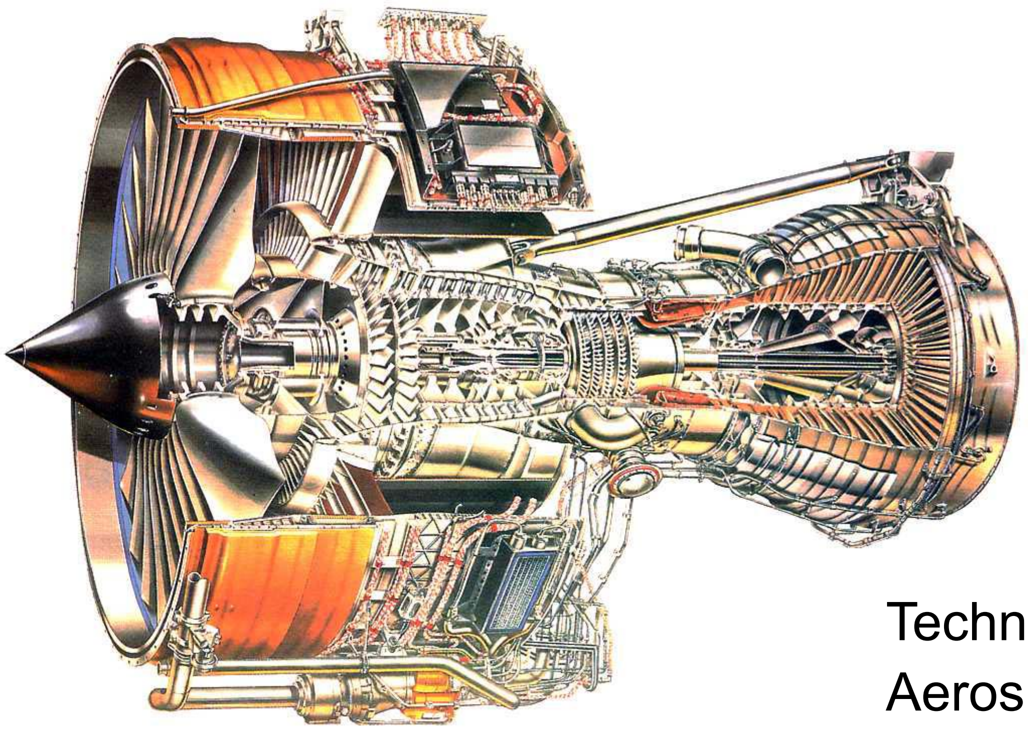
11th Israeli Symposium on
Jet Engines and Gas
Turbines, October 2012
Technion, Israel

Principle And Practice Of Hotwire Anemometry In Turbomachinery Applications



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Introduction

Advantages of Hot wire Anemometry

Ideal tool for Measurement of Perturbation Quantities in Time Domain

- High Frequency Response (~ 10^2 kHz) ➔ Accurately follow transients
- Wide Velocity Range
- High Accuracy / High Signal to Noise Ratio
- Signal Analysis: Output is continuous analogue signal

  ➔ Both Time and Frequency Domain analysis is possible

Challenges of Hot-wire in Turbomachinery Flows:

- Transonic Multi-Dimensional Flow with Large Independent Fluctuating Components
  - HW Data Reduction for Compressible Subsonic / Transonic Flow ($0.4<M<1.2$) problematic
- Flow phenomena generating instantaneous fluctuations of density, velocity, temperature and angle is coupled but not necessarily correlated.
  - Wire Voltage (V) ➔ Function of Density (ρ), Velocity (V), Temperature (T_o) and Angle (ϕ)
- High Speed ➔ High Frequency Response Needed
  - Thinner Wires, Higher Wire Temperature needed (Reliability issues)

Objectives

Development and Validation of X-Hotwire Methodology for Turbomachinery flows:

Experimental Technique Development Requirements:

- Practical : Absent of Closed Loop Wind Tunnels Varying Each Flow Quantity Independently
- Reliable / Repeatable ➔ Precise & Accurate Results
- Applicable in Wide range of Flow Conditions (from Subsonic to Transonic)
- Intuitive: Based on Scientific Concepts, not Empirical Collapse of Data

➔ Limitations and Capabilities Well Known

Validation and Exemplary Implementation

- 2-D Fluctuation Measurements in Compressible Subsonic / Transonic Flow regimes

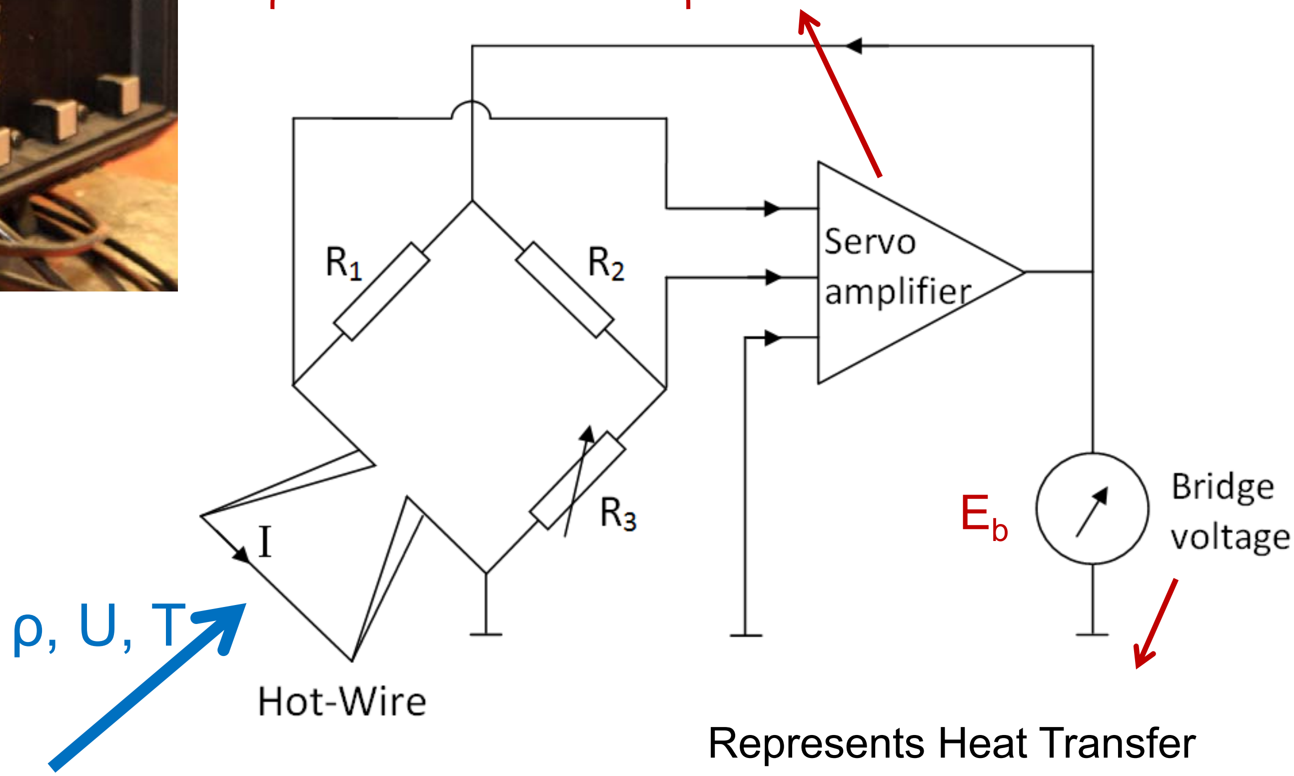
Downstream of a Gas Turbine Fan

- Instantaneous Mass Flow, Velocity, Density, Pressure are Measured

Constant Temperature Hotwire Anemometry

Wheatstone Bridge

Keeps Bridge in Balance via Controlling current to the wire
$\therefore R_{wire}$ ($\rightarrow T_{wire}$) is constant

