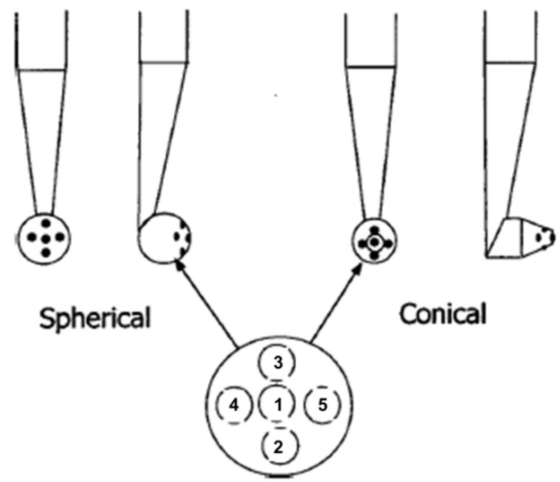
Input:

$$B_\alpha = \frac{p_4 - p_5}{Q'}, \quad B_\delta = \frac{p_1 - p_3}{Q'}$$

where $$Q' = p_2 - 0.25 \times (p_1 + p_3 + p_4 + p_5).$$

Output:

$$\alpha, \delta, A_t = \frac{p_2 - p_t}{Q'}, \quad A_s = \frac{p_2 - p_s}{Q'}.$$



Calibration Data Analysis

- Nulling method

Step 1: Align the probe so that the center hole is pointing towards a reference position.

Step 2: Rotate probe until P2=P3. This is the Yaw angle.

Step 3: Calculate Pitch Angle Pressure Coefficient [(P4-P5)/(P1-P2)].

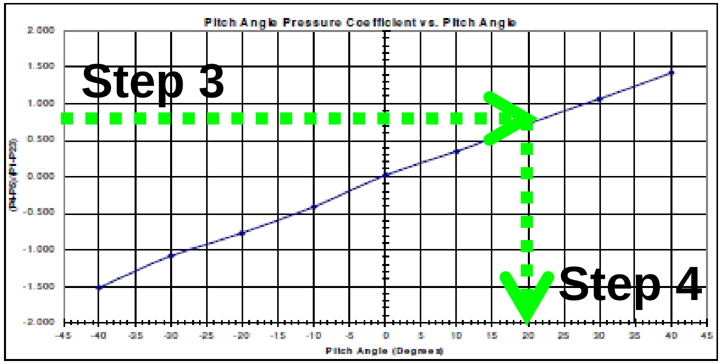
Step 4: Determine Pitch Angle.

Step 5: Determine Velocity Pressure Coefficient [(Pt-Ps)/(P1-P2)].

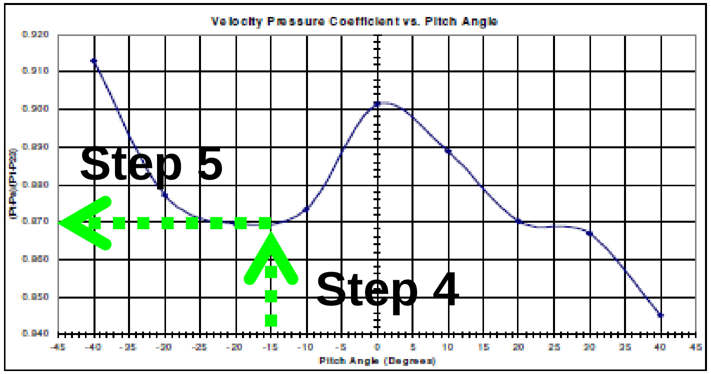
Step 6: Calculate Velocity pressure (Pt-Ps).

Step 7: Determine Total Pressure Coefficient [(P1-Pt)/(Pt-Ps)].

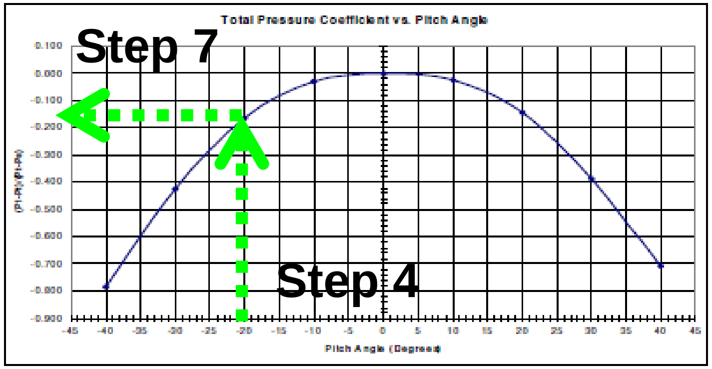
Step 8: Calculate (P1-Pt) and obtain Pt.