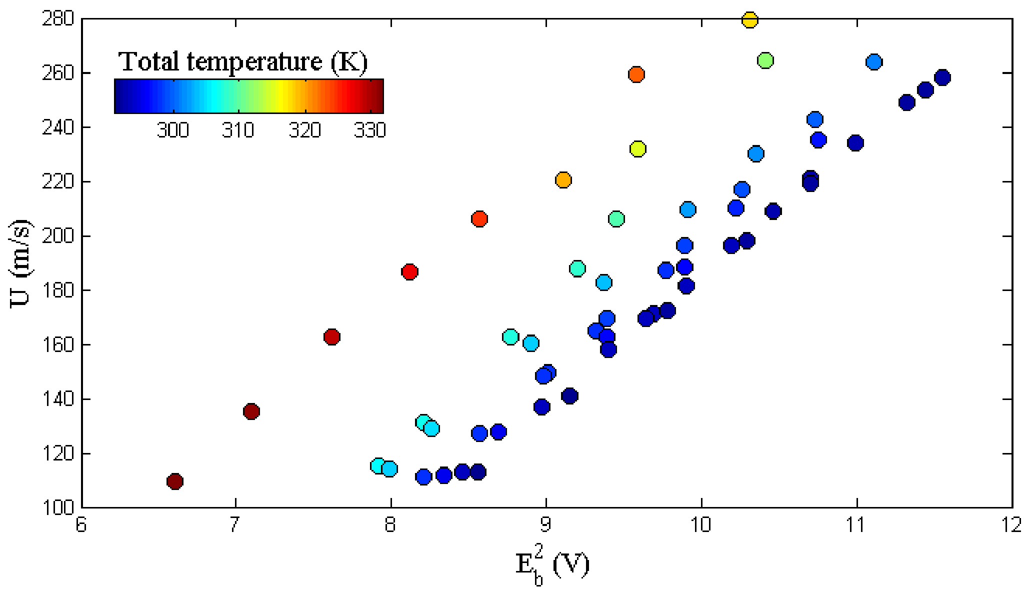


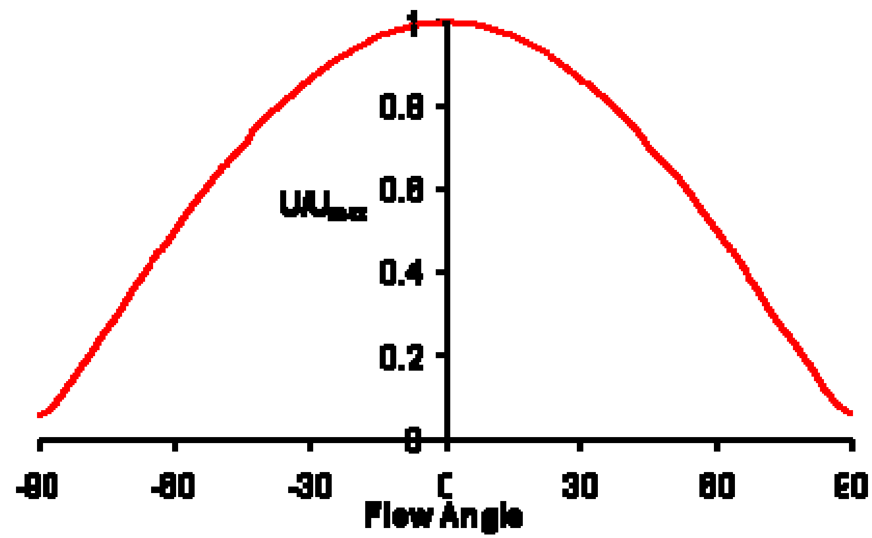
Represents Heat Transfer
$\therefore$ Measure of Flow Properties

- Low Sensor Thermal Inertia
- High Servo Loop Amplifier Gain

$\Big\}$ High Frequency Response

Hotwire Voltage Dependency





Bridge Voltage is Sensitive to Variations in Velocity, but also:

a. Total Temperature

b. Density

c. Flow angle

$$\boxed{E \;=f(\rho, U, T_0, \phi)}$$

Conventional Methodology

Sensitivity analysis:

$$\boxed{\frac{e'}{\overline{E}} = S_\rho \frac{\rho'}{\overline{\rho}} + S_u \frac{u'}{\overline{U}} + \cancel{S_{T_0} \frac{T_0'}{\overline{T_0}}} + S_\phi \phi'}$$

$$S_\rho(\rho,U,T_0,\phi) = \left.\frac{\partial \log E}{\partial \log \rho}\right|_{U=const.,\ T_0=const.,\ \ \phi=const.}$$

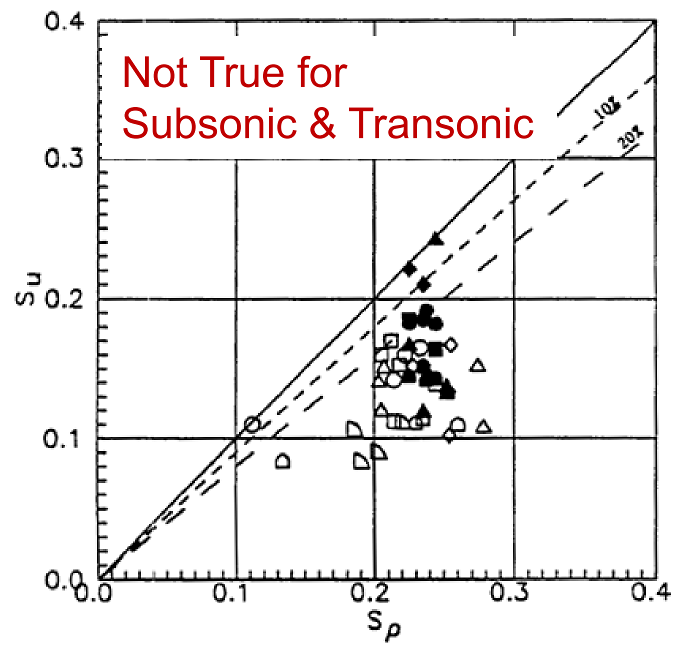
$$S_u(\rho,U,T_0,\phi) = \left.\frac{\partial \log E}{\partial \log U}\right|_{\rho=const.,\ T_0=const.,\ \ \phi=const.}$$

$$S_{T_0}(\rho,U,T_0,\phi) = \left.\frac{\partial \log E}{\partial \log T_0}\right|_{\rho=const.,\ U=const.,\ \ \phi=const.}$$

$$S_\phi(\rho,U,T_0,\phi) = \left.\frac{\partial \log E}{\partial \phi}\right|_{\rho=const.,\ U=const.,\ \ T_0=const.}$$

In supersonic flow $S_\rho = S_u$;

$$\Rightarrow \frac{e'}{\overline{E}} = S_\rho \frac{\rho u'}{\overline{\rho U}} + S_{T_0} \frac{T_0'}{\overline{T_0}} + S_\phi \phi'$$



- Parameterizing one parameter at a time while others remain constant

➔ Impractical ➔Non-Physical (Purely Empirical) ➔Not Reliable

Dimensional Analysis

Dimensional Analysis of Thin Heated Wires:

$$Nu = f(Re, Pr, M, Gr, \ \tau, \ \frac{l}{d}, \ \phi) \qquad \tau = \frac{T_w - \eta T_0}{T_0} \qquad \eta = f(Re, M, \ \phi)$$

(η = Recovery factor)

High speed air flow for a given probe at constant overheating:

Pr , ***l / d*** and ***τ*** are constant and negligible **natural convection** (if $Gr < Re^3$)

$$\boxed{Nu = f(Re, M, \ \phi)}$$

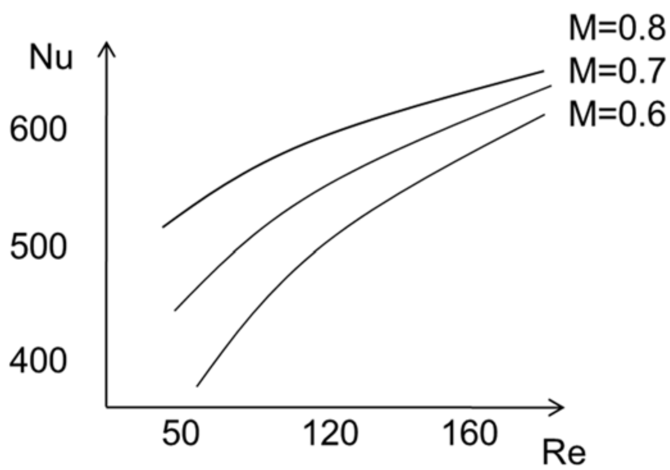
$$Re = \frac{\rho U \, d_w}{\mu} \qquad Nu = \frac{h \, d_w}{k} \qquad M = \frac{U}{\sqrt{\gamma R T_s}}$$

$$\left(h = \frac{q''}{(T_w - T_r)} \quad and \quad q'' = \frac{E_w^{\ 2}}{AR_w} \right)$$

=?

Non-Dimensional Methodology

$$Nu = f(Re, M, \phi)$$

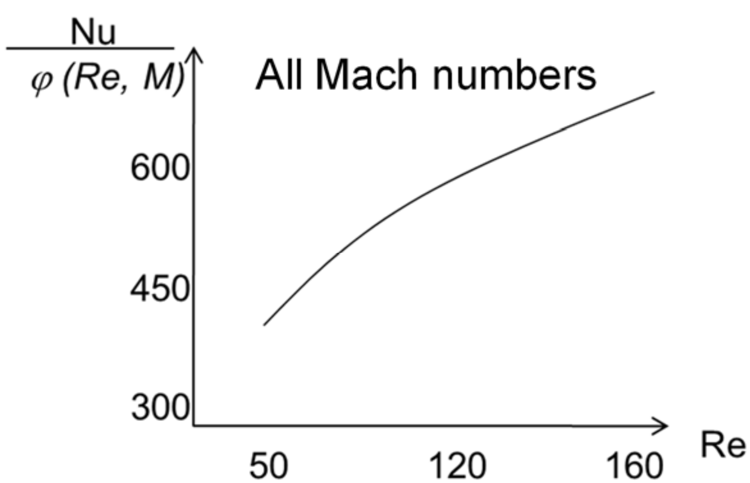


$$Nu_{corr}(Re) = \frac{Nu\,(Re, M)}{\varphi(Re, M)}$$

Where;

$$\varphi(Re, M) = 1 + A(M)\left[1.834 - 1.634\left(\frac{Re^{1.109}}{2.765 + Re^{1.109}}\right)\right] \times \left[1 + \left(0.3 - \frac{0.0650}{M^{1.670}}\right)\left(\frac{Re}{4 + Re}\right)\right]$$

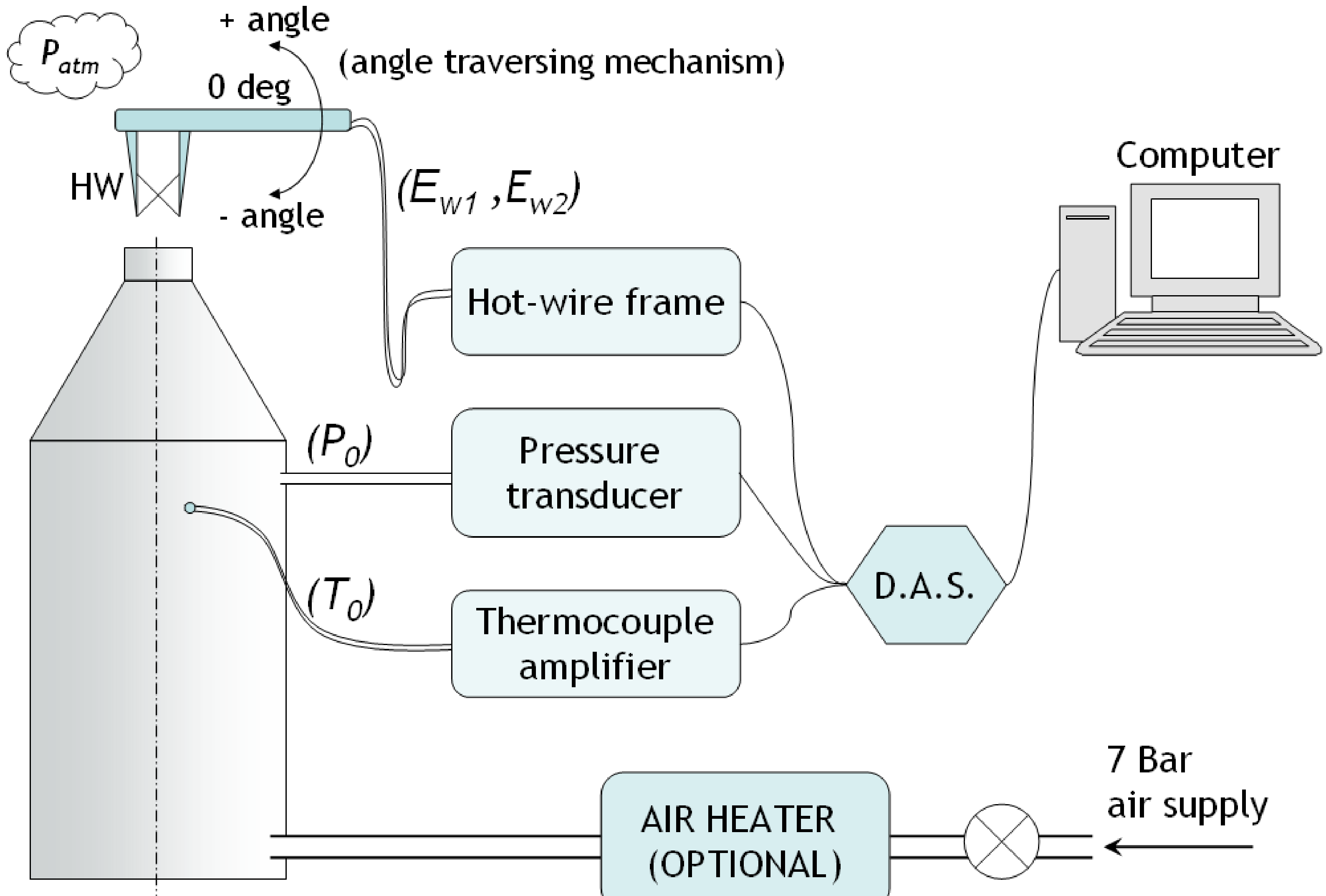
$$A(M) = \frac{0.6039}{M} + 0.5701\left[\left(\frac{M^{1.222}}{1 + M^{1.222}}\right)^{1.569} - 1\right]$$



$$\Rightarrow \quad Nu_{corr} = f(Re, \phi)$$

Required Calibration Facility

The calibration setup schematic view:



Wire Temperature Calculation

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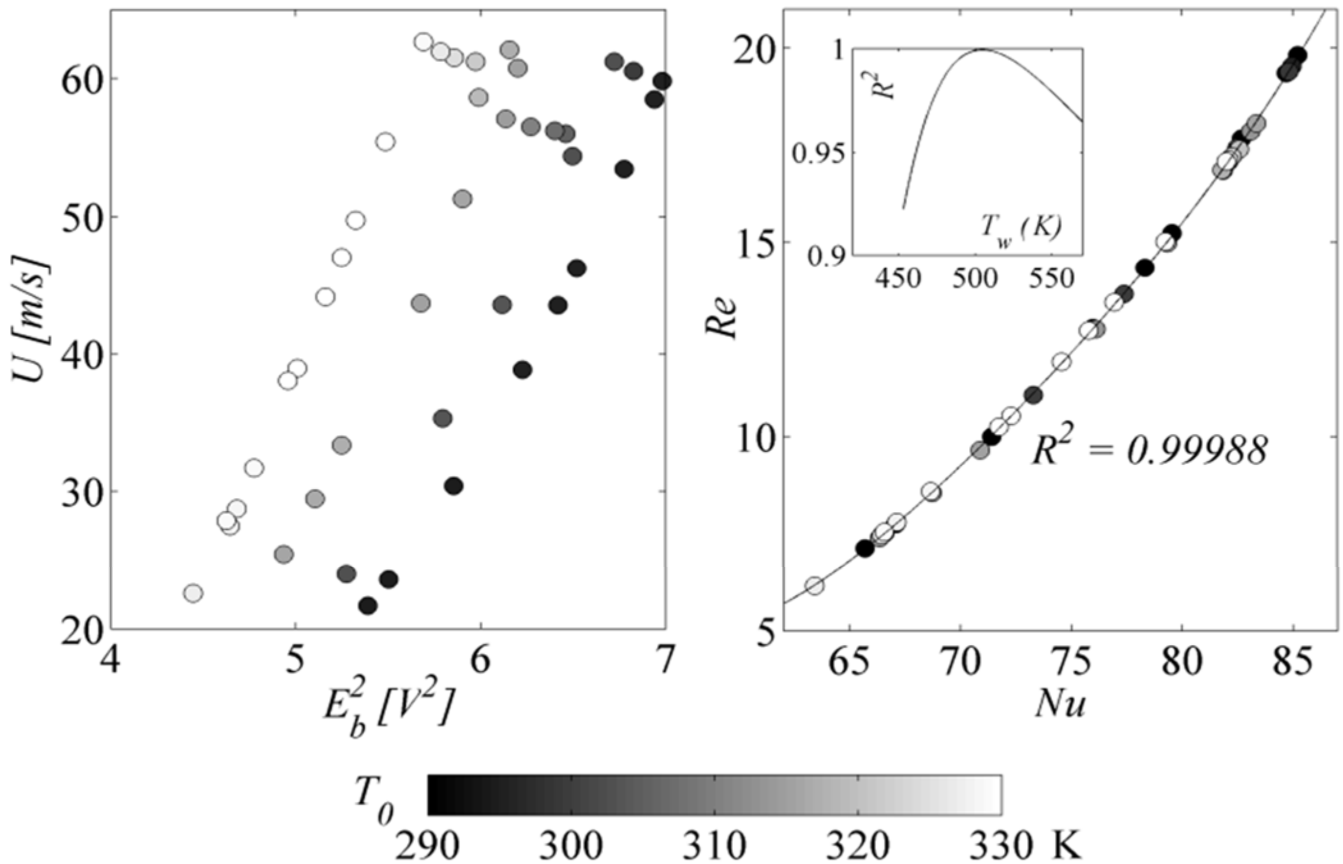
$$Nu = \frac{h\,d_w}{k} \Rightarrow h = \frac{q''}{(T_w - T_r)}$$