Pitch angle vs. Pitch angle pressure coefficient



Pitch angle vs. Velocity pressure coefficient



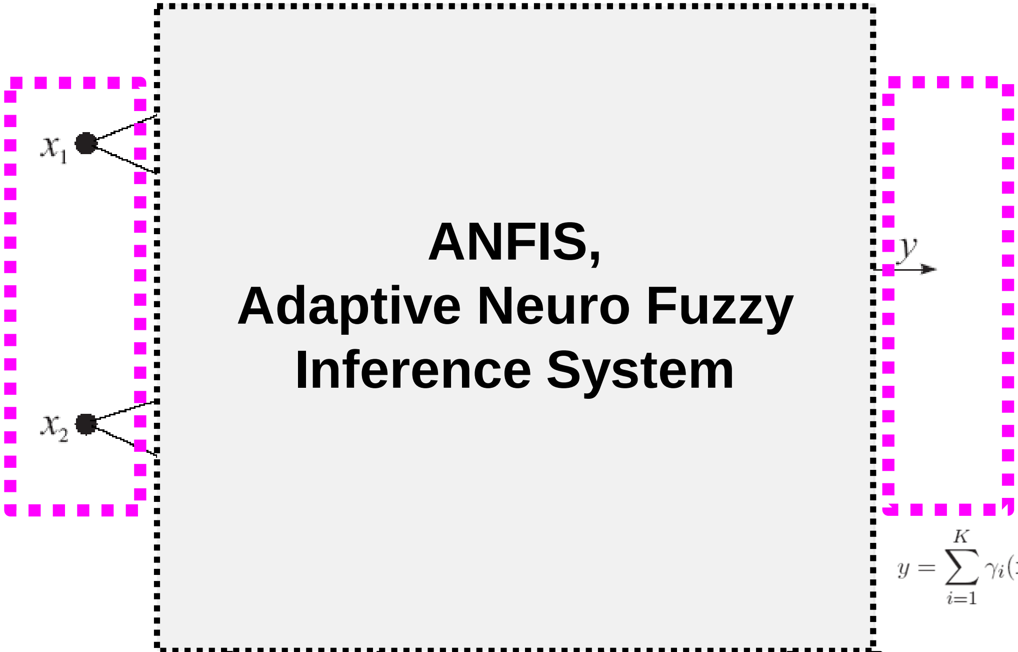
Pitch angle vs. Total pressure coefficient

Calibration Data Analysis

- Non-nulling method

INPUT

- Yaw and Pitch angle pressure coefficients



OUPUT

- Yaw angle
- Pitch angle
- Total and Static pressure coefficient

$$y = \sum_{i=1}^{K} \gamma_i(\mathbf{x}) b_i \quad \text{with} \quad \gamma_i(\mathbf{x}) = \frac{\prod_{j=1}^{p} \exp\left(-\frac{(x_j - c_{ij})^2}{2\sigma_{ij}^2}\right)}{\sum_{i=1}^{K} \prod_{j=1}^{p} \exp\left(-\frac{(x_j - c_{ij})^2}{2\sigma_{ij}^2}\right)}$$

Nodes in this layer contains membership functions

This layer chooses the minimum value of two input weights

Every node of these layers calculates the weight, which is normalized

This layer includes linear functions, which are functions of the input signals

Compute the overall output by summing all incoming signals

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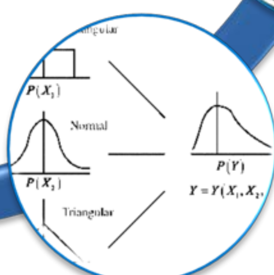
Future Work

Calibration of 3D Pitot Tubes and Flow Measurements of Smokestack Emissions

Pitot tube characterization
- Characterization of yaw and pitch angle for different types of 3D pitot tubes
- Flow visualization by CFD and PIV

Standard traceability
- Integration of wind tunnel and traverse stage for 3D pitot tube calibration

Calibration method and facility establishment
- Comparison of calibration methods (nulling and non-nulling method)



Uncertainty evaluation
- Evaluation of uncertainty evaluation and calibration procedure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