For Ma<0.1 and given ϕ ➔ *Nu=f(Re)*

Least Square Fit of Wire Temperature as Free Parameter

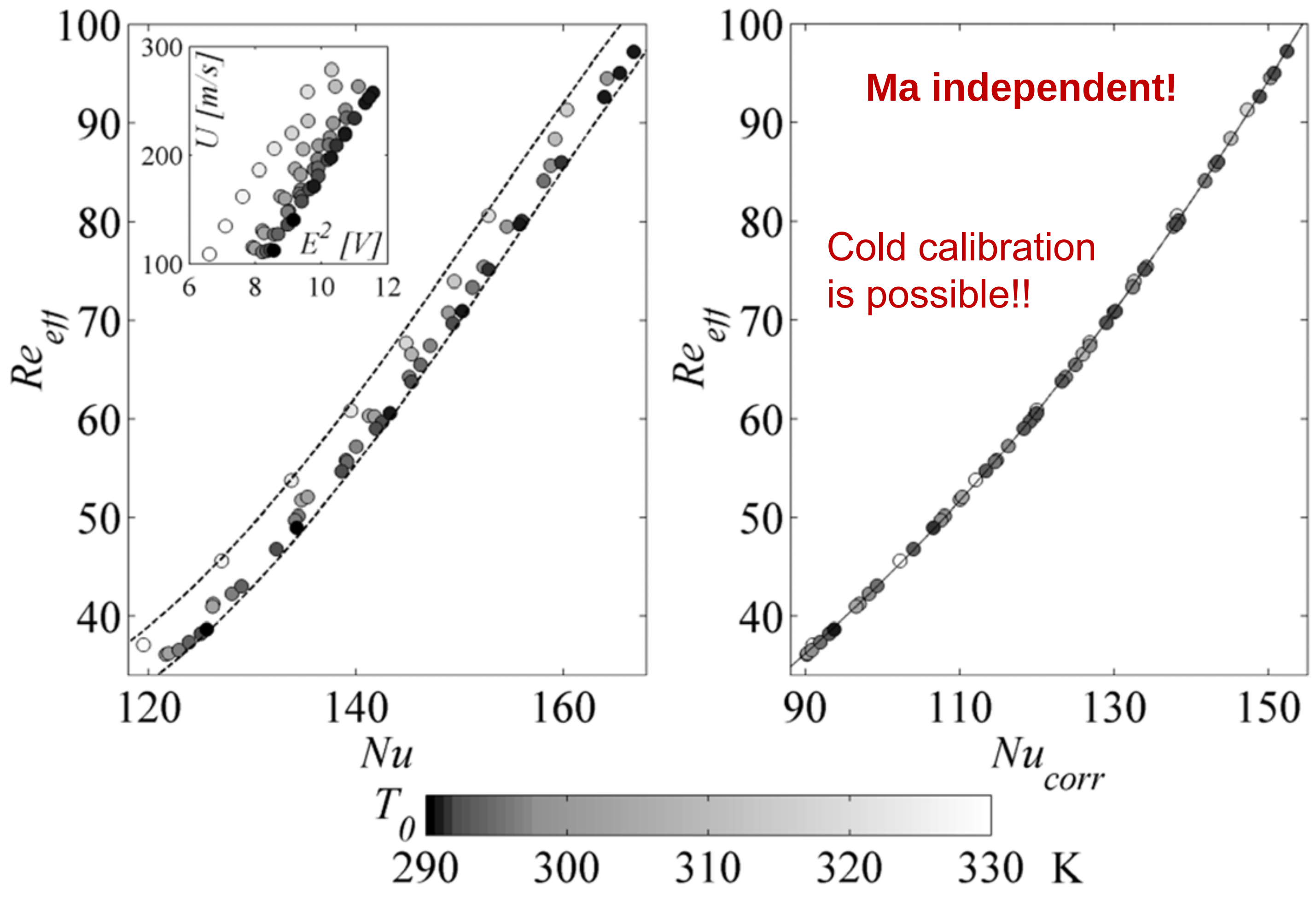


✓ Correct T_{wire} Collapses Population of Re-Nu Data onto Single Curve

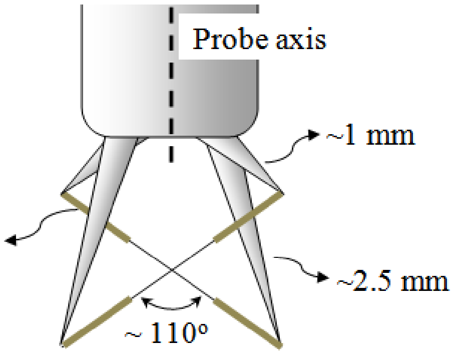
Mass Flux Calibration

$$Nu_{corr} = f(Re, \phi)$$

$$Nu_{corr}(Re) = \frac{Nu\,(Re, M)}{\varphi(Re, M)}$$

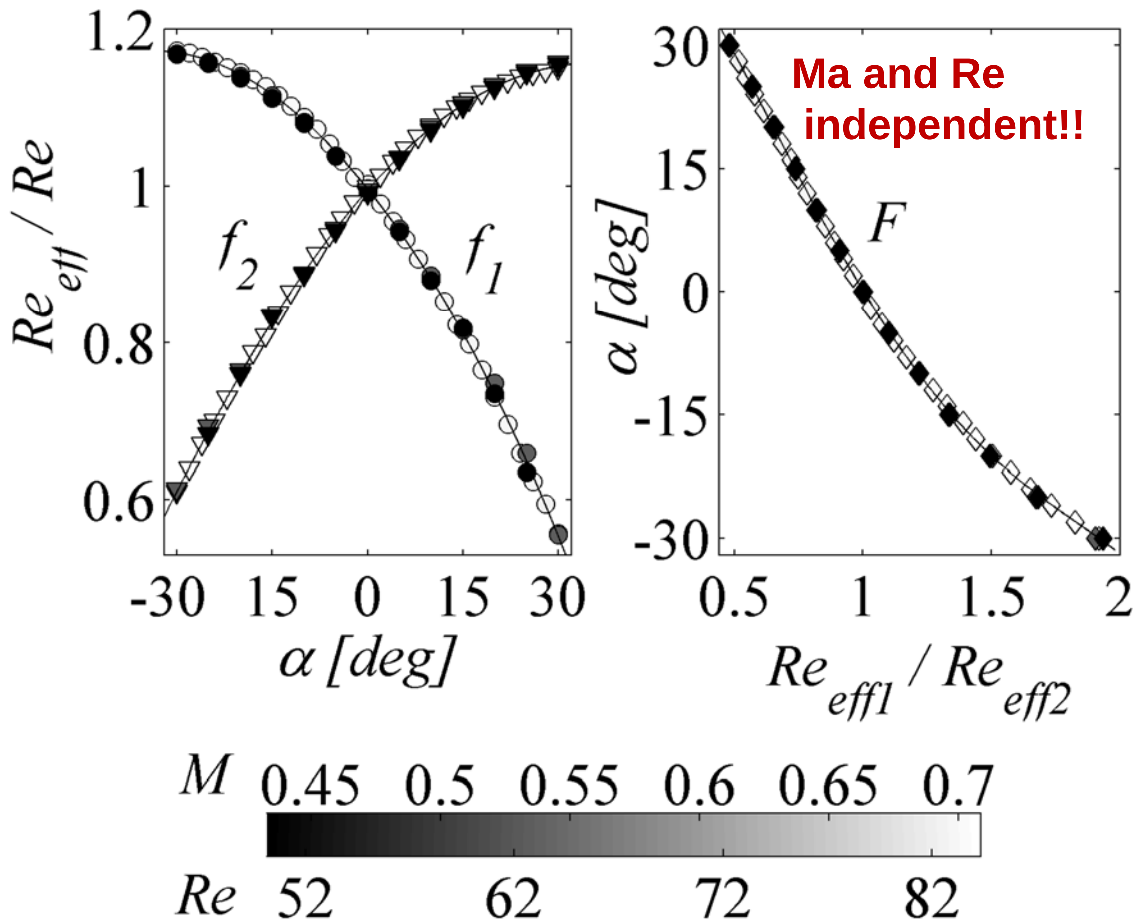


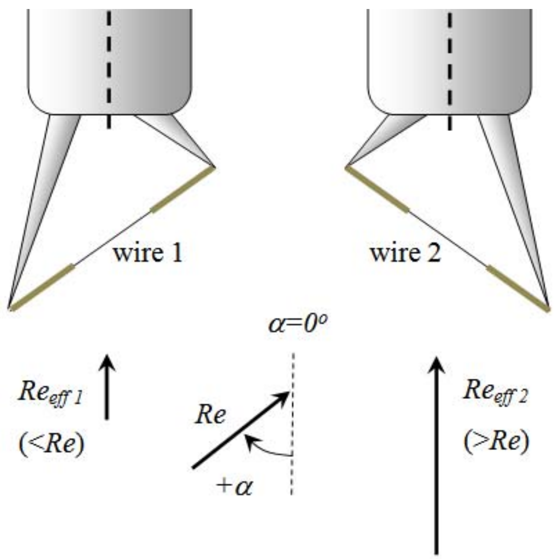
Angular Calibration



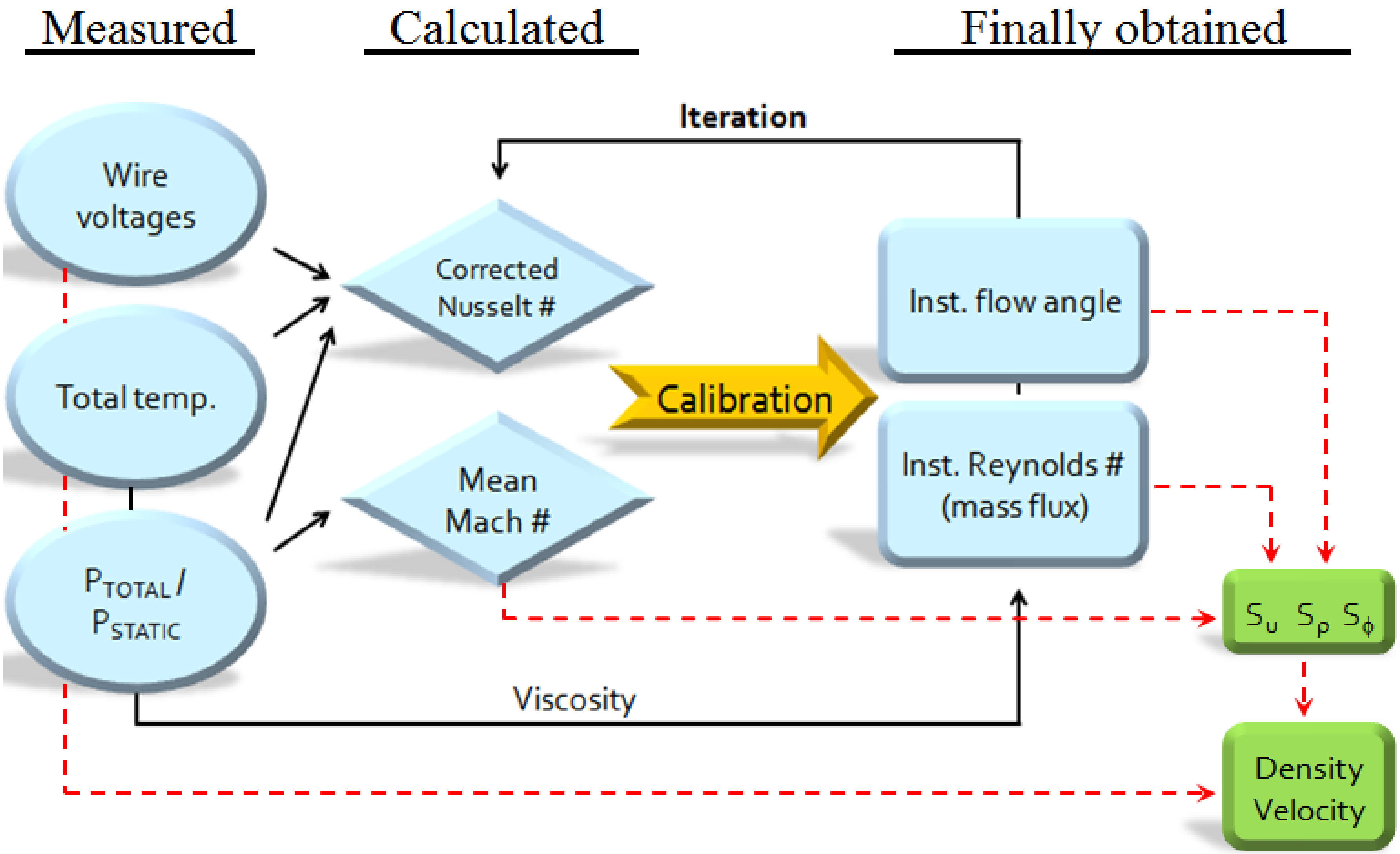
Re_{eff} : Same Nu if the probe was aligned at the reference position

$$\left.\begin{aligned} Re_{eff1} &= Re \; f_1(\phi) \\ Re_{eff2} &= Re \; f_2(\phi) \end{aligned}\right\} \frac{Re_{eff1}}{Re_{eff2}} = \frac{f_1(\phi)}{f_2(\phi)} \Rightarrow \phi \Rightarrow Re$$





Procedure Steps



- Mass flux uncertainty is 1.8 % (95% confidence level)
- Flow angle uncertainty is 1.1 degrees (95% confidence level)

Sensitivity Analysis

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$$\frac{e'}{\bar{\bar{E}}} = S_\rho \frac{\rho'}{\bar{\bar{\rho}}} + S_u \frac{u'}{\bar{\bar{U}}} + S_\phi \phi'$$

Logarithmic differentiation of Nu gives:

$$Re = f(\rho, U, T_0) \qquad M = f(U, T_0)$$

$$\eta = \eta(Re, M, \phi)$$

$$S_\rho = \frac{1}{2}\left(\frac{\partial logNu}{\partial logRe} - \frac{1}{\tau}\frac{\partial log\eta}{\partial logRe}\right)$$

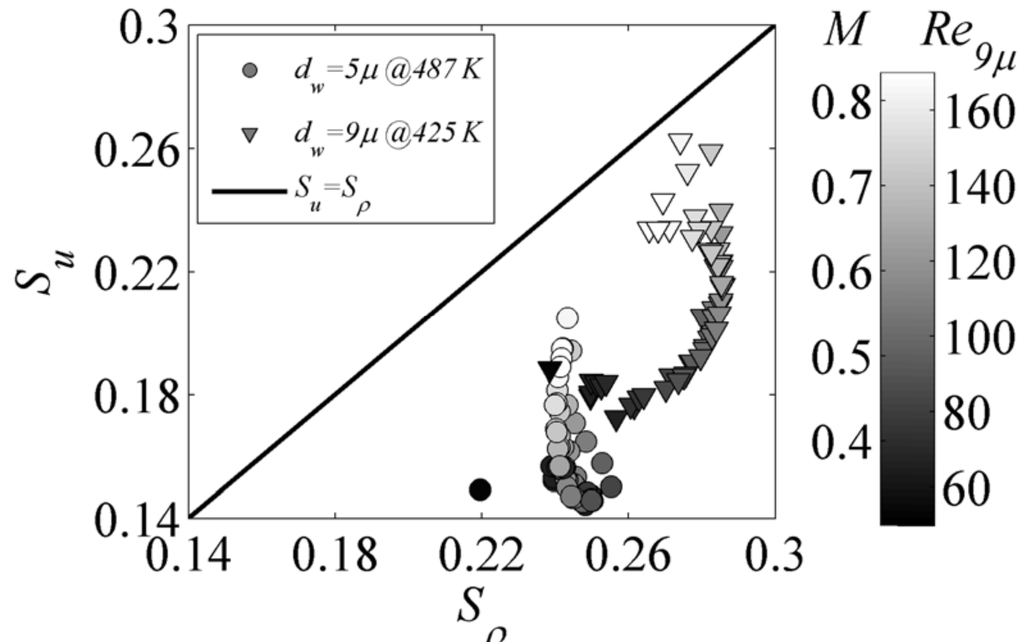
$$S_u = S_\rho + \frac{1}{2\alpha}\left(\frac{\partial logNu}{\partial logM} - \frac{1}{\tau}\frac{\partial log\eta}{\partial logM}\right)$$

$$S_{T_0} = \frac{K}{A_w} + \frac{1}{2}(K - 1 - n_t) + m_t S_\rho + \frac{1}{2}(S_u - S_\rho)$$

$$S_\phi = \frac{1}{2}\left(\frac{1}{\tau}\frac{\partial log\eta}{\partial \phi} - \frac{\partial logNu}{\partial \phi}\right)$$

$$K = \partial logR_w / \partial logT_w \qquad n_t = (\partial logk / \partial logT_0)$$

$$A_w = \partial logR_w / \partial logI \qquad m_t = (\partial log\mu / \partial logT_0)$$



$$\begin{bmatrix} \frac{e_1'}{\bar{\bar{E}}_1} \\ \frac{e_2'}{\bar{\bar{E}}_2} \end{bmatrix} - \begin{bmatrix} S_{\phi 1} \\ S_{\phi 2} \end{bmatrix} \phi' = \begin{bmatrix} S_{\rho 1} & S_{u1} \\ S_{\rho 2} & S_{u2} \end{bmatrix} \begin{bmatrix} \frac{\rho'}{\bar{\bar{\rho}}} \\ \frac{u'}{\bar{\bar{U}}} \end{bmatrix}$$

Δ [S_ρ /S_u] with Δτ is limited to 8 % ➔[ ] ill-conditioned

➔ Δ [S_ρ /S_u] with Δd_{wire}= 5μm to 9 μm up to 20 %

✓ **Instantaneous Density AND Velocity Fluctuations can be Computed**

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Why Should You Care?

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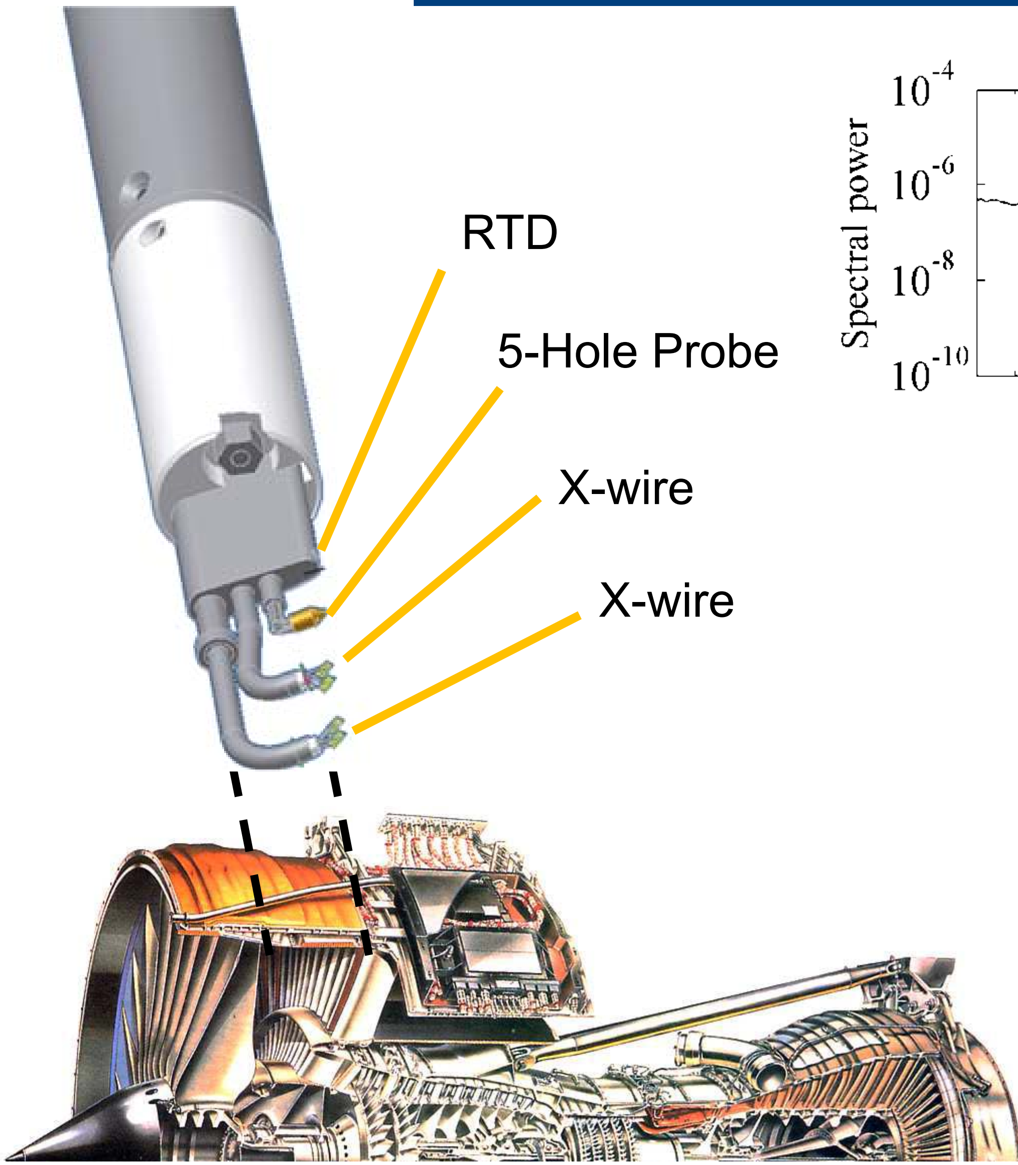
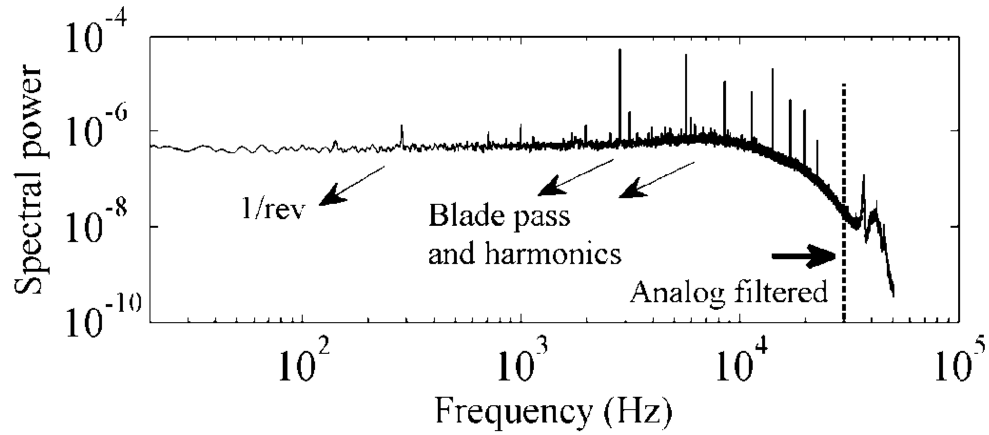
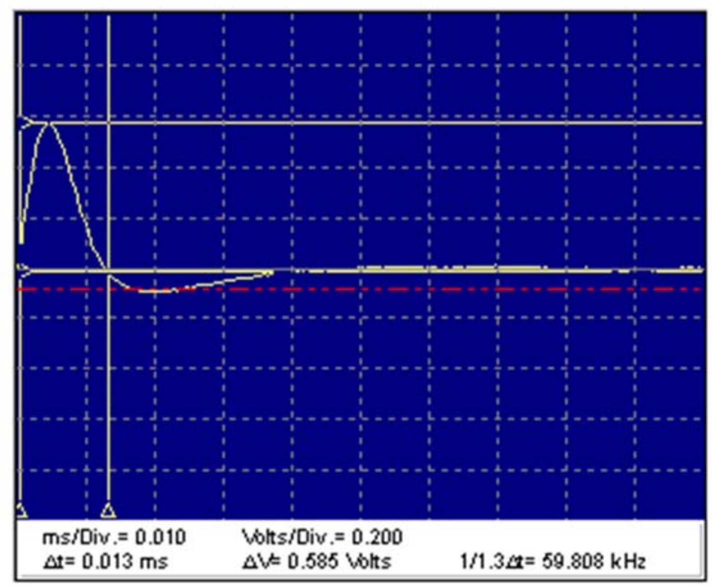




5µm wire (~60kHz @M=0.8)



Exemplary Analysis

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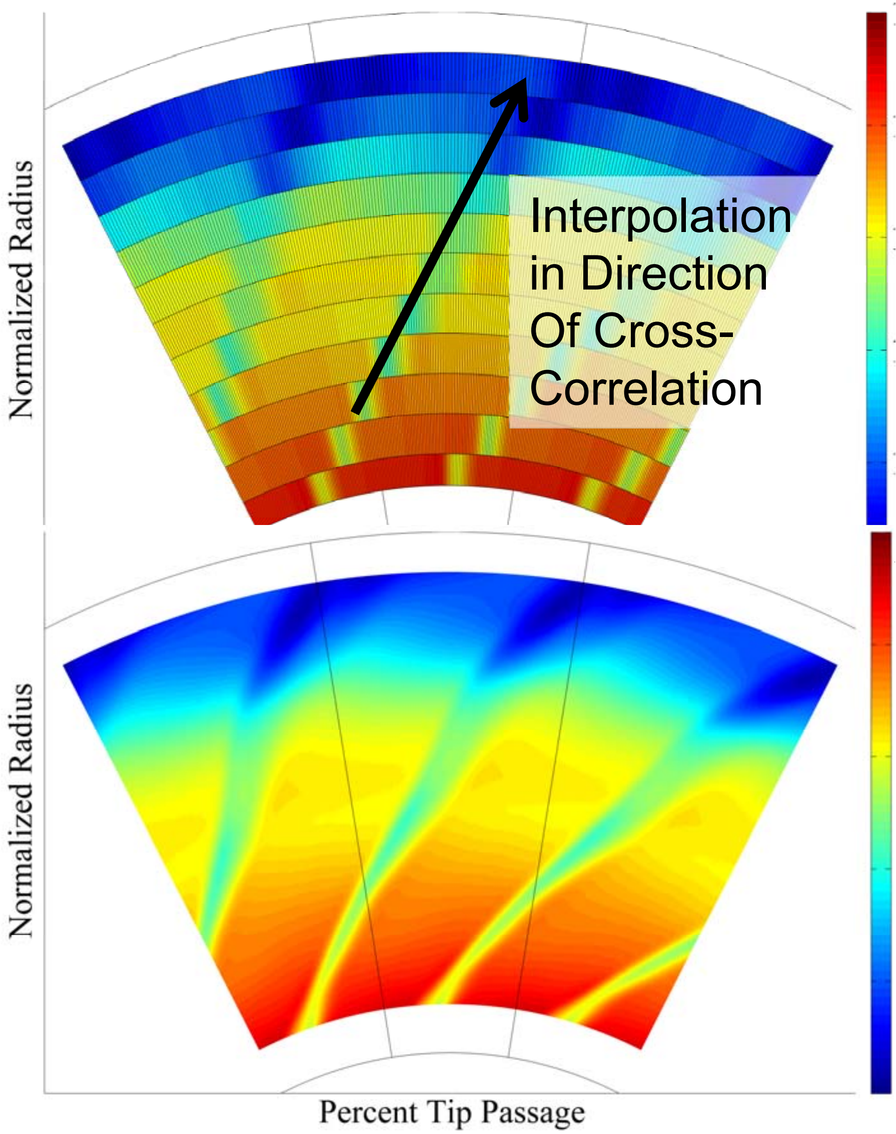
Mass Flux [kg/m_2-s]



This is not CFD!!!!

Possible to Calculate:

- Mass flux
- Angle
- Velocity
- Density
- P_o

Independent Fluctuation of Each Component
+
Blade to Blade Variation of Each Component

Data Useful in:

- Time/Frequency Domain Analysis
  - CFD Validation
  - Test-Aided Design
  - Performance Characterization
  - Length/Time Scale Identification
  - Effects of Manufacturing Tolerance
  - Noise Spectra

Separation of ρ and U

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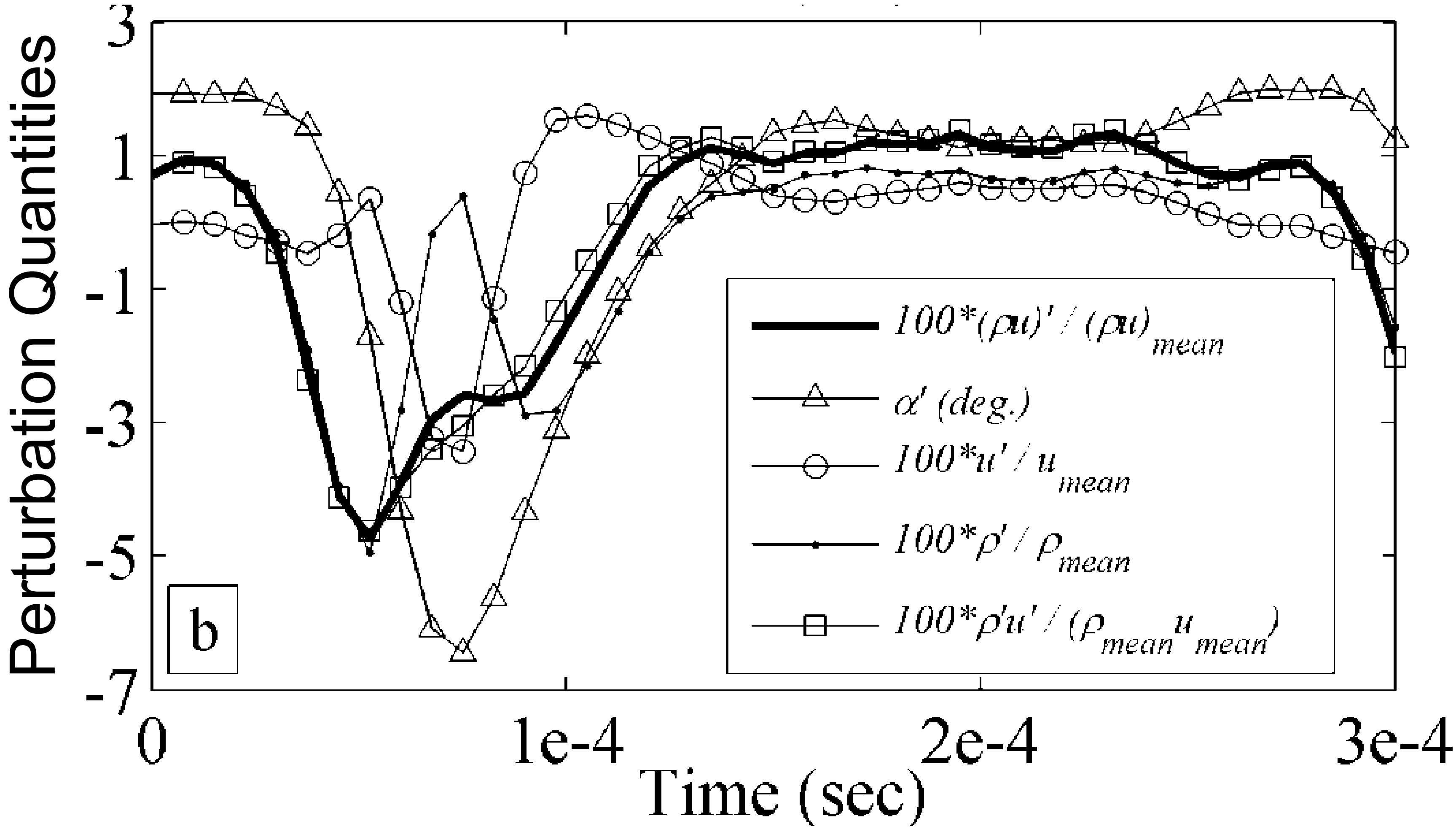
The Perturbation Quantities in a Real Gas Turbine Fan



For The First Time: Instantaneous Velocity & Density in Compressible Flows

Summary & Conclusions

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Demonstrated Novel High Speed Cross-Hotwire Operation Scheme:

- Practical
  - Nondimensional Parameters (Re, Nu, Ma) and widely accepted correlations are used
  - No need for closed loop wind tunnels
  - Effort equivalent to that of operation in isothermal low speed flows
- Accurate
  - Instantaneous mass flux and flow angle can be determined within 1.8% and 1.1° uncertainty (95% confidence level)
- Valid over a wide range of Reynolds and Mach numbers (Subsonic + Transonic)
  - Calibrations obtained in cold jet (e.g. T_0=290K) are valid at measurement environments (e.g. Gas turbine fan where T_0=335K).
- Instantaneous density and velocity fluctuations can be independently computed
- Application is demonstrated by measurements conducted in gas turbine fan

Associated Publication

Technion

Cukurel, B., Acarer, S., Arts T., “A Novel Perspective to High Speed Cross-Hotwire Calibration Methodology”, *Experiments in Fluids,* Vol. 53, pp. 1073-1085, 2012.